Cleaning Up Large Groundwater Plumes to Drinking Water Standards: Dynamic Groundwater Recirculation at Reese Air Force Base – 17248

Kelly Houston *, Scott Potter *, Suthan Suthersan *
* ARCADIS US, Inc.

ABSTRACT

Overall cleanup of large plumes is perceived as being impossible because of issues of scale, contaminant mass accessibility, time to achieve cleanup, and cost. As a result, when a groundwater pump and treat (P&T) remedy is applied to larger plumes, the focus is usually hydraulic containment of contaminated groundwater to prevent further plume migration, rather than a total restoration objective. Recent experience with dynamic operation of groundwater extraction, treatment, and strategic reinjection (collectively referred to as dynamic groundwater recirculation [DGR]) demonstrates that large plume remediation can be accomplished cost effectively and in a timely manner. The insight from operating DGR remedies at multiple sites has demonstrated that contaminant mass residing in a complex aquifer setting is most appropriately described by a three-compartment model, which is a new revelation in contaminant hydrogeology redefining what is possible in restoration.

A large-scale application of DGR was implemented under a firm fixed price contract at former Reese Air Force Base (AFB) located in Lubbock, Texas. The strategy was successful in restoration of a sole-source drinking water aquifer affected by a 3-mile long trichloroethene (TCE) plume. DGR allowed groundwater P&T rates to be decreased from over 3,400 liters per minute (lpm) to less than 1,500 lpm through initial optimization efforts. The DGR strategy focused extraction and reinjection on two key objectives: 1) maximizing contaminant mass recovery and 2) maintaining hydraulic control of the plume. Extraction and injection wells were dynamically operated and cycled to maintain a remediation pace that restored 0.8 to 1.2 hectares of the plume per week over a 6-year period. Plume cleanup to drinking water standards was achieved in 9 years of optimized operation.

INTRODUCTION

Over the past decade, improvements in characterization techniques have helped unmask the role that back diffusion plays in aquifer restoration. This in turn has driven a shift in how we are viewing the outcomes that are possible from groundwater cleanup efforts. For complex sites (where contamination is significant in scale or difficult to access), this has allowed a shift to strategies that achieve source removal and sufficient reductions in contaminant flux to protect receptors, as an alternative to achieving drinking water maximum contaminant levels (MCLs) on a plume-wide basis. There are other sites, however, where groundwater is the sole drinking water source and achieving MCLs will always remain the goal.

Former Reese Air Force Base (AFB) is located roughly 16 kilometers (km) west of Lubbock, Texas and opened in 1941. It had a flight training mission for pilots until its closure in 1997 under the Base Realignment and Closure Act (BRAC). Contamination consisting mainly of petroleum hydrocarbons and chlorinated solvents that had been used to clean aircrafts stood in the way of the transfer and re-development of the base property. The main challenge was an extensive TCE plume in groundwater that extended off-base, covering a total distance of approximately 4.8 km. The aquifer involved is the sole drinking water source for the region, so while considerable in both scale and lithologic complexity, restoring the aquifer to unrestricted beneficial reuse was the primary goal of the restoration effort [1].

BACKGROUND

In 2004, the Air Force initiated an effort to complete the cleanup of the Reese AFB TCE plume within 10-years. The concept of accelerating plume-wide groundwater cleanup at Reese AFB from a baseline of 100 to 1,000 micrograms per liter (µg/L) of TCE across the bulk of the plume, to less than the MCL (5 µg/L) within a 10-year timeframe was initially met with a healthy dose of skepticism. The water table is 100 feet below ground surface, and the plume configuration was complicated by the presence of paleochannels, changes in depositional environments, discontinuous confining units, nearby operating supply wells, and the presence of multiple, independent contaminant sources that contained different constituents and release times. Beyond the challenges associated with size, depth, and required magnitude of concentration reductions, there was the challenge of collecting and interpreting data from over 700 monitoring, remedial extraction, irrigation, and domestic wells to make remedial decisions. Prior to adjusting the strategy, the most recent 5-year review evaluation concluded there was at least 50 years of further remediation required.

In order to break out of this paradigm for the project, an approach was needed that could cost-effectively improve the short-term efficiency, reliability, and performance of the remedy, while at the same time enhancing the pace of plume-wide cleanup. At the scale of the Reese plume footprint, an approach focusing on mass flux, hinged on adaptive operation and optimization using real-time performance data, was deemed necessary. This strategy would require treatment system components that could be relocated or augmented to adjust treatment configurations and drive the overall rate of cleanup – in contrast with the “fixed” operational configuration typically employed to control plumes of this magnitude.

This adaptive approach was what ultimately yielded success. The collective process required to achieve cleanup at Reese included upfront recalibration of the conceptual site model (CSM), crafting of a flexible combined remedy that made use of the existing infrastructure already invested in and that could drive plume-wide cleanup progress, and adaptive operation of that remedy through constant feedback from plume wide performance data. The insight stemming from successful restoration at Reese AFB and other projects employing DGR approaches has refined our understanding of how contaminant mass moves through the subsurface and, more importantly, has redefined what is possible in large plume cleanup.

APPROACH

The approach taken to optimize restoration and eventually achieve drinking water MCLs at the Reese TCE plume included refinement of the CSM, optimization of the existing remedy based on the revised CSM, and finally adaptive implementation of a revised and multifaceted remedy. The revised remedy included a plume-wide DGR strategy combined with engineered reductive dechlorination (ERD) in a relatively small footprint of the overall plume.

Refinement of the Conceptual Site Model

An honest refinement of the CSM, unburdened by allegiance to historic precedent, was integral to the success of the Reese project. Thirty years ago, the concept of a CSM had much narrower definition, and was grounded in the belief that complex hydrogeologic systems could be adequately represented by simple equivalents. Today, CSMs are significantly more detailed as a result of greater resolution from advanced characterization techniques, improved knowledge of source mass behavior, and the ability of modeling techniques to simulate the effect of fine-scale processes on contaminant fate and transport. Therefore, while CSMs remain a streamlined understanding of site conditions, modern CSMs incorporate far more information than their forebears to ensure that they are truly representative of the complex site conditions.

