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Use of Environmental Sequence Stratigraphy (ESS) as an Environmental Forensic Tool to Identify Chlorinated Solvent Sources at a Complex Site in Silicon Valley, California

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Abstract

This paper presents a case study for a complex contaminated groundwater site impacted by a historical release of chlorinated solvents in Silicon Valley, California. The original conceptual site model (CSM) inferred a contaminant migration pathway based on the groundwater gradient interpreted from groundwater elevation data, which is based on the underlying assumption that the subsurface conditions are homogeneous. However, the buried channel deposits render the underlying geology highly heterogeneous, and this heterogeneity plays a significant role in the subsurface migration of contaminants. Chemical fingerprinting evidence suggested that contamination at the downgradient property boundary was related to an off-site contaminant source. But, this alone was not a compelling argument. However, Environmental Sequence Stratigraphy (ESS), a geology-based environmental forensic technique, was applied to define the permeability architecture or the "plumbing" that controls subsurface fluid flow and contaminant migration. First, the geologic and depositional setting was synthesized based on regional geologic data, and representative facies models were identified for the site. Second, the existing CSM and site lithology data were reviewed and existing lithology data were graphically presented to display vertical grain-size patterns. This analysis focused on the nexus between the depositional environment and the site-specific subsurface data resulting in correlations/interpretations between and beyond data points that are based on established stratigraphic principles. The depositional environment results in buried river channels as the primary control on subsurface fluid flow, which defines hydrostratigraphic units (or HSUs). Finally, a hydrostratigraphic CSM that includes maps and cross sections was constructed to depict the HSUs present as a framework to integrate hydrogeology and chemistry data. This study demonstrates that: 1) Highly permeable buried river channel deposits control subsurface fluid flow and contaminant transport, and have distinct chemical constituents and concentrations (*i.e.*, they represent distinct HSUs), 2) Mapping of such HSUs is feasible with existing boring log data, 3) In settings such as the Santa Clara Valley where groundwater flow is governed by subsurface channel deposits, a hydrostratigraphic mapping approach is superior to a depth-based aquifer zonation approach, and 4) For heterogeneous subsurface, a detailed geology-based definition of the subsurface is an integral component of an environmental forensic analyses to determine contaminant source(s) and pathways.

Keywords

Environmental Sequence Stratigraphy, Hydrostratigraphic Units, HSU, Contaminant Sources, Source Identification, Migration Pathways, Depositional Environment, Chlorinated Solvents, Environmental Forensic Tool

1. Introduction

At a contaminated site, it is generally understood that a conceptual site model (CSM) is an indispensable road map for the remedial investigation and throughout the remediation life cycle. Among the components of the CSM, contaminant sources are of the most critical as they are the starting points of the migration pathways, which controls ultimate distribution (or extent) of contaminants (Lu, 2015 [1], Lu *et al.*, 2016 [2], Lu, 2016 [3]). This is especially true for complex sites where geological heterogeneity is the "norm" rather than the "exception".

Conventional site investigation typically relies on the assumption of homogeneous subsurface conditions where "hot spots" (*i.e.*, areas with distinctively higher COC concentrations exceeding cleanup levels) are identified and addressed during remediation (Lu *et al.*, 2016 [2]). Hot spots often represent only a small subset of the entirety of source contamination. While identified hot spot areas are good targets for remediation, they may not be representative of contaminant source areas, and other undiscovered source areas may continue to contribute COCs to site groundwater (and to vapors in the vadose zone) so that persistent plume and vapor issues may prevent site closure for a long time.

The Silicon Valley site presented herein is a prime example of a complex site where the subsurface heterogeneity is defined by the geology and controls fluid flow and contaminant migration, and these conditions have a significant effect on source identification. At this site, despite considerable source remediation work over the past two decades, increasing contaminant concentrations were observed in monitoring wells at the supposed "down-gradient" property boundary from the source area, and a CERCLA five-year review recommended additional source remediation. Using the ESS approach, two channel deposits underlying the site were mapped, one of which could be traced back to the on-site source area, and another which was oriented oblique to the presumed groundwater gradient and was interpreted as a contaminant pathway from an off-site source. Analysis of contaminant constituents associated with these two pathways revealed differing "chemical fingerprints" and indicated that these channel deposits are in fact separate and distinct hydrostratigraphic units (HSUs). These findings enabled the responsible party to differentiate which monitoring wells were representative of on-site-related contamination, and those impacted by off-site sources. The multiple lines of evidence provided by hydrostratigraphic mapping and groundwater chemistry fingerprints indicate off-site contaminant contributions to "downgradient" property boundary monitoring wells.

2. Environmental Sequence Stratigraphy

"Environmental Sequence Stratigraphy", or "ESS" as used herein, refers to the application of both the concepts of sequence stratigraphy and facies models (discussed below) to the types of datasets collected for environmental groundwater investigations, which are typically at the outcrop or reservoir unit scale (tens to hundreds of feet vertically, hundreds to thousands of feet laterally).

