FACT SHEET

Environmental Sequence Stratigraphy (ESS)

Introduction

Complex geological conditions pose challenges to designing successful remedial actions and achieving remedial goals within reasonable timeframes. With improved site investigation techniques, sites that have been challenging to address are often found to have more complex geology than originally defined. Environmental sequence stratigraphy (ESS) is an enhanced approach to characterize aquifer heterogeneity and predict contaminant fate and transport by understanding geologic depositional environments. ESS allows for more informed subsurface predictions of geological factors affecting site remediation. ESS is an established best practice for the development of conceptual site models (CSMs) as outlined by the United States Environmental Protection Agency (Shultz et al., 2017).

Technology Background

Groundwater flow and mass transport are controlled by the geometry and interconnectivity of high and low permeability layers within sedimentary aquifers. These layers are referred to as facies. Sequence stratigraphy is a correlation technique developed to predict heterogeneity and connectivity more accurately between boreholes based on lateral changes within the depositional environment. Figure 1 is a CSM showing the types of depositional environments in which ESS can be successfully implemented.

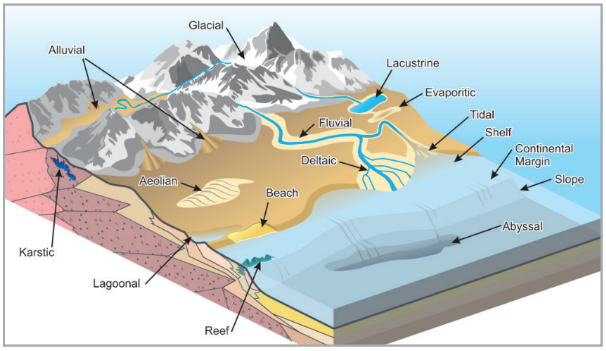

Figure 1. Depositional Environments Suitable for ESS Application (Courtesy of Battelle)

How Does It Work?

The ESS methodology as outlined by Schultz et al. (2017) can be conducted in three iterative steps using existing data to the extent possible. These steps include:

1) Evaluate the Depositional System: Regional geologic and geospatial data are compiled to build detailed knowledge of the geological history and identify which specific facies models are applicable.
2) Determine Grain Size Trends: Early in the ESS process, existing subsurface site data are reviewed to determine vertical grain size trends which are then compared and validated against previously identified facies models.
3) Correlate and Integrate into an Enhanced CSM: Validated vertical grain size trends are then used for subsurface correlation within a series of cross-sections to build a three-dimensional (3-D) geologic framework of the CSM. Hydrogeologic and chemistry data are also used to interpret hydrostratigraphic units in the context of the stratigraphy.

How Can It Help?

Following the ESS methodology above, zones of contaminant transport and storage can be refined in the CSM and inform additional data collection needs, remedial design, and remedial action. Overall, the ESS process can help to:

- ☐ Characterize aquifer heterogeneity;
- ☐ Identify preferential groundwater flow pathways;
- ☐ Improve prediction of contaminant fate and transport; and
- ☐ Optimize remedial design and cost efficiency.

Case Study 1: Joint Base Anacostia-Bolling | **Case Study 2: Naval Base Kitsap-Keyport** | **Conclusions**

Joint Base Anacostia-Bolling

Project Objective: ESS characterization was applied to the Joint Base Anacostia-Boling (JBAB) site to develop a high-resolution stratigraphic framework. ESS was used to enhance the existing 3-D CSM and refine mass discharge estimates.

Site Background: JBAB is a 905-acre Department of Defense (DoD) property located in Washington, DC, where underlying groundwater was impacted by chlorinated volatile organic compounds (cVOCs). Prior high-resolution site characterization (HRSC) studies found that the underlying aquifer was comprised of a heterogenous mixture of high-permeability sands and gravels and low-permeability clays and silts. HRSC data were used to construct a 3-D Environmental Visualization System (EVS) model based on computer kriging techniques to characterize the nature and extent of cVOCs beneath the site. However, the interpreted plume from this method did not align with the observed groundwater flow direction and challenges arose in calculating the contaminant mass discharge estimates.