When the initial CSM for Reese was developed in the early 1990’s, contaminant data and water levels were organized to indicate that plume movement was entirely consistent with groundwater potentiometric maps (Figure 1). This was an expected outcome considering the concepts of contaminant transport and groundwater modeling applications at the time based on homogeneous and isotropic plume behavior. This CSM intrinsically assumed that soil complexities could be effectively averaged to reproduce behavior at all wells, despite all soil borings showing a complex soil profile across the plume varying from clay to gravel. This interpretation was extended to subsequent wells and boring locations as investigations expanded, inadvertently screening the potential to observe certain types of behavior that we now know to control plume behavior.

Anisotropy is typically framed as a property of soils, where permeability affecting the movement of water and contaminants is different depending upon direction; however, anisotropy can also be an effect driven by the larger scale hydrostratigraphy of the aquifer. The initial CSM concluded the aquifer was effectively isotropic at the plume scale and that there was no preferred pattern of plume movement largely because asymmetrical drawdown local to historically operating extraction wells was not identified. This interpretation became the basis for the initial positioning of the P&T extraction wells, and was also used to identify off-site private wells potentially at risk. It was not until after remedy implementation, when perimeter monitoring wells were found to contain VOCs consistent with the core of the plume and extraction wells immediately downgradient of the plume were not recovering any contaminant mass, that it became evident that the CSM required an update.

The early CSM had resulted in a failure to achieve an operating properly and successfully (OPS) designation as required by the Record of Decision (ROD) even though the project was 5 years into the remedy. In 2004, the transition of the project to a program whose goal was to complete the cleanup in a 10-year timeframe created the opportunity to rethink both the CSM and the existing remedy. A careful review of the historic contaminant data and plume-wide hydrostratigraphy yielded some important findings relative to the previous interpretation. Most notably, the groundwater plume appeared to be moving in a direction that was approximately 30-40 degrees off the observed hydraulic gradient. In addition, it was also observed that at approximately 1 to 2 km intervals along the plume axis, contaminant transport and mass distribution patterns changed [2].

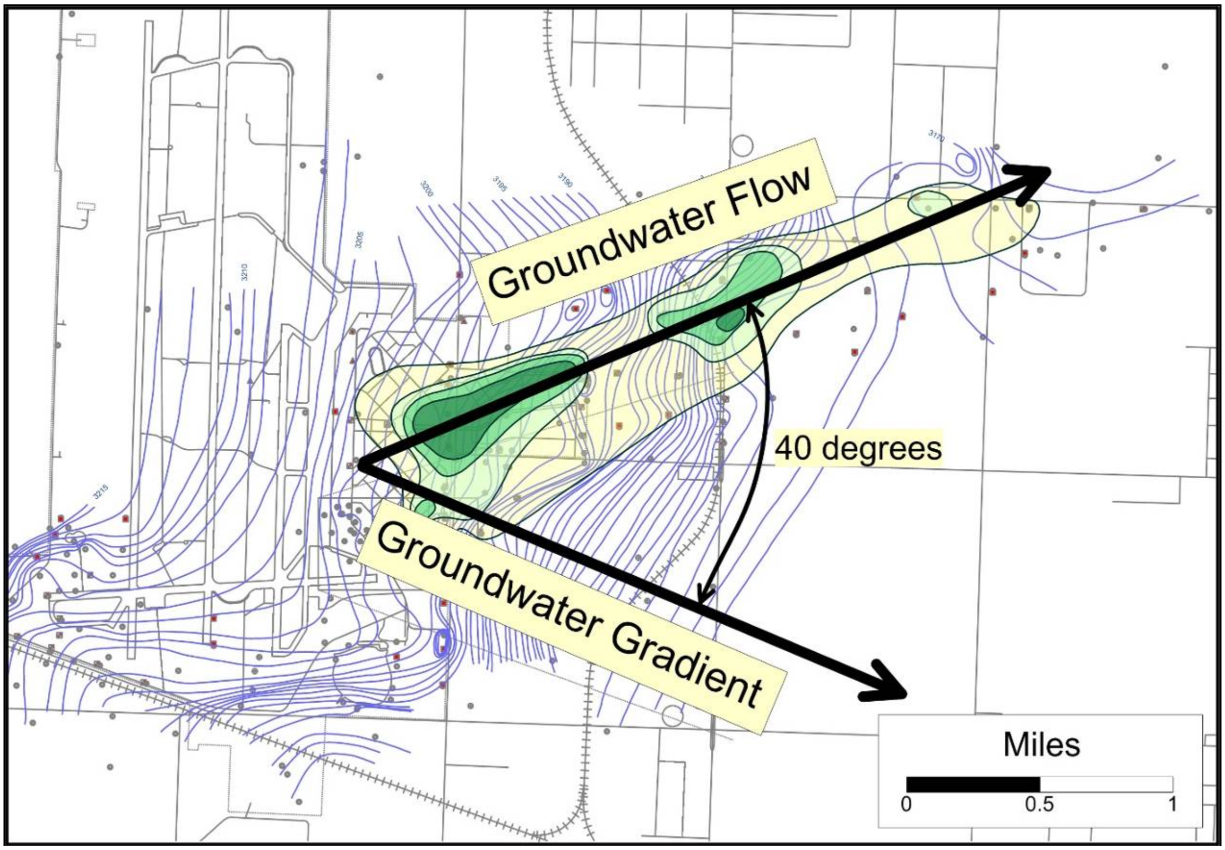

Fig. 1. Groundwater flow is not aligned with the potentiometric gradient. The anisotropic plume movement resulted from the larger scale hydrostratigraphy of the geology.