ESS analyses have been applied to groundwater remediation and water resource studies since the 1990s (Ehman and Cramer, 1996 [4]; Ehman and Cramer, 1997 [5]), and the importance of advanced stratigraphic methods for understanding aquifer heterogeneity has been emphasized by numerous authors (e.g., Koltermann and Gorelick, 1996 [6]; Weissmann and Fogg, 1999 [7]; Biteman, *et al.*, 2004 [8]; Ponti, *et al.*, 2007 [9]; Payne, *et al.*, 2008 [10]; Scharling, P. B., *et al.*, 2009 [11]). Most groundwater basins have had regional scale stratigraphic analysis undertaken which should be carefully integrated into remediation studies (e.g., USGS Water Supply Papers at https://pubs.er.usgs.gov/browse/usgs-publications/WSP). However, the number of published studies which have applied these concepts to data from remediation sites is very limited (e.g., Ehman and Cramer, 1996 [4]).

The science of sequence stratigraphy was initially developed in the petroleum industry based on basin-scale reflection seismic studies, and identification of termination of seismic reflectors on continental margins as related to global sea level changes for petroleum exploration purposes (e.g., Mitchum *et al.*, 1977 [12]). However, during the decades since this seminal work the concepts have been applied at increasingly smaller scales on well logs and cores, outcrops, and petroleum reservoirs (Van Wagoner *et al.*, 1990 [13]). Sequence stratigraphy and facies models represent current best practice for predicting and delineating the geometry and continuity of subsurface strata.

3. Site Geological and Hydrogeological Setting

This site is representative of many contaminated groundwater sites in the Santa

Clara Valley, or "Silicon Valley" of northern California (**Figure 1**). The groundwater table in the basin is relatively shallow (approximately 10' below ground surface [bgs]), contaminant concentrations in groundwater are locally high, and the highly urbanized area is characterized by dense commercial and residential construction. Groundwater plume migration poses vapor intrusion risks.

The heterogeneous aquifers in the Silicon Valley are composed of high-permeability sand and gravel-rich channel-fill deposits encased in low permeability clay and silt floodplain deposits and/or paleosol horizons. The sandy channel deposits result in complex groundwater flow and contaminant migration pathways that are not reliably discerned with groundwater gradient maps. This results in challenges in contaminant plume characterization (particularly with comingling plumes) and remedy design, performance, and monitoring.

4. Depositional Setting and Fluvial Channel Facies Models

The Quaternary alluvial stratigraphic section, which comprises the impacted aquifers in the Silicon Valley, was deposited in fluvial channel and floodplain environments by mildly sinuous (anastomosing or meandering-type) streams

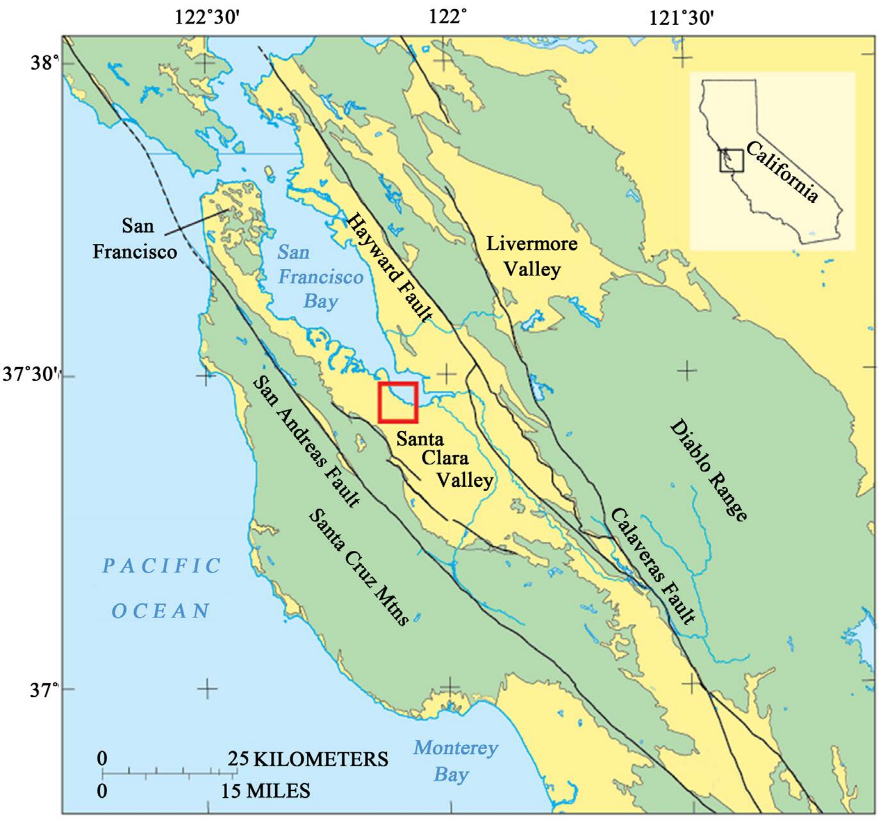

Figure 1. Map showing location of the Santa Clara Valley in the southern San Francisco Bay region, California. Alluvial lowlands (yellow) are distinguished from bedrock uplands (green). Principal faults are shown in black. Red box indicates general location of case study site (Modified from Wentworth *et al*., 2014 [14]).

draining the Santa Cruz Mountains and flowing into San Francisco Bay (Figure 1). As these channels migrated across the landscape, sand and gravel were deposited in channel axes and possibly point bars. During flooding events, silts and clays were deposited outside the channels in the floodplain, and rivers periodically abandoned their previous courses and formed new channels. Figure 2 presents the various depositional components resulting from an anastomosing river.

