Groundwater Protection and the Development of Risk-Based Contaminated Soil Clean-Up Standards Using Computer Modeling

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Abstract

In the early days of remediation of hazardous waste sites in the United States, regulators required the regulated parties to remediate their sites to pristine, or background concentration levels. The superfund experience, under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), demonstrated that an inordinate amount of money and effort was required to bring a site to clean levels under this definition. A new approach

is gaining wide acceptance by regulators and regulated parties where clean-up standards for soil are established on the basis of risk. The risk standards for groundwater are set with the aid of computer models, which are used as tools to predict the contaminant transport and concentrations at potential receptor sites. Regulators in New Hampshire, USA, following the lead of other states, are using a combination of computer models to establish generic clean-up standards for soils across the state. The authors outline the procedure for setting clean-up standards, and detail the benefits of the risk-based approach. The benefits include more realistic clean-up goals, opportunities for responsible parties to more readily achieve final site closure, and a significant cost savings.

1.0 Background

At hazardous waste sites where contaminated soils pose a threat to groundwater quality, remediation efforts often focus on physical off-site removal or some means of on-site mechanical removal (soil vapor extraction, etc.) to the extent where the soil can no longer produce leachate at concentrations to degrade groundwater quality in the aquifer. This extent is defined as the allowable contaminant concentration in the soil. In the early days after the United States enacted CERCLA (Superfund) regulations, most environmental regulators assumed the conservative position that if contamination could be detected in soil, it must be removed or remediated to natural background levels. As laboratory techniques became more accurate with ever-smaller detection limits, the level of remediation was subsequently increased. This position, while protecting groundwater quality, caused millions, possibly billions, of public tax dollars to be wasted on soil remediation activities that were not necessary

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to protect groundwater quality.

There is a more recent shift towards basing the extent of remediation to the achievement of allowable contaminant concentration levels in the soil. These allowable levels are based on predictions of the resulting aquifer contamination, and the risk that the subsequent migration of contaminants in the aquifer poses to the human population and the environment downgradient of the contaminated site. Determining the allowable concentration for the hundreds of chemicals commonly found in the soil at hazardous waste sites has perplexed government regulators for years. Now, with new and powerful computer models developed to predict the fate and transport of chemicals as they migrate through the vadose zone, modelers are able to predict aquifer contamination levels using specific site and chemical characteristics. Regulators in the United States have recently begun to use these computer models to establish „risk-based“ rather than „rule-based“ clean-up standards.

2.0 History of Regulation in the United States

Groundwater is the primary source of drinking water for over sixty percent (60%) of the population living in the United States of America (USA). In rural areas, the dependence on groundwater sources can approach eighty-five percent (85%); and it is typically the only source of drinking water available.

Prior to the late 1970's very little attention was focused on groundwater protection, even with the tremendous dependence on groundwater sources in the United States (US). That changed dramatically due to a discovery made in the 1970s in a small community of Love Canal, NY, USA. Love Canal was the site of the US’s first highly publicized toxic waste dump. Vast quantities of chemicals were buried at Love Canal during the 1940's and 50's. Excavations during the late 1970's and early 80's revealed the terrible truth behind the "out of sight, out of mind" hazardous waste disposal techniques employed in the early and middle 20th century. Investigations at Love Canal confirmed the suspicion that drummed toxic waste did not remain contained for very long. Once breached, the steel drums leached toxic compounds into the surrounding soils and ultimately into groundwater. As if that discovery was not bad enough, it was also discovered that the contaminated groundwater was being consumed by local residents as drinking water.

Politicians were compelled to address the growing public health concerns associated with these toxic waste sites (mainly contaminated drinking water issues). In an initial effort to begin tracking toxic chemicals, the United States government passed the Resource Conservation and Recovery Act (RCRA) in 1976. Continued public pressure compelled Congress to pass the **C**omprehensive **E**nvironmental **R**esponse **C**ompensations and **L**iability **A**ct (CERCLA) in 1980. CERCLA gave the U.S. government the ability to tax sales of specific chemicals, and by doing so, earmark the tax revenue for the eventual restoration of confirmed hazardous waste sites across the nation. The huge reserves of money accumulated within this fund, earned it the nick-name *Superfund*.

Superfund paid for much of the education, experimentation, technology development, implementation of the technology, and problem assessment dealing with contaminated sites. Despite the vast expenditures, the primary objective of the program had not been met. That objective was to clean up confirmed hazardous waste sites to natural background levels quickly. This truth is all too striking in the following statistics. From 1980 to present, Superfund has spent approximately 30 billion U.S. Dollars on clean-up activities across the nation. Of the more than 2,000 toxic waste sites classified as Superfund eligible, to date less than 100 have been considered "clean". Over the same time span, some 30,000 additional sites have been scheduled for investigation to determine if they will also be placed on the Superfund list for remedial action (Giunta/Enmarch-Williams, 1996).