These observations drove the evolution of the CSM from a single simplified system, to a macro-system comprised of several smaller interconnected systems. This conclusion was also a logical fit with the scale of the plume – it would not be unreasonable to expect noticeable differences in the depositional environment over a 5 km long plume. As a result, the refined site-wide CSM reflected anisotropy driven by geologic structure, and 5 different areas were identified with their own conceptual model based on unique geology, distance from source areas, and contaminant distribution (Fig. 2). The distance from the source impacts how long contaminants have been present at a location, which in turn affects the degree to which contaminants have been able to migrate into stationary fractions of the aquifer. This means the way plumes appear does not always reflect the processes by which they were created. For example, contaminants in the aquifer nearest source areas were almost uniformly distributed not because contaminants were moving uniformly but because 50 years of exposure allowed coarse and fine grained soils (soils with higher and lower permeability) to become impacted at similar concentrations through heterogenous advection and diffusion. At the leading edge of the plume, where contaminants had been present for the least time, the plume tended to be limited to the most permeable channels conveying the mass flux. This contrast in conditions naturally lead to a realization that different remedial approaches would likely be more effective in different portions of the plume.

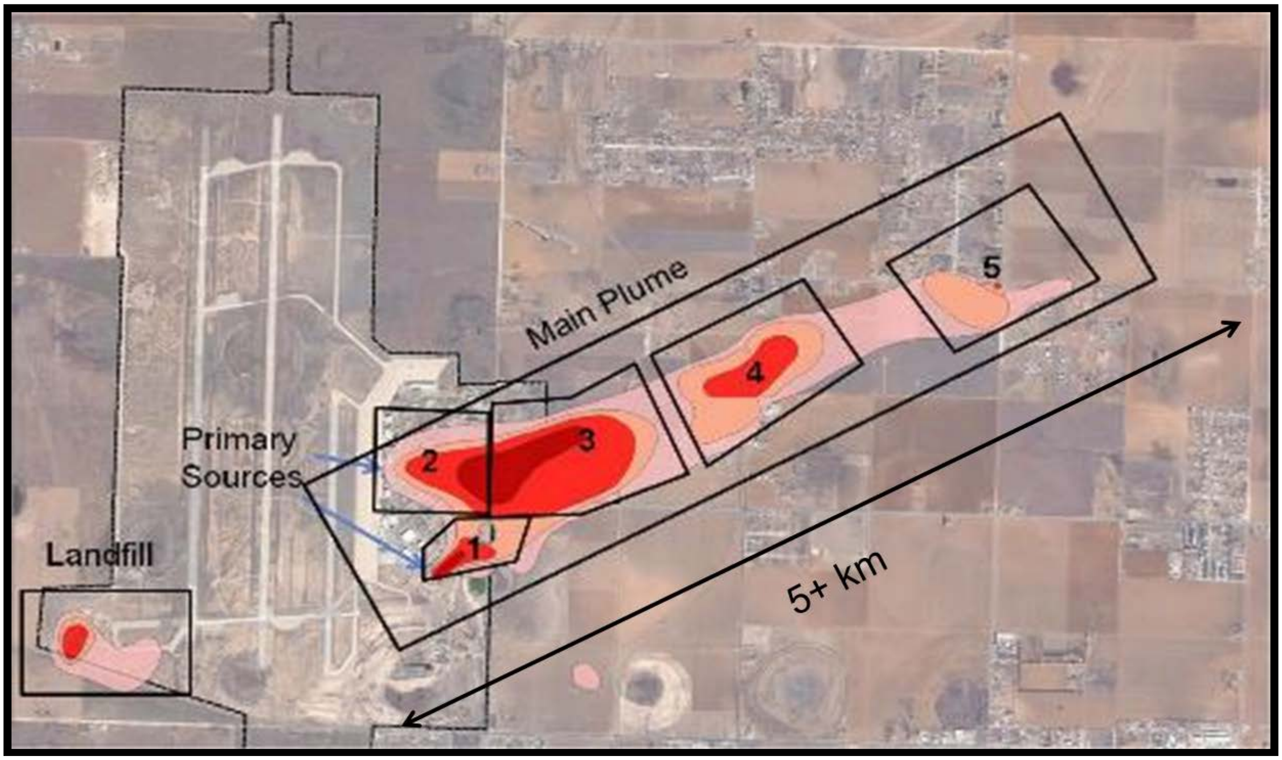

Fig. 2. The refined site wide CSM was divided into 5 distinct areas based upon geology, distance from the source area, and contaminant distribution.

Optimization of the Existing Remedy

As part of the base closure process, a regulatory order issued in the 1990’s required implementation of a conventional P&T system to achieve plume containment. Air stripping with carbon adsorption were employed to treat the extracted water and the treated water was re-injected into the aquifer. Location of extraction wells and pumping rates were influenced by the previous interpretation of plume structure and driven by conceptualizations built from solutions to the advection-dispersion equation governing groundwater flow in homogeneous and isotropic settings. Operated between 1997 and 2004, the limitations of the CSM had resulted in the ongoing operation of multiple extraction wells outside of the plume footprint and during this period of operation there was little change in plume footprint (Fig. 3).