Groundwater flow and contaminant transport occurs primarily within the permeable channel deposits, and the variable orientation of channels deflects contaminant migration directions from the regional groundwater gradients. This can cause plumes to appear to spread laterally, and assume complex plan-view morphologies (*i.e.*, Figure 3). Due to this channelized groundwater flow in the Silicon Valley and large number of source areas in proximity to one another, many plumes have become commingled, creating challenges for defining plume sources and predicting or controlling plume migration.

5. Review and Format Existing Subsurface Data and Apply Stratigraphic Principles for Correlations

The database for this project consisted of boring logs (from direct push, hollow-stem auger, and mud-rotary drilling methods), well construction diagrams, and chemical analyses from groundwater samples. Graphic grain size logs were constructed from the boring log information to highlight vertical grain size patterns captured in the boring logs. As shown in Figure 4, fining-upward channel fill sands encased in floodplain silts/clays are apparent which allows for mapping of individual channel deposits.

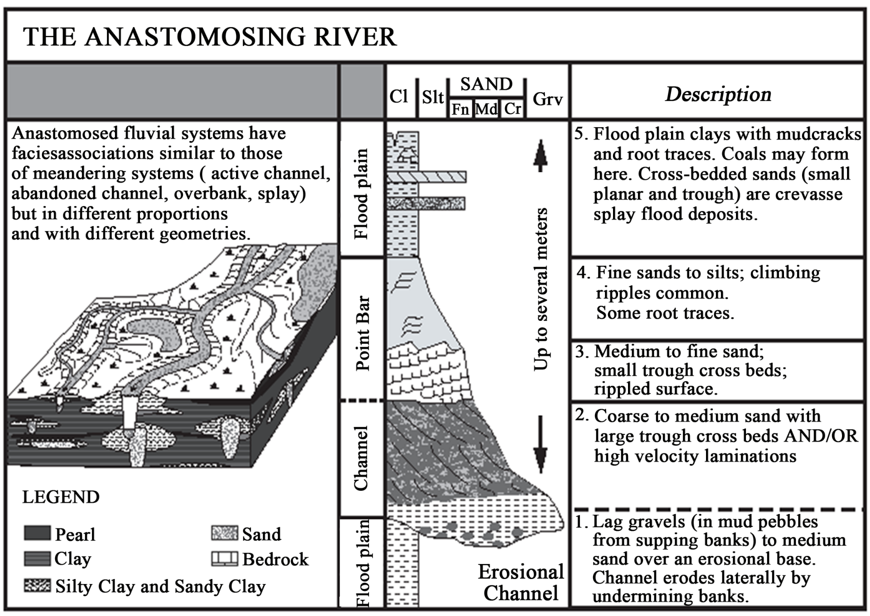

Figure 2. Depositional components of anastomosing river depositional environment including fining upward vertical grain size pattern, representative of channel fill deposits.

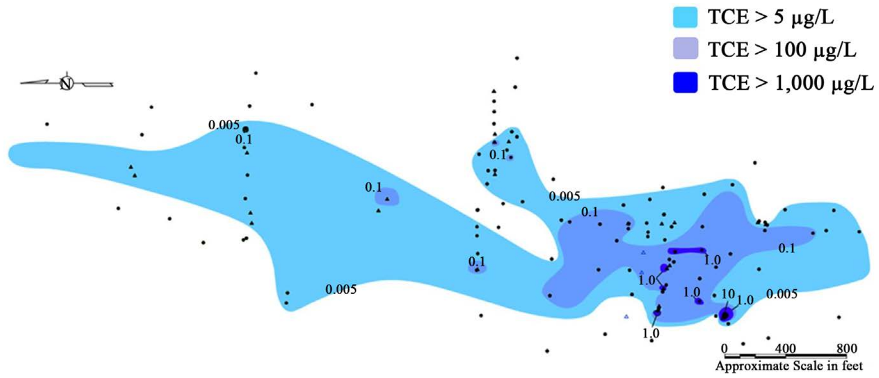

Figure 3. TCE isoconcentration map of the Silicon Valley B1 aquifer zone groundwater plume discussed in this case study ("the plume"). Note 1) irregular plume morphology resulting from channelized groundwater flow pathways and groundwater extraction, and 2) "bull's eyes" of isolated wells showing high concentration resulting from well screens penetrating multiple channel deposits (separate HSUs) containing groundwater with relatively higher contaminant concentrations.