The realization of what appeared to be the dismal failure of Superfund had a similar political affect as the discovery of Love Canal. After evaluating over 15 years of data associated with Superfund sites, the environmental community realized that the idea of quickly achieving pristine conditions at all hazardous waste sites by paying great sums of money for primarily one technology (groundwater pump and treat) was unrealistic.

The reasons were twofold. First, toxic chemicals, once introduced into the environment, were a lot more difficult to remove than anyone had anticipated. Second, regulatory clean-up goals initially set for sites were found to be unattainable, consequently causing huge amounts of expenditure for little gain. Regulations at that time specified that the site could be considered closed only after the clean-up goals were met. In the case of toxic clean-up, initial high concentration chemical masses were removed quickly. However, remedial action follows a law of diminishing return, such that an exponentially increasing input of time and money was needed to remove the final remnants of low concentration toxins.

In an attempt to reduce the enormous expenditures and to reverse the appearance of total failure for Superfund, the environmental community arrived upon a more cost effective way of marrying regulation and clean-up. A new approach was developed in which regulatory agencies are more willing to relax remedial clean-up goals based on the associated level of ***risk*** to human health and the environment.

This new approach of setting clean-up goals based on risk, followed by determining the appropriate remedial action was given the acronym RBCA (pronounced Rebecca) which stands for **R**isk **B**ased **C**orrective **A**ction. In a majority of contaminated sites, RBCA would most certainly allow less stringent clean-up levels to be mandated, while still protecting human health and the environment. As such, a greater contaminant mass might be allowed to remain in-situ. This will result in a reduction in remedial costs and will allow sites to achieve closure status much sooner than by past standards. Thus, sites are remediated faster and less expensively.

The three most dramatic ramifications of this radically new, yet totally logical, change in direction are: 1) regulators and responsible parties are now able to negotiate and establish *more realistic clean-up goals*, 2) *significant cost saving* throughout the remedial process may now be realized, and 3) a much greater opportunity for responsible parties to *achieve regulatory closure is now a reality*. In short, the implementation of a Risk Based Corrective Action through the use of computer models saves significant quantities of time and money while being protective of human health and the environment (Cook, Giunta, and Enmarch-Williams, 1998).

Standard procedure until recently dictated that in order for regulators to relent from the background level clean-up standard the responsible party would be required to perform an expensive, site-specific risk assessment of the threats the site posed to human health and the environment. Individuals and small businesses usually could not afford these studies which again left them with only one option: clean-up to background. For years, the regulated community pleaded regulators to develop a list of generic soil clean-up standards. These standards would be established such that soil containing less those prescribed concentrations for specific contaminants would still be protective of human health and the environment at all sites. The universal applicability of these standards requires they be conservative and that they be developed by using site and soil characteristics indicative of the regulated region, that reflect the maximum contaminant infiltration into the groundwater which could occur in the region.

3.0 Risk Based Soil Clean-up Standards

3.1 Method Development

The State of Oregon Department of Environmental Quality was an early visionary in developing methodologies for the using computer models in a risk-based approach to setting clean-up standards. Anderson (1992) described a methodology for determining chemical specific clean-up goals using computer modeling. From the numerous computer models available for both the vadose zone and the saturated water-table aquifer (van der Heijde/Elnawawy, 1993), two computer models, Seasonal Soil Compartment Model (SESOIL) and Analytical Model of Transport 1-, 2-, and 3-Dimensional Waste Transport (AT123D), both originally produced for the EPA, were selected. SESOIL was used to model chemical specific leachate flow in the vadose zone and AT123D was used for contaminant transport through the aquifer. The computer simulations were used to establish the threshold levels of soil contamination which would not adversely affect groundwater quality. This original work prompted other states to pursue „risk based“ clean-up methodologies. In April 1995, Wisconsin’s Department of Natural Resources codified in their *Soil Cleanup Standards* „risk based“ chemical specific soil clean-up standards using modeling

(WIDNR, 1995).

