Environmental Modelling & Software 46 (2013) 12–20

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Stochastic cost optimization of DNAPL remediation – Field application

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ARTICLE INFO

Article history:
Received 13 November 2011
Received in revised form
2 April 2012
Accepted 9 May 2012
Available online 12 June 2012

Keywords:
Stochastic cost optimization
Uncertainty
DNAPL
Calibration
Monte Carlo simulation
East Gate Disposal Yard
Thermal source treatment
Enhanced bioremediation

ABSTRACT

A stochastic remediation design optimization methodology implemented in the program Stochastic Cost Optimization Toolkit (SCOToolkit) was successfully applied to evaluate remediation options at the East Gate Disposal Yard (EGDY) at the former Fort Lewis, now Joint Base Lewis-McChord (JBLM), Washington. Non-optimized forward simulations based on calibrated parameters and their uncertainty inferred from data prior to actual thermal source remediation system implementation at the site indicated a low probability of the actual thermal system design meeting remediation criteria in a reasonable time frame. Calibration using additional data collected during thermal treatment reduced prediction uncertainty, but still predicted a high probability of taking more than 100 years to reach compliance criteria using the actual thermal treatment design with no additional remedial action. Stochastic optimization of the thermal treatment design indicated larger treatment areas were needed to capture source mass due to uncertainty in source delineation. The expected cost for the enlarged thermal treatment system was estimated to be $22M, which is nearly twice that of the actual system, suggesting that additional characterization to reduce source delineation uncertainty or consideration of an alternative strategy that is less sensitive to delineation uncertainty may be warranted. Stochastic optimization of whey injection was investigated to accelerate source zone dense nonaqueous phase liquid (DNAPL) dissolution and enhance dissolved plume biodecay. The optimized design indicated a 93% probability of meeting compliance criteria by 2100 with an expected net present value cost of $4.7M. Whey injection substantially shortened the remediation time compared to no whey injection. The results indicate that the proposed stochastic cost optimization approach is able to reduce expected remediation costs, increase the probability of achieving remediation objectives, and identify data characterization needs.

1. Introduction

Parker et al. (2013) describe a methodology for optimizing the design and operation of dense nonaqueous phase liquid (DNAPL) site remediation and monitoring to meet specified performance criteria with minimum cost considering uncertainty in predicted performance and monitoring data implemented in the Stochastic Cost Optimization Toolkit (SCOToolkit). The program consists of five major components:

- Physical model module: A semi-analytical physically-based model simulates source zone decay, dissolved plume evolution, and the impact of both thermal source remediation (TSR) and electron donor (ED) injection on source zone and dissolved plume evolution.
- Parameter estimation and uncertainty module: A restricted maximum likelihood parameter estimation module uses prior information along with available field data to estimate field-scale parameters and their uncertainty and residual model uncertainty.
- Monte Carlo (MC) module: A stochastic routine produces equiprobable realizations of remediation performance considering parameter uncertainty and residual model uncertainty.
- Cost module: Computes the net present value (NPV) distribution and the expected NPV (ENPV) cost from the MC realizations.
- Optimization module: Optimizes specified remediation design and monitoring variables to minimize ENPV cost including penalty costs for non-compliance.

DOI of original article: 10.1016/j.envsoft.2012.05.002.

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doi:10.1016/j.envsoft.2012.05.003

Table 1
EGDY site remediation history (USACE, 2008).

Date	Activity	Location
1995	Pump-and-treat systems installed in Vashon Aquifer	One near EGDY second near highway I-5
2003–2005	Integrated pump test in Areas 1 and 3 in Nov 2003 and Sep 2005, respectively	EGDY
2003–2005	Source flux measurements in Areas 1 and 3 in Nov 2003 and Sep 2005, respectively	EGDY
2005–2006	Pump-and-treat system at EGDY reconfigured	EGDY
2003–2006	ERH and monitoring in Areas 1, 2 and 3 in Dec 2003–Aug 2004, Feb 2005–Aug 2005, and Oct 2006–Jan 2007, respectively	EGDY
2005–2006	Whey injection pilot tests	EGDY
2005–2007	Post-ERH monitoring in Areas 1,2 and 3 in May 2005, Sep. 2005, and Feb 2007, respectively	EGDY
2006–2008	Post-treatment soil coring in Areas 1,2 and 3 in Apr 2006, Apr 2006, and Mar 2008, respectively	EGDY
2009	Pump-and-treat system installed in Sea Level Aquifer	Near hospital

Parker et al. (2013) also present several hypothetical problems to investigate cost and performance reliability implications of various source zone thermal treatment monitoring strategies, statistical treatments of outlier data to determine “no further action” status, and specification of compliance penalty dates. In the present paper, we present a field application of the cost optimization methodology to a complex multisource, multiaquifer chlorinated solvent plume at the Logistics Center National Priority List Site East Gate Disposal Yard (EGDY) located at Joint Base Lewis-McChord (JBLM) in Washington State (Fig. 1).