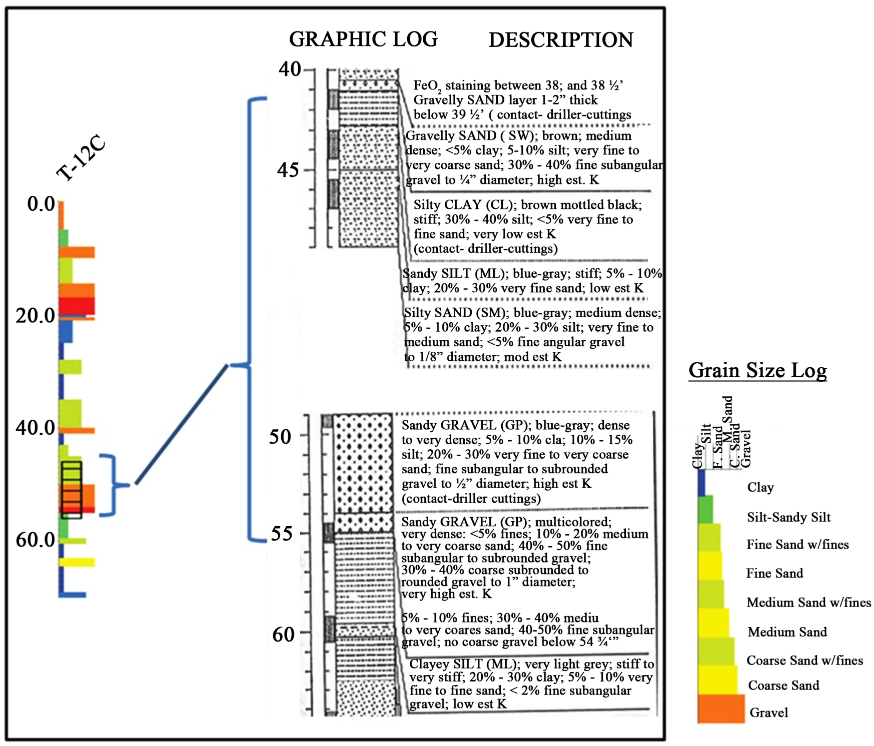

Figure 4. Fining-upward channel fill sequence. Portion of a boring log from the site illustrating a clear fining-upward sequence from 55' to 41' bgs representing a channel-fill and point bar deposit (see **Figure 2**). Basal gravel lag and overlying fining-upward sequence occurs at 41' below ground surface (bgs). Lithologic contacts were identified on the basis of sampling, cutting returns and drilling behavior. Graphic grain size log (at left) shows this fining-upward sequence within a well screen interval.

In order to address increasing contaminant concentrations in areas downgradient of the onsite source area, cross section A-A' (location shown on **Figure 5** and cross-section shown on **Figure 6**) was prepared.

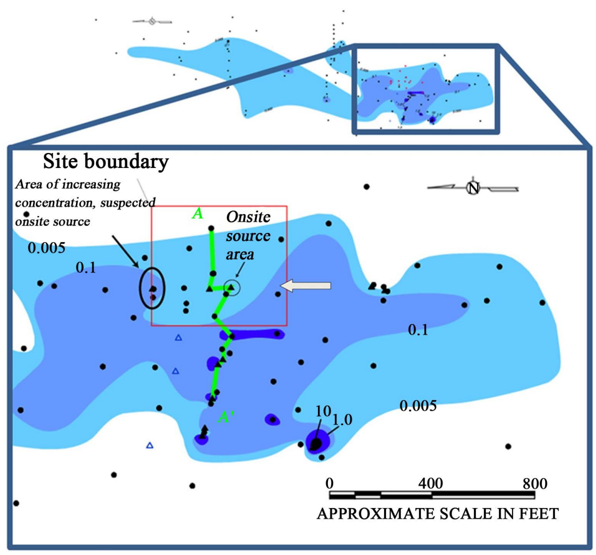

Figure 5. Map of a portion of the B1 aquifer zone TCE plume showing onsite source area, area of increasing contaminant concentrations, site property boundary, direction of presumed groundwater flow based on inspection of water level maps (white arrow), and location of cross section A-A'.