The New Hampshire Department of Environmental Services (NHDES) followed lead States like Oregon and Wisconsin and after reviewing the scientific basis and the performance record of the new methodologies, adopted the *Interim Policy for the Management of Soils Contaminated From Spills/Releases of Virgin Petroleum Products* in September of 1991. The „Interim Policy“ was optimistically received and quickly won support from the regulated community. It was the first policy in New Hampshire that addressed individual petroleum compounds, allowed scientific evaluation, and, based on individual compound risk analyses, allowed for closure of sites even though petroleum constituents may have still been detected within site soils. The program was such a success, business and industry quickly requested the program be expanded from petroleum compounds to all compounds regarded as „hazardous wastes.“

Because the computer simulations were indifferent to the type of chemical modeled, expanding the „risk based“ analyses to hazardous wastes was the logical next step in the process. Work progressed on the ground water leaching analyses with the computer model, and also the risk characterization for the generic sites. The result lead to the adoption of the Risk Characterization and Management Policy (RCMP) in September of 1996 (NHDES, 1996). To establish the criteria set out in this document, leachate migration through the vadose zone and throughout the aquifer was simulated for one hundred and forty seven specific chemicals.

3.2 Description of the Computer Models

3.2.1 SESOIL

The modeling tool selected by the NHDES was the combination of two coupled models, SESOIL and AT123D. The selection of these models was based, in part, on the success that other states had using the same models, in particular the States of Oregon, Wisconsin, and Massachusetts. SESOIL is a one-dimensional compartmental model for vertical water flow and contaminant transport in the vadose zone. It breaks the vadose zone into compartments of soil (for adsorption), soil moisture (dissolved chemical species), and soil vapor (volatilized chemical species). Water flow is based on the unsaturated zone water balance model of Eagleson (1978).

The model incorporates the processes of precipitation (P), infiltration (I), surface runoff (SRO), evapotranspiration (ET), capillary rise from the water table (CR), soil moisture retention (ΔS), and groundwater recharge (U). Moisture flow within SESOIL is based on the following water balance equation:

$$P + CR - ET - \Delta S = SRO + U \tag{1}$$

and

$$I = P - SRO \tag{2}$$

For moisture flow the model assumes a homogenous, isotropic soil column with uniform effective porosity and unsaturated hydraulic conductivity. It follows that the soil moisture content is also assumed to be uniform along the length of the column for each respective time step. The model utilizes a climatic data base compiled for the US to assign hydrologic input parameters. The water flow is driven by a series of statistically derived storm events, using the climatic data input.

The model computes the pollutant transport using the average monthly hydrologic cycle results. Pollutant transport is computed on a daily basis by computing a pollutant mass balance for each compartment, and assuming equilibrium partitioning between the different phases (dissolved, sorbed, vapor and pure). The mass balance equation is:

$$O_{(t-1)} + I_{(t)} = T_{(t)} + R_{(t)} + M_{(t)} \tag{3}$$

where $O_{(t-1)}$ = Original species mass in compartment,
$I_{(t)}$ = Species mass input,
$T_{(t)}$ = Species mass transformed,
$R_{(t)}$ = Remaining species mass, and
$M_{(t)}$ = Mass lost to other compartments.

The pollution cycle of SESOIL accounts for the residual pure phase as well as the fate processes of advection, adsorption, volatilization, vapor phase diffusion, first-order transformations such as biodegradation and hydrolysis, complexation, and residual pure phase. Input parameters include site dimensions, extent of contamination, soil characteristics, climate data, and chemical properties. The climatic data required is generally gathered from the region in which the site is located. In the US, climatic data has been compiled in a large data base from available weather stations across the country.

The chemical characteristics required for the pollution cycle are typically gathered from the literature (e.g. Lyman, Reehl, and Rosenblatt, 1982). A complete presentation of the theory and internal functions of the model can be found in Hetrick, Scott and Barden (1994).

3.2.2 AT123D

SESOIL is typically run in conjunction with AT123D, which is an analytical transport model for the saturated water table aquifer. SESOIL provides the data for the vertical mass transfer of the specific contaminant to the groundwater table. The migration of the contaminant with the ambient groundwater flow is simulated by

AT123D. The name can be misleading: this model is essentially a one-dimensional groundwater flow model. The second and third dimensions refer to the model's computation of dispersion/diffusion effects, in which the contaminant plume may spread out in the vertical and transverse directions from the advective flow. It is an analytical model, and assumes a homogeneous aquifer in which groundwater flow velocities (v) are computed for steady-state horizontal flow under a small gradient. Effects of anisotropy are handled by varying the dispersivity tensor (*D*). The model accounts for advective and dispersive transport of the contaminant species, and includes retardation (R), and first-order transformation (decay) processes (λ). Transport is computed using the standard advection-dispersion equation (ADE):

$$\frac{\partial C}{\partial t} = \nabla \bullet \left(\frac{D}{R} \bullet \nabla C \right) - \nabla \bullet \frac{v}{R} C + \frac{M}{\Phi R} - \lambda C \tag{4}$$

The ADE includes a term for mass loading (M). The effective porosity is represented by Φ. The user must specify the points downgradient for which the time-series concentration values are desired. Yeh (1981) provides a more detailed discussion on the theory and use of AT123D.