Results: The ESS CSM for the JBAB site was based on the interpretation of three distinct stages of deposition including: 1) during initial Pleistocene rifting, coarse-grained fan deltas formed along the margins of the early Anacostia Valley; 2) during subsequent Pleistocene sea-level fall, coarse-grained ancestral Anacostia River braided river sediments were laid down on the valley floor; and 3) during the Holocene sea-level rise, the valley was inundated resulting in the deposition of finer-grained thick, muddy floodplain and tidal marsh/estuary sediments. The redefined CSM in Figure 2 identified that two distinct horst and graben structures (normal faults) exist in bedrock beneath JBAB. It was recognized that sediments displaced by normal faults act as effective barriers to prevent or limit groundwater flow. Groundwater was noted to principally flow from east to west through preferential pathways created by channel deposits and in some areas fan deposits of coarse-fine sand with gravel, instead of the previously considered northward flow direction. As a result, cVOCs in groundwater were reinterpreted to be from two separate source zones. Insights identified by the new ESS CSM were incorporated into the existing 3-D EVS model to refine kriging estimates and better visualize hydraulic flow pathways and zones of greatest mass discharge (NAVFAC, 2021a and 2021b).

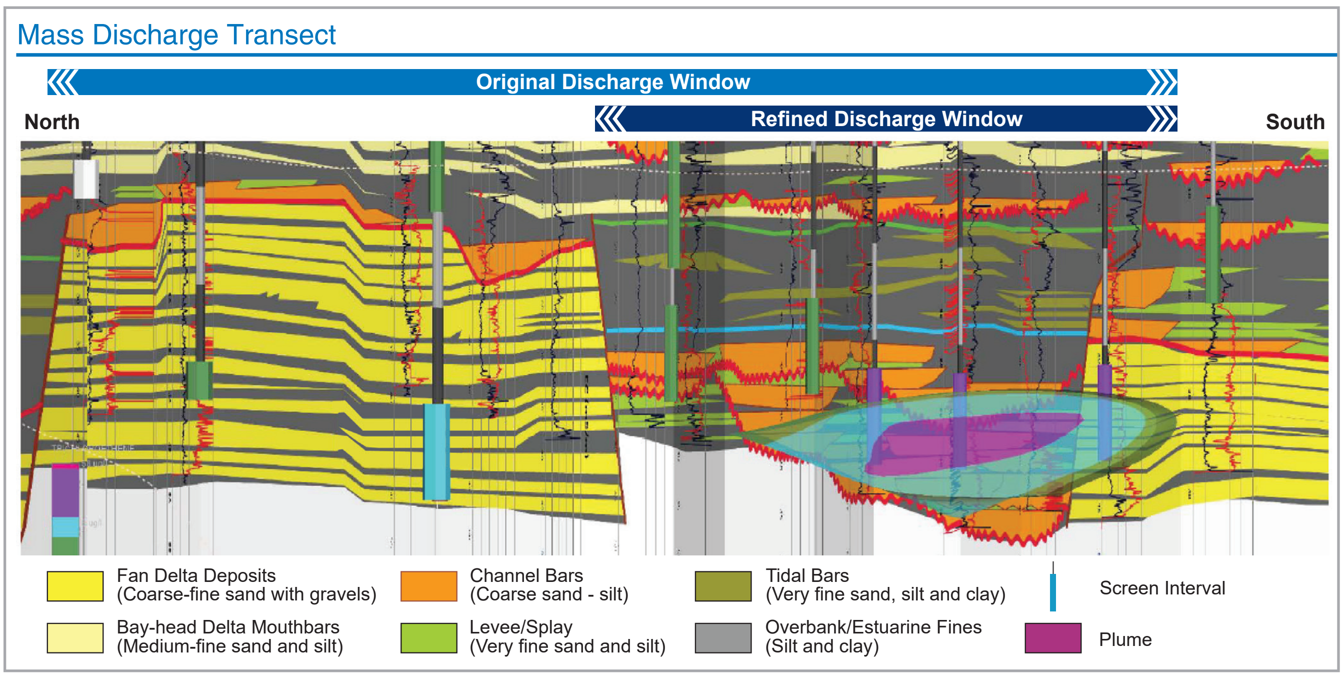

Figure 2. Mass Discharge Window as Refined after ESS Analysis (Courtesy of NAVFAC)