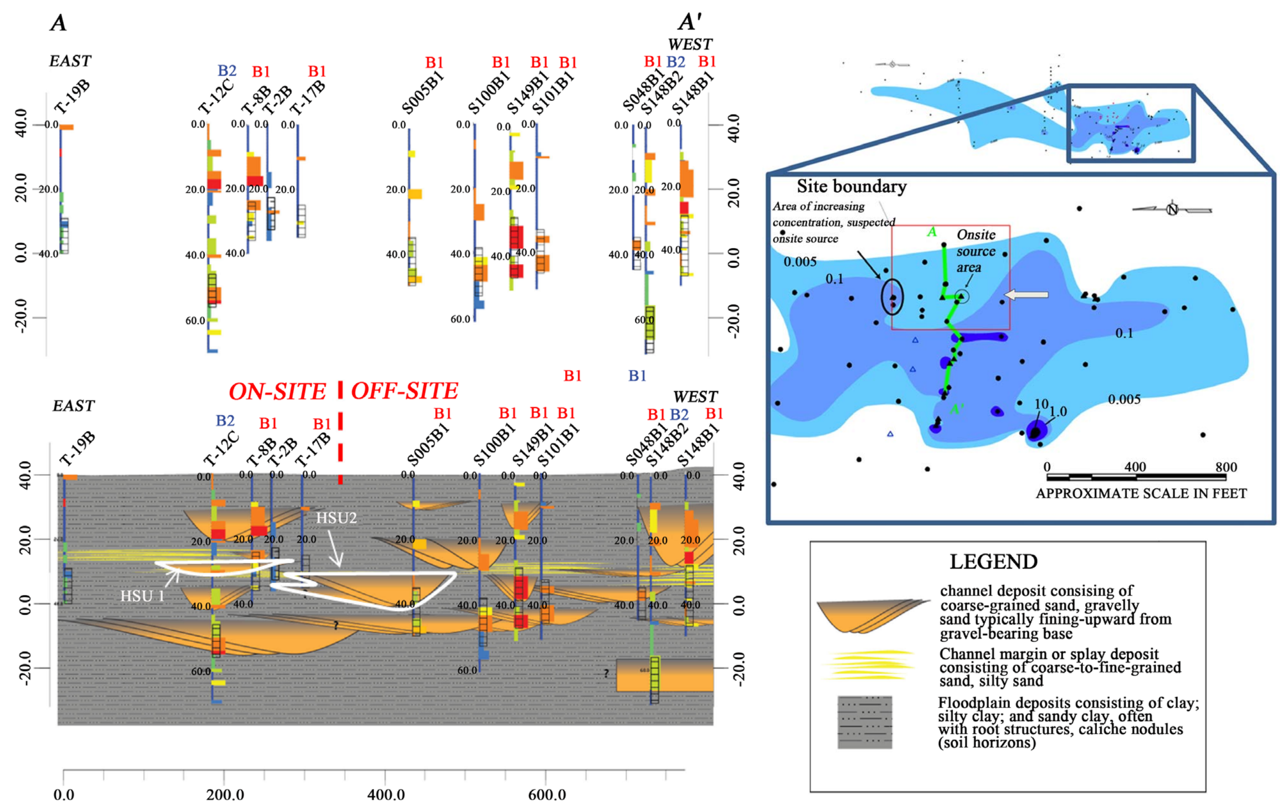

Figure 6. Uninterpreted (top), and interpreted (bottom) cross section A-A' from study area. General groundwater gradient is to the north (out of the plane of the cross section towards the viewer, and towards the left on the map view). "B1" or "B2" at the top of the boring indicates aquifer zone designation corresponding to the screened interval of each well. Note that many "B1" wells are screened across multiple channel deposits (e.g., S005B1, S149B1, S101B1), and that, while T-12C is designated a "B2" well, it is in fact screened in the same channel unit as "B1" designated wells S005B1, S101B1, and S101B1. See Figure 4 for legend for graphic grain size logs created from boring logs. Channel dimensions interpreted based on detailed mapping at the site and closely-spaced high-resolution datasets at other nearby sites in the same stratigraphic interval.

The following principles of stratigraphic interpretation in fluvial deposits were applied to correlate the grain size patterns between boring logs, as depicted in **Figure 6**.

- Channel deposits tend to have erosive bases and relatively flat tops, and clays make superior correlation markers (likely paleosol horizons);
- Gravels define channel bases and grain size fines upward.

Channel margins are sharp and erosive, and result in strong segregation of channel-fill sands and gravels from floodplain clays.

Inspection of cross section A-A' (**Figure 6**) reveals that onsite groundwater monitoring wells designated as B1 aquifer zone wells (T-8B, T-2B, T-17B) are screened in a shallower, isolated channel complex (indicated as HSU-1) relative to the offsite wells S005B1, S100B1, S149B1, S101B1, and S048B1. Onsite well T12C, which is designated as a B2 aquifer zone monitoring well, is screened within the same HSU as offsite wells designated as B1 monitoring wells. This highlights the confusion related to depth-based water-bearing zones for plume mapping in channelized aquifers. Offsite well S005B1 is screened across multiple channel deposits, and TCE concentrations are significantly higher in this well, suggesting that groundwater in the shallower channel indicated as "HSU-2" contains a relatively high concentration of contaminants. Thus, some well data result in a high concentration "bulls eye" on the B1 aquifer zone plume map (**Figure 5**).

Extensive on-site contaminant source removal over time resulted in significant decrease in VOC concentrations in groundwater near the source area, but little to no decreases in VOC concentrations at the downgradient property boundary of the on-site source area. The in-situ bioremediation performed in the source area resulted in generation of vinyl chloride (VC) as a daughter product. However, monitoring well T-9B at the downgradient extent of the property showed increasing VOC concentrations, up to 390 μg/L, an order of magnitude higher than other on-site wells. In light of the observed control of channels on groundwater chemistry observed at the site (e.g., **Figure 6**), a detailed ESS analysis was undertaken to map HSU-1 and HSU-2 and evaluate a potential hydrostratigraphic connection from T-9B area to the south (**Figure 7**).

As mentioned, on-site monitoring wells typically contain VC, occurring as a daughter product of TCE. Freon-113 is associated with the off-site source and was not used in on-site operations. Thus, VC is unique to the on-site source and Freon-113 is unique to the off-site source. After completing the ESS assessment, groundwater contaminant chemistry data (trichloroethene [TCE], tetrachloroethene [PCE], *cis*-1,2-dichloroethene [cDCE], vinyl chloride [VC], and Freon 113 [freon]) were interrogated with respect to the updated stratigraphic framework (*i.e.*, HSUs) to provide an independent line of evidence for off-site related contamination (**Figure 8**).

Cross section B-B' (**Figure 8**) is oriented such that it includes on-site wells along the path of HSU 1, and then traverses to the south west to include the