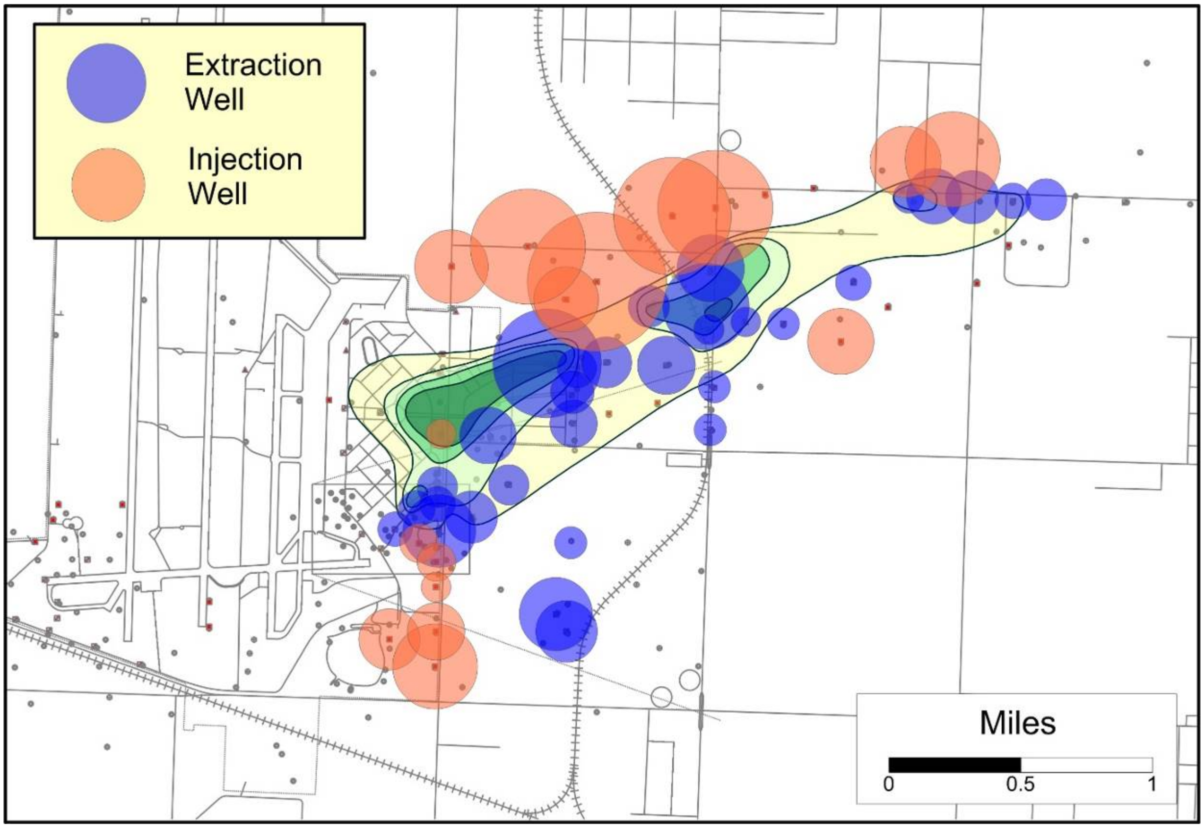

Fig. 3. Extraction, treatment and reinjection system in 2004 prior to system optimization with total extraction rate of 2,500 lpm (circle area denoting well location is proportional to flow rate). Pumping distribution was based on potential plume movement inferred by water level elevations.

Recognition of flow system anisotropy supported a significant re-engineering of the capture approach. Significant contaminant concentrations downgradient of the source could only be present if they were hydraulically connected to source areas, and these were the zones where pumping was focused. The new strategy was simple: focus on the contaminant mass flux through the preferred pathways. A numerical model was developed using MODFLOW with a supplemental piece of MODALL software to consider the current site data and support a strategic change to where groundwater was extracted and re-injected [3]. The resulting modifications took a 2,500 lpm system with 32 extraction wells and non-strategic re-injection, and reduced it to a 1,100 lpm system with 20 extraction wells and more strategic re-injection. While groundwater extraction was reduced by nearly 60%, the overall contaminant mass removal increased by 25% (Fig. 4). These changes resulted in immediate savings, and created flexibility to consider further modifications of the remedy to more effectively drive aquifer restoration [4] (Landers, 2011).

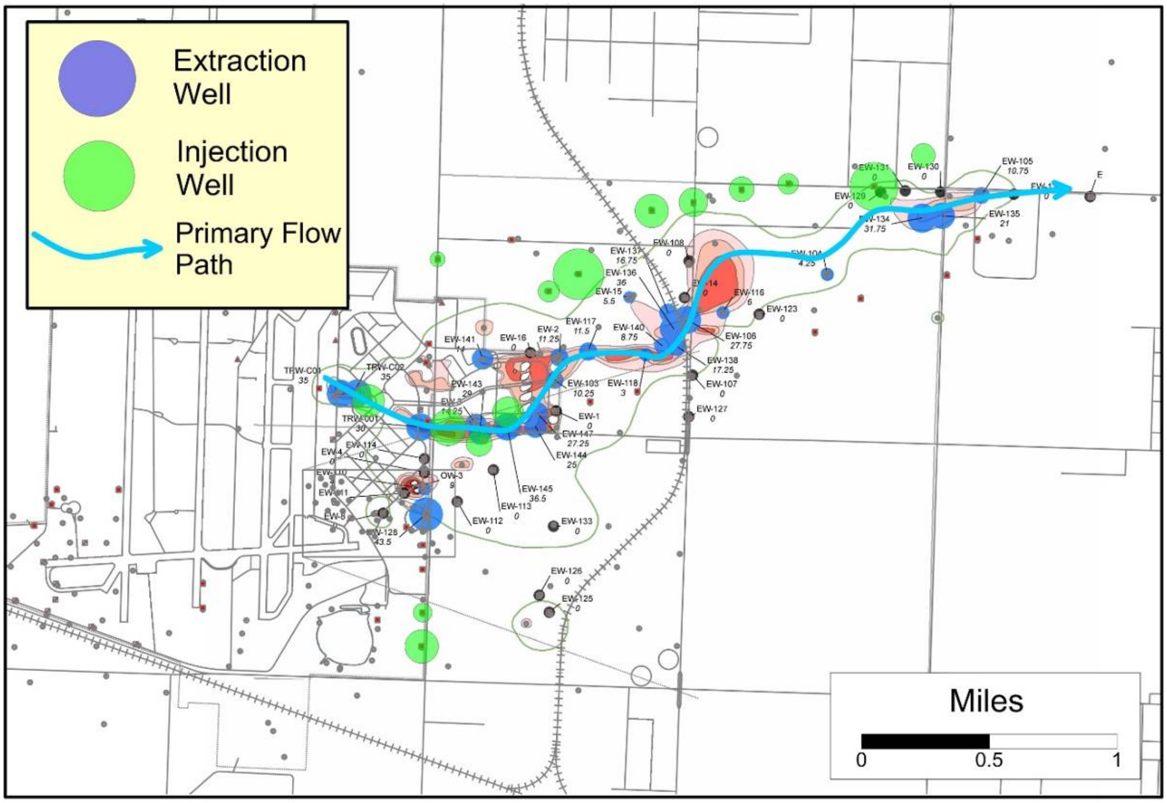

Fig. 4. Extraction, treatment and reinjection system in 2009 after system optimization (1,300 lpm – circle area denoting well location proportional to flow rate). Pumping distribution was based on contaminant mass flux and revised understanding of preferred groundwater flow paths.