Outcome: Insights gained from the refined JBAB ESS CSM resulted in direct cost savings to the Navy by discontinuing the need for installation of up to three additional monitoring wells to the north. The refined CSM significantly reduced the estimated discharge zone of impacted groundwater into the Potomac River, providing a basis to optimize the future remedy selection and design approach.

Return to Menu

CASE STUDY 2

Naval Base Kitsap - Keyport Operable Unit 1 Former Landfill

Project Objective: An ESS characterization study has been implemented at the Naval Base Kitsap (NBK) Keyport Operable Unit 1 (OU1) site to better delineate the regional aquitard contact, aid in fate and transport modeling, and refine the CSM.

Site Background: NBK Keyport is a 340-acre Navy property located adjacent to the town of Keyport, Washington on a small peninsula located between Dogfish Bay and Liberty Bay within the central portion of the west side of Puget Sound. The OU1 site is approximately 9 acres in size and consists of a former landfill bordered by an estuary wetland. Groundwater beneath the former landfill is impacted by cVOCs and other contaminants. The selected remedy of phytoremediation and monitored natural attenuation was predicated on a CSM that emphasized cVOCs present above 15 feet below ground surface (bgs) within two source areas. A revised CSM was needed to optimize the remedial approach due to the extended restoration timeframe determined from long-term monitoring trends.

Results: Evaluation of the depositional history for the OU1 site found that the impacted aquifer consists of Holocene to Pleistocene-aged heterogenous tidal flat deposits, glacial drift deposits, and fluvial/floodplain deposits (Figure 3). The ESS CSM was based on the interpretation of three distinct stages of deposition in ascending order including: 1) deposition of fluvial and boggy floodplain/flood basin sediments during the Olympia interglacial period (*Basal Aquitard in Figure 3*); 2) erosion and burial of Olympia sediments during deposition of the Vashon till during the Vashon Stade glaciation (*Hydrostratigraphic Units [HSU] No. 2 and 3 in Figure 3*); and 3) erosion of glacial bluffs and redistribution of sediment upon the Holocene sea-level rise, resulting in the construction of the modern tidal flats of Dogfish Bay (*Fines-Rich Heterolithic [FRH] facies in Figure 3*). The refined CSM for the OU1 site found that significant amounts of cVOC mass were stored within the low-permeability sediments beneath the landfill waste body to depths of over 55 feet bgs, acting as ongoing source zones. Contaminants can slowly back diffuse from these low-permeability areas. The regional aquitard was observed to be extensive throughout the site. However, historical observations of isolated gravel lenses within the regional aquitard were verified and ESS mapping and interpretations identified them to be a network of fluvial channel bodies oriented northwest. The shallow-most zone of the regional aquitard consists of organic-rich silt, clay, and peat. Within localized areas, the aquitard is separated from underlying fluvial channel bodies by less than 5 feet of low permeability fines, which increases the potential for back diffusion of sorbed cVOCs into the fluvial channel network. Geophysical surveys confirmed the presence of these fluvial channels and subsequent analytical data confirmed contaminants are migrating as shown in Figure 3 toward to the northwest within the fluvial channel at a depth of 45 to 55 feet bgs within the upper portion of the regional aquitard.