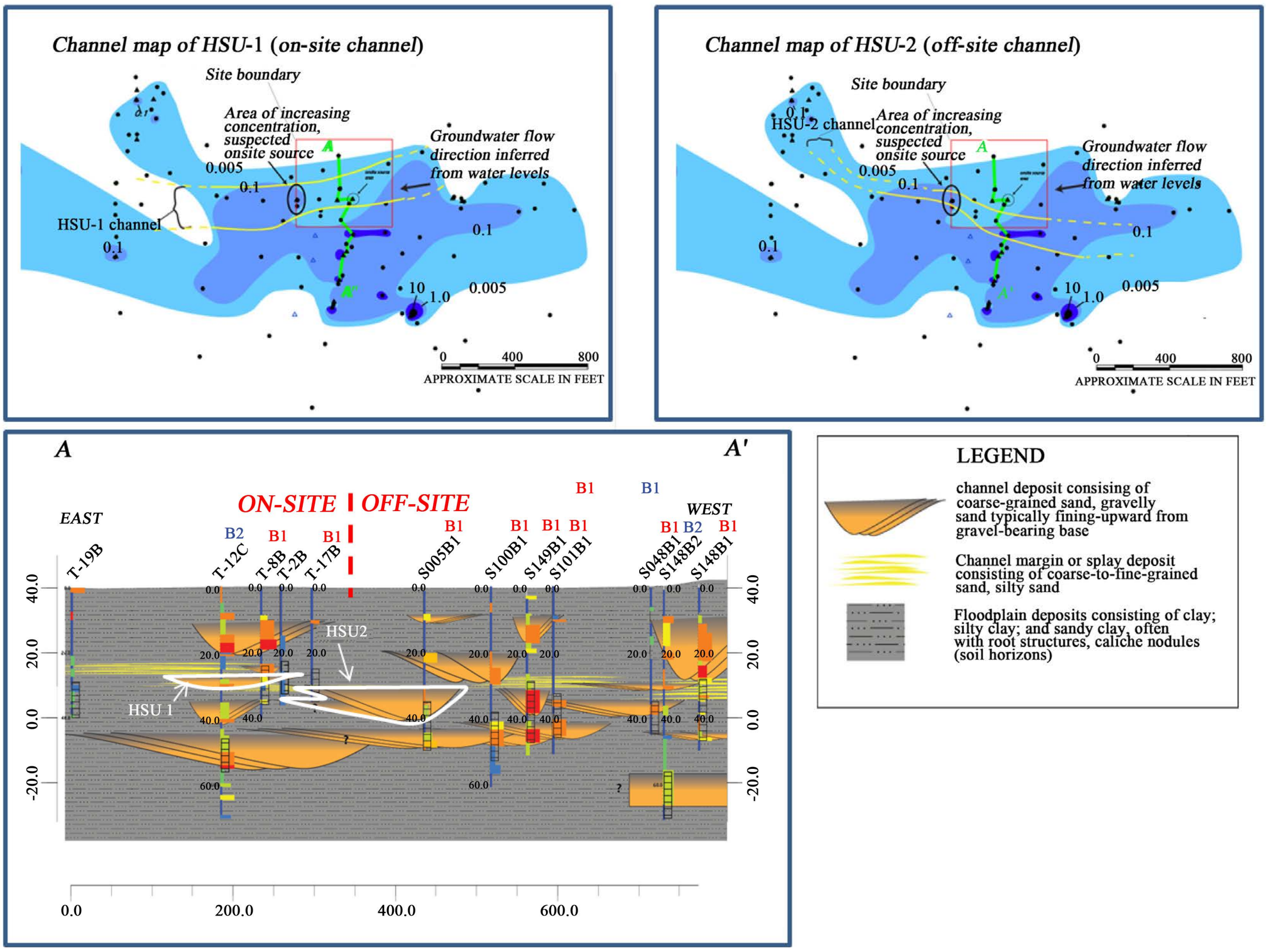

Figure 7. Detailed mapping of HSUs. Maps of HSU 1 and HSU 2 channel axis facies (sand- and gravel-bearing, indicated by yellow outlines), and cross section A-A' (lower figure). The deeper channel HSU-2 provides a direct lithologic connection and hence potential contaminant pathway from off-site sources. Note that the channel widths and morphology depicted on the cross sections are constrained by three-dimensional facies mapping of the channel complexes and floodplain deposits.

high-concentration, deep HSU-2 channel in T-5B. Note that the wells screened only across HSU 1 (T-10B, T-8B, and T-2B) contain groundwater with TCE, cDCE, and VC, and lack Freon-113. The well that is screened only across HSU 2 (T-5B) contains groundwater with Freon-113, and lacks VC. Well T-9B is screened across both HSU 1 and HSU 2 and thus contains mixed groundwater with both indicator parameters (VC and Freon-113).

A similar trend is observed in cross section C-C', which illustrates the continuity of the HSU 2 channel sands, which is corroborated by the chemistry fingerprint. The wells that are screened solely in HSU 2 lack the on-site source indicator VC and contain Freon-113 (T-4B has historically contained Freon-113, but not during the timeframe used to create fingerprint graphs). Well T-9B is screened in both HSU 1 and HSU 2 and contains groundwater that is a mixture of HSU 1 and HSU 2, containing all four analytes.

The chemistry fingerprint data provide an independent line of evidence, and corroborate the geologic interpretation that channel HSU 1 is a contaminant

