Groundwater

Technical Commentary/

On the Effectiveness of Remediating Groundwater Contamination: Waiting for the *Black Swan*

by Donald I. Siegel

Introduction

Thousands of years ago, Aristotle argued that:

> It is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits; it is evidently equally foolish to accept probable reasoning from a mathematician and to demand from a rhetorician scientific proofs. (http://classics.mit.edu/Aristotle/nicomachaen.1.i.html)

Basically, don't push the data more than the data allow.

With respect to contaminant remediation, the groundwater profession ignores this ancient advice. Nassim Talib (2007), in his best seller, *The Black Swan: The Impact of the Highly Improbable*, argues that unsuspected outliers dominate human endeavors far more than predictable outcomes. If the groundwater profession could, in fact, permanently cleanup heterogeneous aquifers with complicated contaminant histories to drinking water standards, it would be a *Black Swan* of high order, a game changer. Such ability would validate low maximum concentration limits (MCLs) established by regulatory agencies as targets for cleanup standards. But we wait for a *Black Swan* to do this, a technology that works at a scale suitable to get the job done.

Discussion

I see little evidence that we can cleanup *seriously* contaminated groundwater to drinking water standards and keep it that way, except where residual contaminant plumes naturally attenuate after we remove an original source and treat the contamination—particularly that generated by hydrocarbons (e.g., gasoline)—in oxygenated water table aquifers (e.g., Newell and Connor 1998; National Academies Press, 2000).

In contrast, remediating solvents, rad-waste, and even hydrocarbons in *heterogeneous* geologic settings can be profoundly difficult and meet long-term drinking water standards. Yet, many still seem to buy into the continued regulatory demand that it needs to be done. We could instead try to show why it can't be done yet, which might serve the public interest better.

Last year, the National Research Council reviewed decades of failed attempts to cleanup Superfund sites (National Academies Press 2013). Payne et al. (2008) argued 5 years earlier in their text, *Remediation Hydraulics*, that "representation of the subsurface through large-scale averages and steady-state observations cannot adequately support groundwater remedy designs." They paint a dismal history of cleanup success and urge caution and humility in the face of subsurface heterogeneity. Stroo et al. (2012) recently reviewed the great uncertainties and difficulties of cleaning up solvents to drinking water samples. These pieces have collectively synthesized extensive academic research and broad consulting experience which shows what we have known for decades: that we can't cleanup complex contamination. Why hasn't this information reached regulatory and legislative ears to arrive at more realistic expectations?

Two fundamental reasons preclude cleaning up groundwater contamination to drinking water standards in complex settings.

Preferential Flowpaths

You can't cleanup contamination if you cannot find the contaminant source in the subsurface, and then, where it goes. Jacob Bear introduced the concept of *reference elemental volume* decades ago, showing that the noise inherent with small-scale measurements of aquifer properties obscures the true signal. Contaminant sources and near-source plumes commonly occur at the scale of a football field or so. At this scale, local stratigraphic and

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structural complexities lead to preferential flowpaths that diverge, refract, from presumed directions based on water levels from typical monitoring wells.

Hydrogeology texts usually contain cartoons showing refraction of groundwater flowpaths *vertically* across units with different hydraulic conductivities, but often neglect showing refraction which applies to the *horizontal* plane too with changing hydraulic conductivities. Even presumed "homogenous" aquifers have order-of-magnitude variability in hydraulic conductivity at the centimeter to meter scales. Nano Trace Technologies (http://www.nanotracetech.com/home.html), a firm specializing in subsurface tracing and remediation, reported that out of their many tracing field experiments, a large majority identified flowpaths diverging 20 to even 90° from expected directions (M. Otz, personal communication, 2013).

Heavily instrumented groundwater research sites including the USGS toxic substances program sites (http://toxics.usgs.gov/), the MAcro-Dispersion Experiment (MADE) site in Alabama (Zheng et al. 2010), and the famed field experiments at the Borden Landfill done by John Cherry's University of Waterloo solvent program (e.g., Pankow and Cherry, 1996) point to the futility of a priori discovering all preferential discrete flowpaths from interpretation or modeling based on standard monitoring well installations consisting of water table monitoring wells and small sets of piezometer nests. The spatial distribution of these cannot insure finding preferential flowpaths diverging perpendicular to the water table or potentiometric contour lines.

If you can't find all the contaminant sources and where the water flows, you can't clean it all up. It's that simple.

Geologic processes deterministically create aquifer systems overlain by randomness. We know, for example, that distributary channels at all scales will "v" downgradient, but we can't a priori tell where the junctions will be. So we are stuck with summary statistics of material properties from small sets of samples from monitoring wells that may not reflect reality, perhaps coupled to geophysical sensing to help us out. Stochastic and Bayesian statistical approaches and multiple model visualizations can lead investigators to the most probable flowpaths within the context of minimal data. This is good to a point. But preferential flowpaths can be so narrow that monitoring wells may not hit them and so the initial dataset distributions upon which probabilistic determinations are made can be incomplete. Basically, the subsurface at the scale we want to remediate contains a sufficient number of "surprises" (e.g., Bredeohoeft 2005), preferential flowpaths, that cleanup becomes far harder than most people imagine.

Dual Porosity

The distribution of preferential flowpaths within matrices of lower hydraulic conductivity containing "dead pore space" leads to the well-known dual porosity issue. Contaminants diffusing into dead pore space later diffuse back into clean water once remediation ends (e.g., Pankow and Cherry 1996). This "bleeding out" can last decades and pop up long after MCLs have been achieved.

Understand, I'm *not* saying that we can't cleanup ground water contamination. We can excavate out shallow sources when we find them and I've seen plumes of solvents and other contaminants reduced an order of magnitude or more even by pump and treat. We can potentially remove contaminant source masses by over 90% (e.g., Stroo et al. 2012). But the residual amount of residual solvent can lead to huge volumes of contaminated water at MCL standards and preclude full cleanup for decades if not longer.

Conclusion

First, I think that groundwater scientists and engineers best serve their clients by coupling their parsimonious site characterization to natural and induced tracer tests designed to directly identify discrete preferential flowpaths before doing remediation. I understand that these experiments also can have problems, but at least if injected tracers do *not* show up in a monitoring well network, then preferential flowpaths occur that have not been intersected by the monitoring well network.

Directly tracing where water goes can also be explained easily to lay people, judges, and lawyers. And, remediation logically can be done more efficiently if preferential flowpaths can be determined from source terms. If these experiments cannot be done, then perhaps groundwater scientists and engineers should indicate to clients and regulatory bodies that full remediation may not be achievable because of uncertainties.

Second, regulatory agencies would better serve the public by accepting the futility of groundwater cleanup in most places, except to brownfield standards at lower standards. Perhaps, regulatory agencies might also reconsider their use of the precautionary principle (see Ricci et al., 2005, for discussion on this) over actual epidemiological evidence behind their setting of very low MCLs in the first place, but that would be another conversation.

Over-pumping the Ogallala Aquifer, in places, has forever lost to humanity a water resource that can be used for future intense agriculture. Groundwater *in the context of drinking water standards* for all practical purposes also has been lost to humanity locally in places because of point source contamination. Perhaps, the same can be said for some nonpoint source contamination of groundwater too where preferential flowpaths and contaminant storage in the subsurface make regional cleanup difficult. Shallow aquifers widely contaminated by septic and some agricultural practices come to mind. Rationally, we might do better to develop more efficient and low cost methods to process contaminated water *after pumping*, rather than chase the chimera of subsurface cleanup.

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