3.3 Procedure for setting clean-up standards

The procedure used in New Hampshire to establish clean-up standards for contaminated sites followed two parallel paths. The first path involved establishing standards based on the risk of human exposure for a typical site. The risk of exposure is assessed based on direct contact (dermal), ingestion (eating), daily ingestion rates, absorption factors, soil to skin adherence factors, exposure frequency, exposure duration, body weight, skin area, target excess lifetime cancer risk, oral cancer potency factor, and age of person. The details of this analysis are beyond the scope of this paper, but typical procedures are described by USEPA (1989, 1991a, b). Three categories of soil subject to human exposure were established. The first category represented high frequency of exposure to both children and adults, with soil contamination readily accessible on the surface, including soils used for growing crops. The middle category is for accessible soils with low frequency of exposure, such as controlled areas within a fence. The last category includes soils not readily accessible, where the frequency of exposure is low for both children and adults. Risk assessments were performed for each of the three soil categories. For each category, a maximum concentration in soil was established for the respective chemical contaminant.

The second path for establishing clean-up standards was to evaluate the exposure potential and subsequent risk due to the migration of the contaminant to the groundwater table, and the subsequent transport to potential receptor sites, such as a well used as a drinking water source, or a groundwater seep or spring. It is this path for which the computer model is used.

3.3.1 Groundwater leaching risk analysis

The first step in developing clean-up standards along this path is to develop a generic release site which is typically representative of the geology of the regulated region. The generic site developed for New Hampshire followed work done in Oregon and Wisconsin, and is shown in Figure 1. A plan-view area of 100 m^2, representing an space 10 m x 10 m, was selected as the contaminated „foot-print“.

The unsaturated zone was 3 meters deep. The contaminant source was placed 1 meter deep with one-meter thick layers of uncontaminated soil above and below the contaminated zone. The generic scenario was intended to simulate a site with a leaking underground storage tank or pipeline.

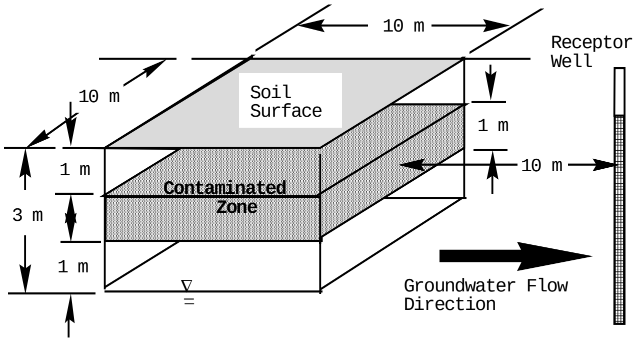

Figure 1. Dimensions and layout of the generic site.

The one-meter thick contaminated source area was assumed to be uniformly contaminated with the chemical of interest at a concentration of 10 parts per million (ppm). This concentration value was established as an average concentration for numerous spills documented in California and Oregon. A potential receptor well was located 10 m away in the down-gradient groundwater flow direction.

The site was then modeled using the combination of SESOIL and AT123D. The input parameters represented conservative values for the geology in New Hampshire. The models were run until they simulated the period necessary for the contaminant concentration in the soil water at the unsaturated soil / water table interface to reach its maximum. Depending on the contaminant, this took anywhere from a few months to a hundred years or more. For some contaminants with high molecular weights and sorption coefficients, such as polynuclear hydrocarbons (PAHs), the model predicted that they would never reach the water table.

Sensitivity analyses were performed on the dimensions and concentrations of the generic site, as described by Anderson (1992). This analyses showed that the concentrations of the chemical predicted at the receptor site were directly proportional to the concentration of the contaminant in the soil. Therefore, a dilution attenuation factor could be used to establish clean-up standards.