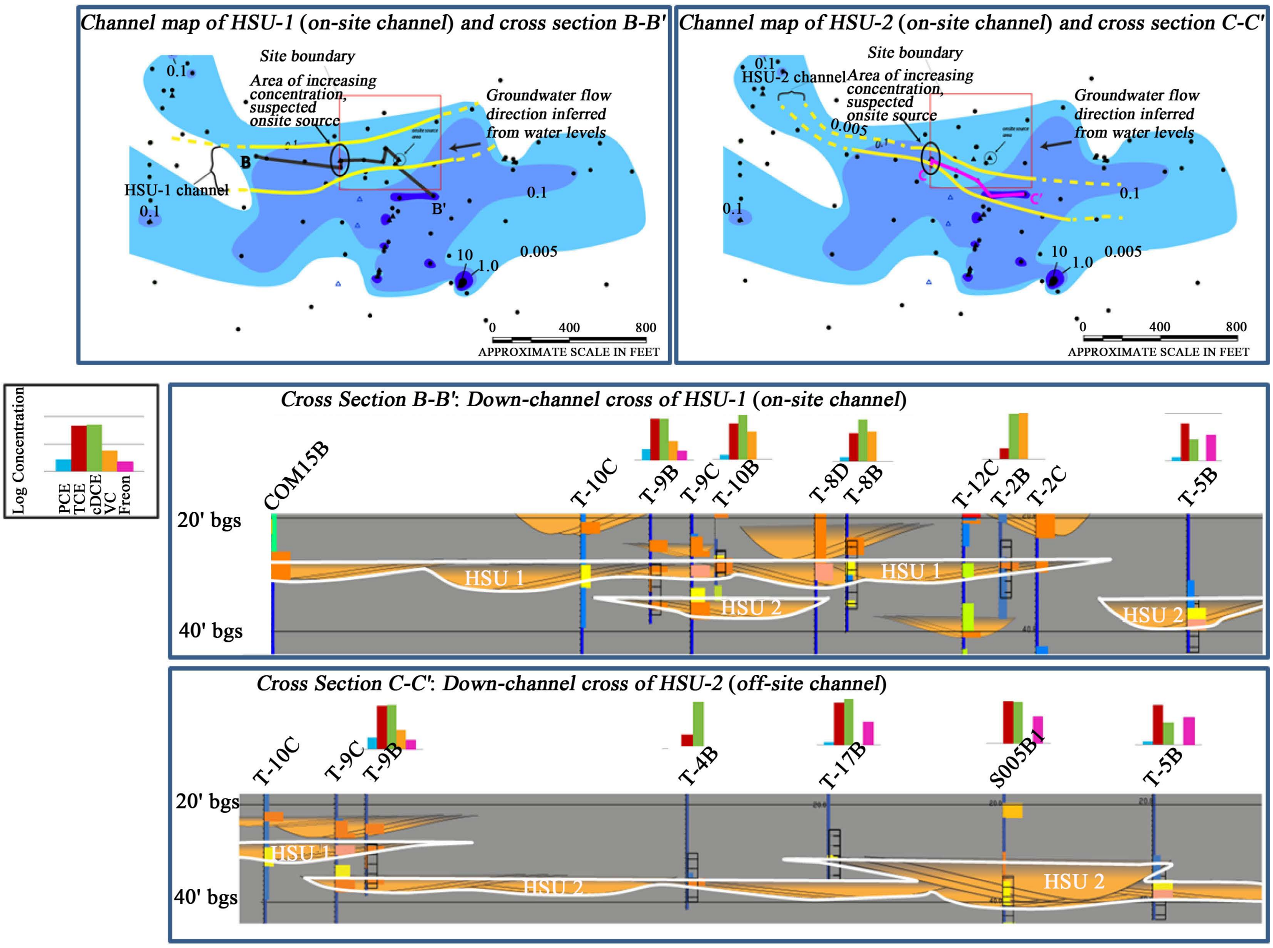

Figure 8. Contaminant fingerprinting. Cross sections B-B' and C-C' oriented down the axes of channel HSU-1 and HSU-2 with contaminant fingerprint charts corresponding to groundwater samples. Fingerprint charts post the log of the concentration of the different indicator contaminants, and as such are useful for discerning the constituents. Fingerprint charts represent an average value of concentrations over the last five years.

pathway representative of the on-site contaminant source and channel HSU 2 is a contaminant pathway representative of the off-site contaminant source.

6. Concluding Remarks

This case study exemplifies why a detailed understanding of the subsurface geology is critical for distinguishing potential source areas and hydrostratigraphic pathways for complex sites. As shown in **Figure 9**, the original CSM inferred an on-site source for the increase of concentrations observed at the property boundary. This was based on the groundwater gradient interpreted from groundwater elevation data, which assumes that the subsurface conditions are homogeneous at the scale of groundwater contaminant migration. However, as presented here, the underlying geology is heterogeneous due to the fluvial depositional environment and resultant channelized aquifer. The updated ESS-based CSM defines HSUs that are the primary control of contaminant migration, as corroborated by multiple lines of evidence (**Figure 10**). This more representative CSM identifies