The EGDY site was used between 1946 and the mid 1970s as a waste disposal site for solvents from cleaning and degreasing operations. Material was transported to the disposal yard in barrels and vats from various operations. About seven barrels of liquid waste per month were disposed during peak operation. A dissolved phase trichloroethene (TCE) plume in a shallow unconfined aquifer evolved from the disposal site with concentrations in the range of hundreds of µg/L in the source area and concentrations exceeding 5 µg/L over 4 km downgradient (Dinicola, 2005; USACE, 2008).

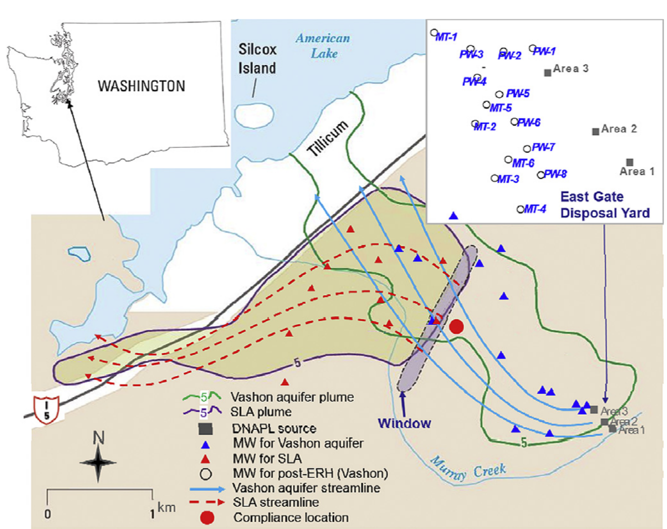

Fig. 1. Location of EDGY site and TCE plume boundary (5 µg/L) as of 2004 (Dinicola, 2005).

The climate at JBLM is characterized by warm dry summers and cool wet winters with a mean annual temperature of about 13 °C and mean annual precipitation of about 1000 mm. JBLM is underlain by a complex and heterogeneous sequence of glacial and non-glacial deposits including a shallow aquifer (Vashon) and a deep aquifer (Sea Level Aquifer, SLA). The Vashon aquifer is unconfined and continuous throughout the JBLM area. It ranges in thickness between about 30 and 60 m. The Vashon and SLA aquifers are separated by a mostly continuous low permeability aquiclude. However, a “window” occurs about 2 km downgradient of the EGDY that allows water and contaminants from the shallow Vashon aquifer to migrate to the deep SLA aquifer (Fig. 1). Groundwater at JBLM generally flows to the northwest in the Vashon aquifer and west-southwest in the SLA aquifer. More details on the site geology are found in Dinicola (2005), Truex et al. (2006), and USACE (2008).

Several remedial actions have been performed at the EGDY site to contain the existing dissolved phase contaminant plume and to accelerate DNAPL mass reduction in source zones as summarized in Table 1. Pump-and-treat systems are currently operating in the Vashon aquifer about 3 km downgradient of the source area to control off-site migration and in the SLA downgradient of the “window” to control the deep plume. About 1260 drums were excavated from former disposal trenches in 2000 to remove waste buried above the water table. To reduce DNAPL mass below the water table, TSR using electrical resistance heating (ERH) was implemented for three source zones between late 2003 and early 2007 (Table 2). More recently, pilot tests have been conducted to evaluate the use of whey injection to accelerate DNAPL dissolution and dissolved plume biodecay.

2. Characterization and monitoring data

To model source zone mass dissolution and transport downgradient, initial estimates of source and aquifer parameters were estimated from Dinicola (2005), Truex et al. (2006), and USACE (2008), as summarized in Table 3. We calibrated model parameters to site data using 2000 as the reference year (t_{cal}) for source mass and source flux using both pre- and post-remediation data. Data include dissolved concentration data, source flux measurements, and measurements of DNAPL mass removed by ERH.

Groundwater flow at the JBLM site was characterized by USACE (2008). Streamlines commencing from each DNAPL source, actual or planned ED injection galleries, and from the “window” locations between the upper and lower aquifer units were digitized and fitted to third order polynomial equations of the form $y = ax + bx^2 + cx^3$ with $R^2 > 0.95$. Since the locations of ED galleries 1 to 3 are immediately upgradient of Areas 1 to 3, their streamlines are similar to those of Areas 1 to 3. The streamline of ED gallery 4

Table 2
Summary of thermal treatment operations at EGDY site (USACE, 2008).

Variable	Area 1	Area 2	Area 3
Treatment area (m^2)	2360	2080	1691
Max depth below ground surface (m)	10	16	9
Treatment volume (m^3)	23,625	135,953	15,368
Energy on date	12/17/2003	02/14/2005	10/11/2006
Energy off date	08/04/2004	08/05/2005	01/26/2007
Duration (days)	231	172	107
Mass removal, TCE + DCE (kg)	2990	1340	1120