Adaptive Implementation of a Revised Remedy

When regulatory decision documents were developed throughout the 1980s and 1990s, they frequently focused on selecting "the remedy" for any given site. Responsible parties, remediation practitioners and regulatory stakeholders now almost wholly embrace the value of a combined remedy approach since the pendulum of technology selection has swung significantly. For complex remediation sites, multiple technologies are brought to bear to utilize the unique benefits of each individual technology to expedite bulk source mass removal, initiate sustaining treatment chemistries, and enable ongoing mechanisms to both eliminate mass flux and achieve remedial goals. Benchmark ROD documents now reflect not only the regulatory-approved treatment remedies, but also the sequencing and adaptive methodology through which the remedy train will be deployed.

Selection of a combined remedy approach was integral to the potential for success at Reese by providing a flexible framework to meet the contractual objective of cleaning up the entire plume in less than 10 years. Employing a combined remedy approach was critical to the revised strategy, given that the 280-hectare footprint of the plume made it necessary to restore an average of 0.8 to 1.2 hectares of aquifer per week.

The individual components of the revised remedy developed for Reese AFB were directly tied to the CSMs of the sequential plume segments and varying approaches to address source mass and diffuse plume areas. Recognition of the complex structure of the plume and the need to complement the modified P&T system necessitated the implementation of different remedies within each sub-areas of the plume. Figure 2 shows the reassessed plume map with all five areas identified in the revised CSM. Area 1 had two hot spots of TCE co-mingled with petroleum hydrocarbons undergoing partial reductive dechlorination. Extraction wells were installed in the center of each hotspot and the extracted water was treated ex situ with granular activated carbon (GAC) sorption prior to being reinjected with added organic carbon substrate to enhance complete reductive dechlorination of TCE. Injected reagents were distributed within Area 1 employing ambient and engineered hydraulic gradients. Area 2 was less impacted than Area 1 and there was no baseline reductive dechlorination occurring. Presence of TCE was concentrated in a narrow channel flowing from west to east where three extraction wells were installed. Extracted groundwater was treated with GAC and reinjected to enhance natural gradients.

Area 3 was approximately a quarter of a square mile and contained most of the TCE mass within the plume. A continuous reagent delivery system was implemented to engineer enhanced reductive dechlorination within this area. Contaminated groundwater was extracted at 900 lpm from 12 wells, amended with organic carbon and reinjected via 36 wells distributed within the Area 3 plume. Based on the continuum of maturity along the plume axis and a high density of the residential supply wells, groundwater extraction and reinjection were the preferred remedial solutions within Areas 4 and 5.

Evolving insights into aquifer hydrostratigraphy informed the approach to remedy selection and operation. While additional direct lithologic mapping of preferential contaminant transport pathways would have yielded a wealth of additional information, it was cost-prohibitive at the scale and depth of the plume. Instead, a groundwater monitoring philosophy was developed that utilized analytical data to support routine (i.e., quarterly) modification of the remedy operation to maintain progress. This approach maintained the focus on areas with higher contaminant concentrations which directly facilitated overall plume contraction.

The most important design innovation that drove the success of the Reese AFB project was the reliance on DGR to overwhelm aquifer heterogeneities and overcome the impacts of matrix-controlled back diffusion through enhanced flushing. Faster cleanup rates (~1 hectare per week), while processing a 60% lower groundwater flow rate, were achieved by strategically manipulating hydraulic gradients and inducing groundwater flow through less permeable fractions within the aquifer profile. With strategic recirculation and the resultant engineered gradients, advective contaminant transport and recovery that occurs through the mobile fraction of the aquifer was enhanced, while also increasing mass recovery from storage zones (i.e., the immobile and stationary fractions, as discussed in more detail below) through heterogeneous advection and diffusion. The awareness of enhanced contaminant recovery from previously conceptualized "storage" zones led to the most important component of the Reese plume remedy. Specifically, the success at Reese is contributed to a dynamic treatment approach reliant on routine monitoring data to continually focus groundwater extraction from wells containing the most mass. In addition, well design specifications included the placement of extraction and injection well screen intervals across multiple fine- and coarse-grained stratigraphic layers to overwhelm the natural heterogeneity of the aquifer, induce horizontal and vertical gradients, and maximize contaminant removal.

DGR is an aggressive physical remediation technique, and is a significant advancement from the conventional applications of groundwater P&T solutions of the past. The DGR technique significantly accelerates the influx of clean groundwater and removes contaminant mass through enhanced concentration and hydraulic gradients, which drive contaminants out of mass storage zones by diffusion and heterogeneous advection. We followed an adaptable implementation of DGR informed from routine analysis of changing contaminant concentrations and hydraulic data with a continuous focus on enhancing the rate of plume clean up.

Figure 5 shows a plot of total footprint (area) and the rate of aquifer cleanup versus time. The circles identify each instance where the rate of cleanup declined, which necessitated a system change to optimize restoration rates and maintain momentum toward the endpoint. This plume cleanup was successful primarily because we incorporated the temporal and spatial changes in aquifer hydraulics and contaminant concentrations into remediation system operation decision-making. The system in Areas 4 and 5 (Fig. 2) was designed to maximize contaminant mass removal rates by extracting from high concentration areas while enhancing flushing by injecting treated water on the plume periphery. The DGR design was also based upon managing the transit times between injection wells and extraction wells while maintaining hydraulic control of the plume. It was also designed to segment the plume by employing multiple cut-off measures and to actively reduce the plume footprint along its entire length.