The ratio of the original soil concentration to the maximum leachate concentration (at the water table) is known as the Dilution Attenuation Factor (DAF), so for the generic site the DAF was computed by:

$$DAF = \frac{10\,ppm}{Max\ Water\ Table\ Model\ Concentration\ in\ ppm} \tag{5}$$

This ratio indicates the percent reduction in contaminant from the original soil concentration to the contaminant concentration in the soil water concentration that reaches the water table. Once the DAF has been established, soil clean-up standards (SCS) can be developed. This is accomplished by simply multiplying the DAF by the drinking water standard (MCL) for the respective chemical contaminant.

$$SCS = DAF \times MCL \tag{6}$$

For example, the modeled DAF for benzene was 67. The MCL for Benzene is 5 parts per billion (ppb), or 0.005 ppm. The soil clean-up standard is calculated by:

$$SCS = 67 \times 0.005\,ppm = 0.335\,ppm \tag{7}$$

Therefore, the soil clean-up standard due to groundwater exposure is 0.33 mg/kg.

3.4 Setting Risk-Based Soil Clean-up Standards

The actual soil clean-up standard used by the regulators is the lowest, or most conservative, of the values derived from each of the two paths (risk of soil exposure, groundwater exposure). Following the sample given above, the standard computed for exposure to groundwater was 0.335, reported as mg/kg for soils. The standard computed for the risk assessment for the first soil category was 26 mg/kg. The soil clean-up standard adopted for Benzene in New Hampshire was 0.3 mg/kg for all three soil exposure categories, since this value is based on groundwater exposure. Although this scenario, where the groundwater standards were the more stringent, was common, there were cases where the standards adopted were based on the risk assessment values. One such case was for carbon tetrachloride. The groundwater

MCL for carbon tetrachloride was 5 ppb, which lead to a soil standard of 100 mg/kg. Carbon tetrachloride is very volatile, and not as readily transported with the groundwater. The risk assessment values for the first soil exposure category was 6 mg/kg. This value was adopted as the soil clean-up standard.

A third scenario occasionally occurred, where the soil standards computed for both paths resulted in concentrations less than the practical limit of measurement by present analytical techniques and equipment. Such was the case for pentachlorophenol, where the groundwater analysis lead to a soil standard of 0.1 mg/kg. The risk assessment path resulted in a soil standard of 3 mg/kg for the first soil exposure category. The smallest concentration level that is currently measurable, known as the practical quantification limit (PQL) was 3.3 mg/kg. Therefore, 3.3 mg/kg was adopted as the soil clean-up standard.

NHDES has also made provisions for a regulated party to perform a similar analysis using site specific information instead of the generic site characteristics presented above. In this case, additional savings may be realized if the regulated party can demonstrate that a higher soil clean-up standard would be appropriate for their site, while still maintaining the same level of protection for human health and the environment.

Normally, the human exposure risks dictate the clean-up levels. Environmental risks can be addressed by using the same procedure as above, only substituting the appropriate groundwater MCLs for environmental receptors, such as wildlife, fish and shellfish, or plants. Risk assessments would examine the risk of exposure for the environmental receptors.

4.0 Cost Savings

Establishing the soil clean-up standards according to the risks either by soil exposure, or by groundwater exposure still allows for some contaminant to remain in the soil. The result is that only the „hot“ spots, were contaminant levels are above the clean-up standards, must be remediated. This typically reduces the remediation area, and the effort which would have been instituted to reduce the contaminant levels to pristine, or background levels. Often times the background levels were zero concentration for the chemicals released.

A study was done by NHDES on the potential cost savings using the risk-based approach to the remediation of petroleum contaminated soils. The results for five of the cases studied are summarized in Table 1. The table lists the amount of soil actually removed and remediated, and identifies the range of total petroleum hydrocarbons (TPH) found in the soil. It should be noted that for just one site, where upwards of eight thousand tons of soil was remediated, the savings would have amounted to over $500,000 US dollars. This money could have been used to remediate other sites.

Table 1. Summary of Potential Cost Savings for Case Studies

Site Name	Soil Removed (tons)	TPH Range (ppm)	Potential Cost Savings
A	1,125	100-400	$73,000
B	3,3640	100-900	$237,000
C	2,300	100-1,000	$150,000
D	6,122	50-500	$398,000
E	7,932	50-500	$516,000

5.0 Summary

This risk-based regulatory approach, combined with powerful computer models, and computer data bases, brings a sound science to a more prominent role in the decision making processes utilized in contaminated site remediation activities. This process saves public funds from being needlessly spent on unnecessary clean-up efforts, while at the same time still protecting human health and the environment. It is a procedure which could be readily adapted for nations worldwide. As improvements are made to computer models, or models are developed specifically for this purpose, the risk-based approach to remediation sites should become readily usable to regulators across the world to establish remedial action levels. The same models and procedures may be used with site specific data to demonstrate the feasibility for exceptions or alterations to the standards set using the generic site scenario.

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