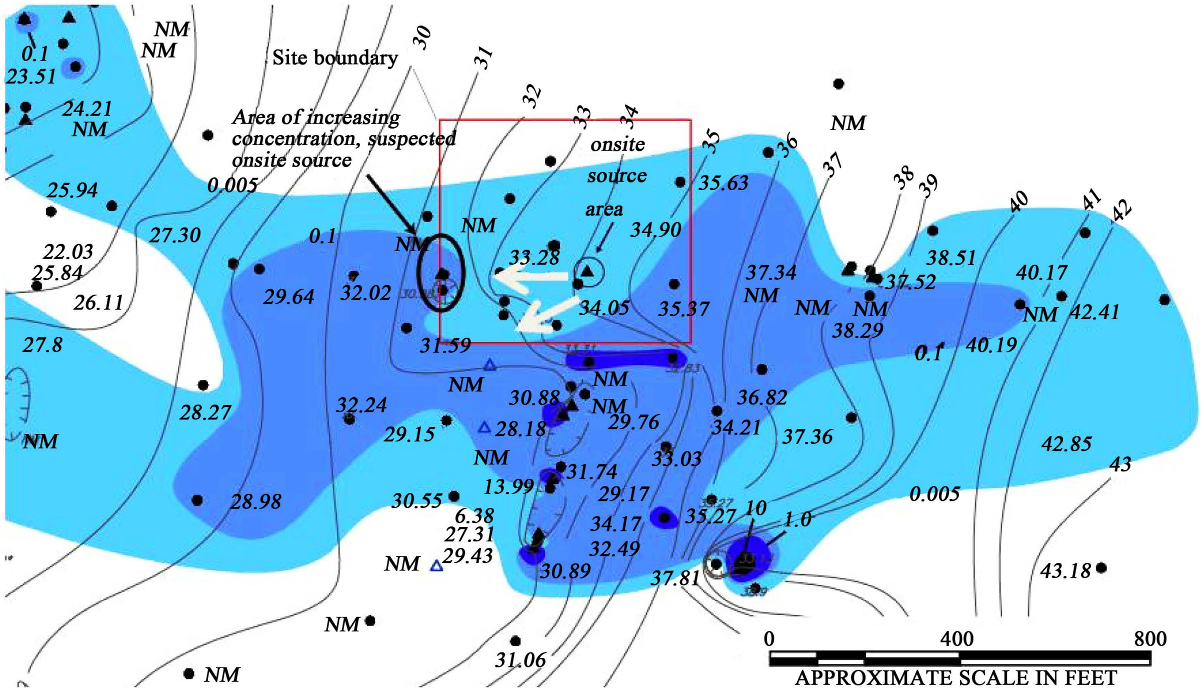

Figure 9. Original CSM based on simplifying assumption of homogeneous aquifer conditions. This interpretation of contaminant migration is based on the groundwater gradient (groundwater elevation contours) and does not focus on the geology and depositional environment. White arrows show interpreted groundwater flow directions and contaminant transport directions from the on-site source to the down-gradient impacts at the property boundary. Based on this assumption, additional source area remediation had been proposed.

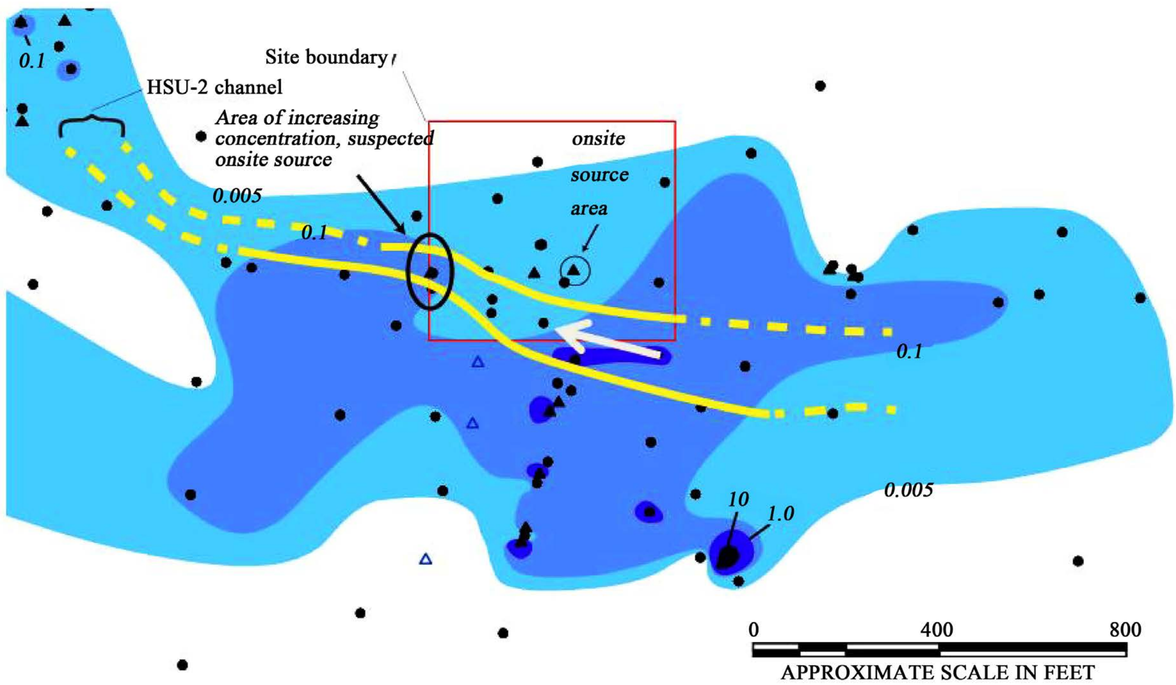

Figure 10. ESS-based CSM focused on underlying geology to define HSUs. The HSU-2 channel (bounded by yellow lines) controls the contaminant migration pathway (white arrow) showing that, unlike **Figure 9**, an off-site source is contributing to the impact occurring at the property boundary. At this complex site, groundwater flow is strongly influenced by lithology, and contaminant transport directions deviate significantly from those predicted from the potentiometric surface maps.

the multiple sources responsible for the commingled plumes. As a geology-based environmental forensic tool, this approach can be a significant asset to forensic analysis of complex contaminated groundwater sites.

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