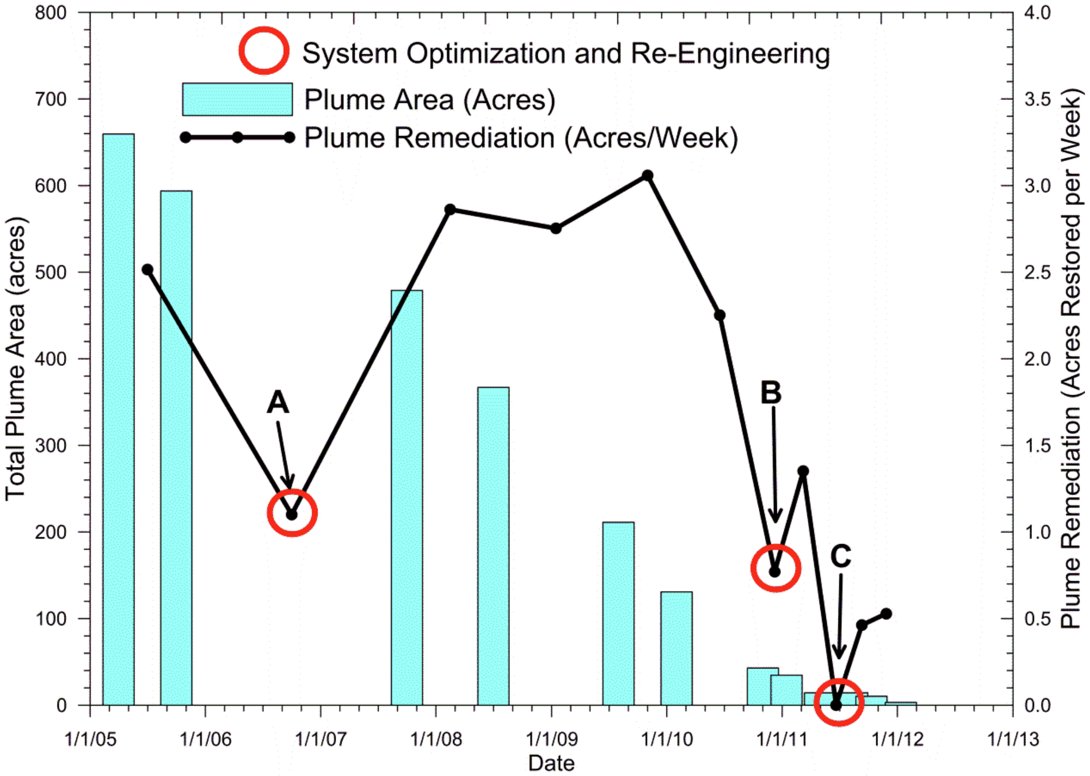

Fig. 5. Plume area in acres at the Reese Air Force Base during optimized remediation. The pace of performance (represented by the line) shows the number of acres cleaned up per week. The circles represent major system optimization events.

RESULTS AND DISCUSSION

Early recognition that preferential contaminant transport was occurring based on geologic factors allowed the rest of the CSM and remedy refinements to fall into place. The incremental improvements followed by rapid declines in TCE concentrations within the different areas of the plume were likely facilitated by dual-directional diffusion due to the enhanced flushing caused by the recirculation [5]. In the flux-focused remediation that was implemented at this site, the relative magnitude of contaminant sequestration (i.e., further forward diffusion into the stationary fraction) compared to bulk mass removal from advective transport zones is negligible and of little consequence. Strategic recirculation and enhanced flushing are the primary contributors towards advective mass removal and achieving remedial end points.

The determination as to which processes were dominant for the site-wide disappearance of TCE was supported by monitoring data from approximately 600 wells located within the footprint of the plume. Data collected from a typical well is presented in Figure 6, which captures all phases of plume evolution over a 15-year monitoring period. This well is located near the former source area and screened across interbedded silt, sands, and gravels that are typical of site conditions.

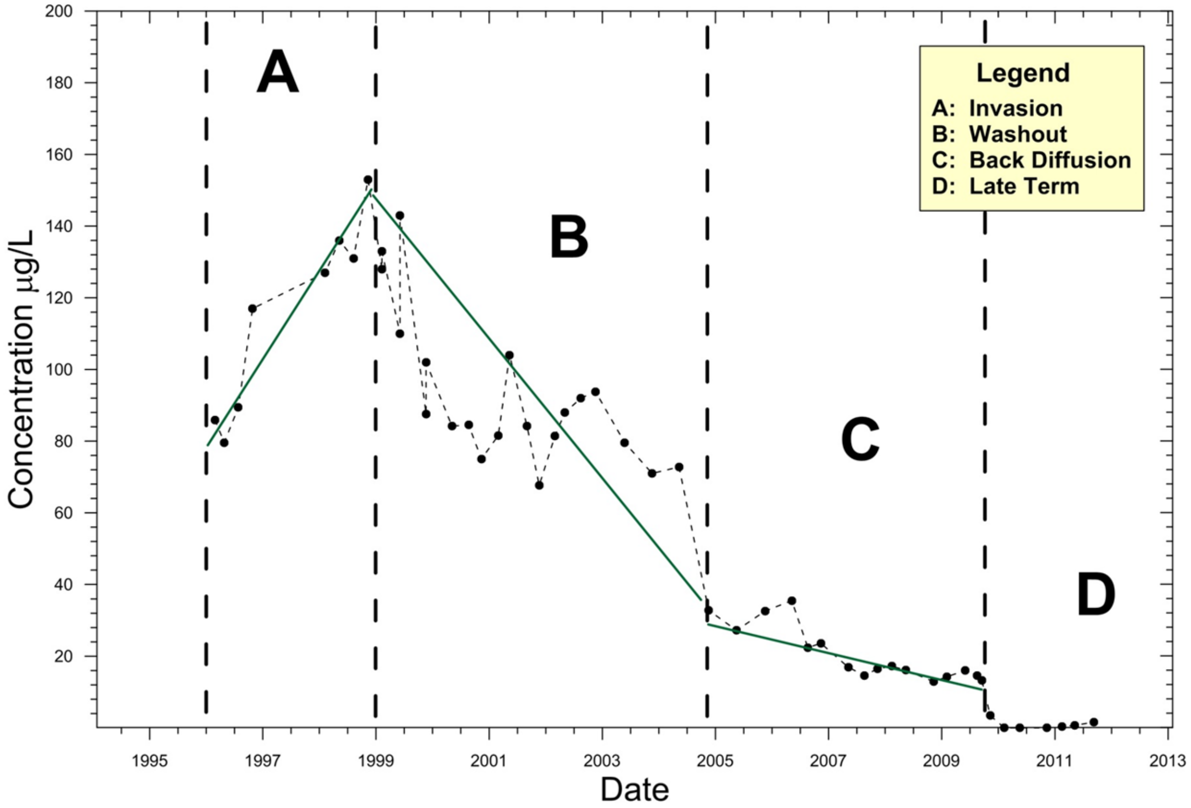

Fig. 6. Fifteen years of monitoring data collected from one well within the Reese AFB plume. TCE data represents (A) plume changes during invasion and maturation; (B) early stage treatment dominated by advection; (C) late-stage treatment dominated by advection and back-diffusion, and (D) end-stage treatment where dual-directional diffusion contributed to widespread TCE disappearance.