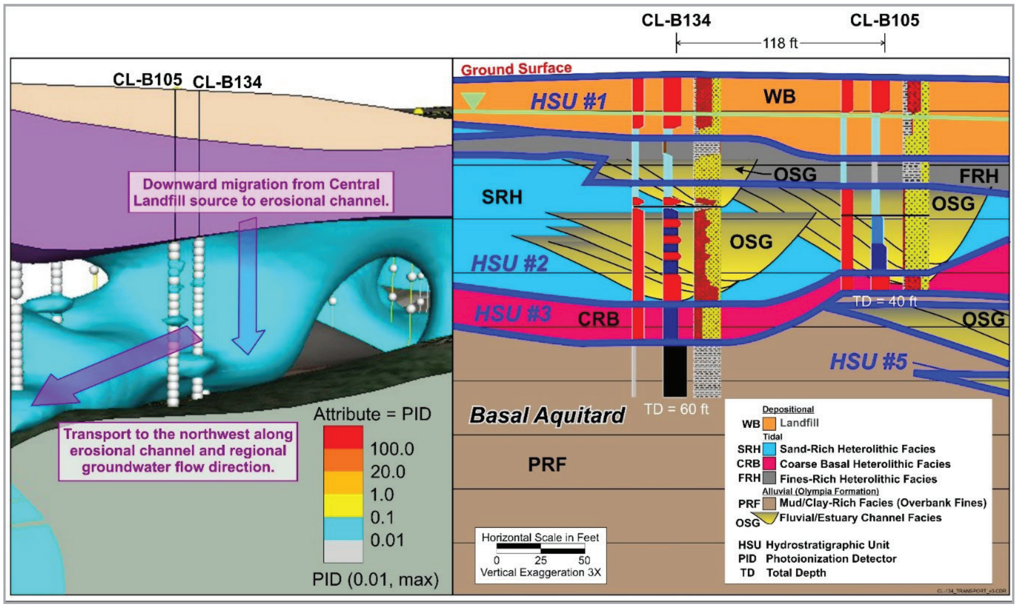

Figure 3. ESS Cross Section Depicting Subsurface Heterogeneity Beneath the NBK Keyport OU1 Site (Courtesy of Battelle)

Outcome: Insights gained from the refined Keyport OU1 ESS CSM influenced all subsequent data interpretations. It was noted that the thick clays logged in the OU1 borings were not necessarily impervious aquicludes preventing cVOC transport. The improved ESS CSM also led to the identification of a network of tidal paleochannels that focused the scoping of further investigations to track contaminant fate and transport.

Conclusions

This fact sheet summarizes the overall ESS methodology, benefits of ESS to site restoration, and provides two case studies which demonstrate the application of ESS techniques to Navy sites. The overall conclusions for the implementation of ESS to improve CSMs are as follows:

- Within sedimentary aquifers, groundwater flow and mass transport are primarily controlled by the geometry and interconnectivity of high and low permeability layers (facies).
- ESS is an integrated characterization approach which utilizes principals of sequence stratigraphy and facies analysis to build or enhance the CSM.
- The ESS methodology relies upon a three-step iterative process to generate robust, geologically defensible results that can be implemented and updated at any point throughout the lifecycle of a remedial site.
- ESS can be implemented to characterize subsurface heterogeneity, map high and low permeability zones, evaluate groundwater flow pathways and areas of mass transport, and assess potential sources of back-diffusion.
- ESS results can be used as a guide to optimize additional data collection and remedial design planning, subsequently improving cost-efficiency for the overall cleanup project.

Disclaimer

References

NAVFAC. 2021a. The Application of Environmental Sequence Stratigraphy at Department of Defense Sites. Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) Contract No. N39430-16-D-1802. May.

NAVFAC. 2021b. Open Environmental Restoration Resources (OER2) Webinar on Environmental Sequence Stratigraphy (ESS) as a Remedy Optimization Tool. July. Available at: https://exwc.navfac.navy.mil/Products-and-Services/Environmental-Security/NAVFAC-Environmental-Restoration-and-BRAC/Training/OER2-Webinars/.

Shultz, M., R. Cramer, C. Plank, H. Levine, and K. Ehman. 2017. Best Practices for Environmental Site Management: A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-17/293.