The invasion phase (A) captures the increase in contaminant concentrations as the plume expands and continues to contaminate the aquifer near the well. The middle phases (B and C) show the declining concentrations because of remediation. The rapid decline during phase B reflects the first stage of mass removal through advective processes from the most permeable pathways. Phase C represents the decreased rate of concentration reductions due to the inherently slower advective removal of contaminant mass from the immobile fraction and the effects of back diffusion. Phase D represents the final stages of remediation, when mass removal from the advection-dominated fraction has been achieved and diffusive processes are the dominant mechanism of mass removal. During this stage, the only contribution to the observed mass flux is back-diffusion from the stationary fraction (i.e., very low permeability soils) where the advection rate is over two orders of magnitude slower than in the primary advective pathways.

Building off the trends in concentration reductions discussed above and shown on Figure 6, we can more accurately rationalize complex aquifer settings as a three-compartment model comprised of the following (Fig. 7):

- Mobile fraction - advective zone comprised of more permeable sands and gravels where pure advection dominates contaminant transport,
- Immobile fraction – advective and storage zones comprised of silty and clayey sands where both slower advection and diffusion dominate contaminant transport, and
- Stationary fraction – a strict storage zone comprised of sandy silts, silts, and clays where diffusion is the only relevant mass transport mechanism.

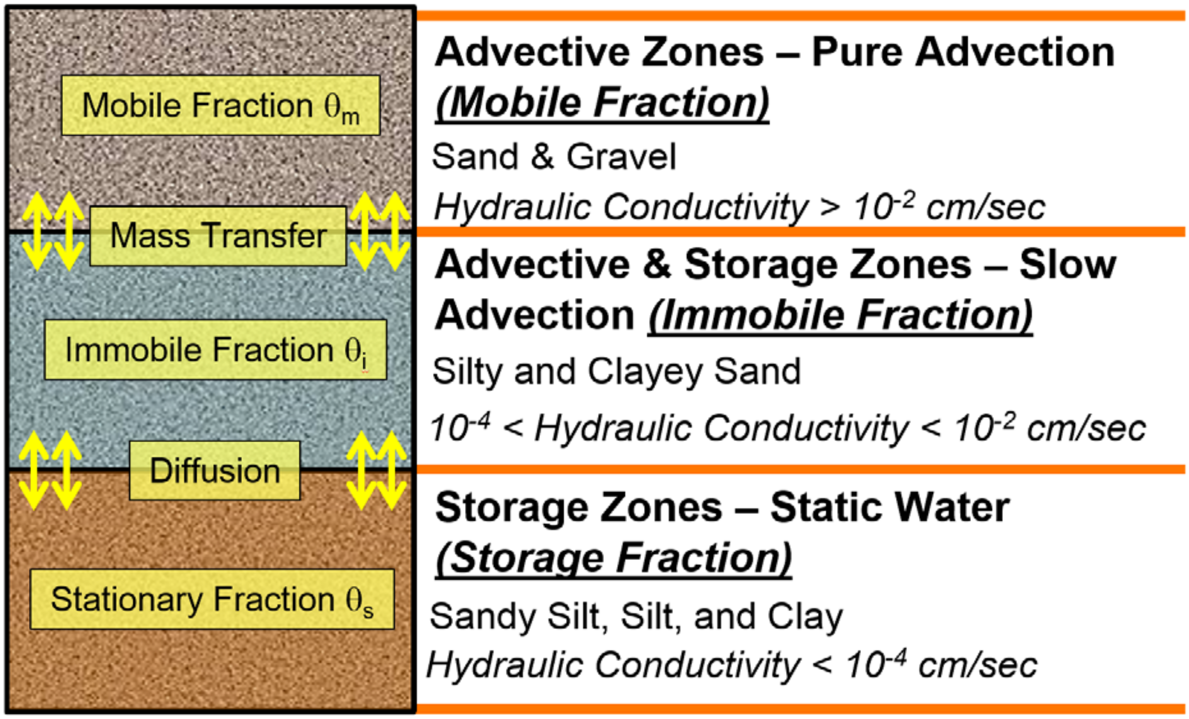

Fig. 7. Summary of three-compartment model for contaminant transport in complex hydrogeologic settings.

The three-compartment model is an evolution in thought from recent conceptualizations of aquifers with dual compartments (or dual-domains) comprised of a mobile and immobile fraction that rely only on diffusive contaminant mass transport between the two [5]. The relatively slow rate of contaminant back diffusion from immobile to the mobile fractions in a dual-domain conceptualization has resulted in estimated cleanup timeframes for some sites on the order of hundreds to thousands of years [7]; however, we now know that heterogenous advection (i.e., transport through both the most conductive and slower conductive fractions) and diffusion control contaminant transport during plume development and that the immobile fraction can be accessed during restoration employing DGR strategies.

The immobile fraction, as defined in Figure 7 where slow advection is a dominant transport mechanism, is absent from the dual-domain conceptualization. Slow advection of contaminant mass in the immobile fraction typically occurs over many decades for most large plumes in complex settings during plume development. Under the dynamic and enhanced gradients generated during DGR, clean water movement through the immobile fraction can occur over a reasonable timeframe (e.g., less than 10 years) for typical stratigraphic thicknesses encountered in complex large plume settings (e.g., 1 meter) for the hydraulic conductivity values reported in Figure 7 (less than 10^{-2} centimeters per second [cm/s]and greater than 10^{-4} cm/s).

CONCLUSIONS

The scale of the groundwater restoration achieved at Reese AFB, to support unrestricted use of an aquifer formerly contaminated with TCE over a 5-km long footprint, is unprecedented. The Site clean-up also made good fiscal sense. The United States Air Force estimated the cleanup has saved taxpayers at least $22 MM [8]. Looking back on the success, there are a few clear takeaways:

- Honest challenging of the CSM allowed an initial breakthrough with the configuration of the existing remedy, cutting operational flowrates (and costs) needed to achieve hydraulic containment (as required by the ROD) while increasing the rate of contaminant mass recovery.

- The application of DGR was extremely successful, likely due to sequestration of contaminant mass in fine grained aquifer materials by dual-directional diffusion, driven by the strategic recirculation of clean water. The ERD remedy was a success as well in the core of the plume with the highest TCE concentrations.

- The adaptive operation and frequent modification of the remedy configuration (including the installation of new infrastructure where and when required) optimized concentration gradients on a regular basis to drive flushing of the contaminant mass from the aquifer.

The methods used to clean up the aquifer under Reese AFB are being replicated in numerous places with tremendous results. While this level of performance will not be true for every site with a large or complex contaminant plume (i.e., the site conditions must be conducive, etc.) we are clearly able to achieve what was unthinkable just a decade ago (Fig. 8). The experience at Reese AFB and other sites shows that the advancements being made in remediation are supporting the real possibility of large-scale restoration, in a world where clean groundwater is one of our most important natural resources.

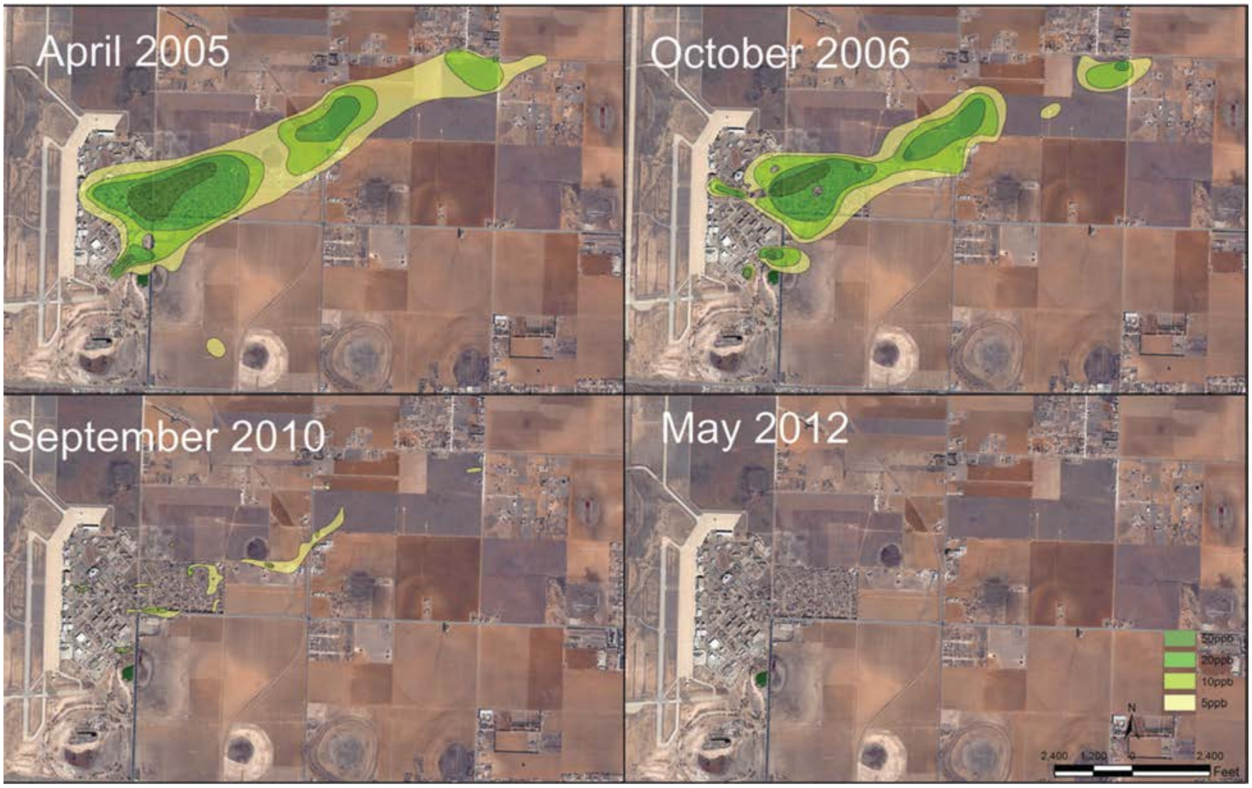

Fig. 8. Observed reduction in TCE plume over an 8-year optimized remediation period at Reese AFB. Shaded plume areas represent plume footprint greater than the MCL (5 μg/L). All compliance monitoring wells are less than MCL in May 2012.

REFERENCES

1. United States Environmental Protection Agency (USEPA), *Administrative Order of Consent, Reese Air Force Base, Docket No. VI-7003-93-1*, July 23 (1993).

2. S. Suthersan, C. Divine, and S. Potter, “Remediating Large Plume: Overcoming the Scale Challenge”, *Groundwater Monitoring and Remediation,* **29**(1), 45-50 (2009).

3. S. Potter, E. Moreno-Barbero, and C. Divine, “MODALL: A Practical Tool for Designing and Optimizing Capture Systems”, *Ground Water*, **46**(2), 335-340 (2008).

4. J. Landers, J. “Groundwater Model Shortens Remediation Project by 20 Years”, *Civil Engineering News,* November, 26-27 (2011).

5. S. Suthersan, S. Potter, and M. Schnobrich, “Groundwater Restoration: Large Scale Benefit of Small Scale Processes”, *Groundwater Monitoring and Remediation,* **33**(3), 31-37 (2013).

6. F. Payne, S. Potter, and J. Quinnan, *Remediation Hydraulics*, pp. 133-146 and 273-315, CRC Press, New York, NY (2008).

7. Interstate Technology and Regulatory Council (ITRC), *Using Remediation Risk Management to Address Groundwater Cleanup Challenges at Complex Sites*, January (2012).

8. R. Zaney, “Taming the “Tower Plume””, *The Military Engineer*, **105**(681), 51-52, (2013)