

FROM 2D CROSS-SECTIONS TO A 3D MODEL: A TOOLSET FOR INTEGRATED DATA MANAGEMENT, MODELING, AND VISUALIZATION

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ABSTRACT

Two-dimensional (2D) cross-sections are a common aid in understanding three-dimensional (3D) subsurface conditions for purposes including environmental restoration, water resource evaluation, and resource extraction. This case study describes translation of the institutional knowledge and interpretations captured on existing 2D hydrogeologic cross-sections into an integrated, dynamic 3D hydrogeologic framework model that flexibly supports site goals. A premium is placed on automation and structured data management, allowing geoscientists to focus on visualization and analysis rather than on data manipulation and model assembly.

INTRODUCTION

Tinker Air Force Base (AFB) is a major logistics center and aircraft, weapons, and engine repair depot located in Oklahoma City, OK. As a result of past waste handling practices, contaminants (primarily chlorinated solvents) are present in groundwater at the Base. Groundwater contamination occurs primarily in the Garber sandstone, which is present across the entire Base and outcrops over the northeastern portion of the Base. Contamination decreases with depth in the Garber sandstone, but extends up to about 200 ft below ground surface (BGS) in some areas. The Garber sandstone is overlain by the Hennessey Formation in the southeast portion of the Base. The Garber sandstone and the underlying Wellington Formation are the main geologic units comprising the Central Oklahoma Aquifer, which is the primary source of potable groundwater in the Oklahoma City area and the water supply source for the Base (via water supply wells perforated between approximately 200 to 750 ft BGS). The Garber sandstone was deposited in a fluvial-deltaic environment and consists of lenticular beds of fine-grained, cross-bedded sandstone interbedded with siltstone, mudstone, and shale. The lower conductivity mudstones/shales exert strong control on groundwater flow and thus contaminant transport, especially where their lateral continuity is greater. Beneath the Base, two laterally continuous mudstone aquitards have been identified within about 200 ft of ground surface. Head differences of approximately 20 to 150 ft occur across these aquitards. Within the intervening aquifer units, vertical head differences are near zero in areas where the intra-aquifer mudstones have little lateral continuity and up to 20 ft in areas of greater mudstone continuity.

HISTORICAL CROSS-SECTION DEVELOPMENT

Given the aforementioned geologic controls on groundwater flow and contaminant transport in the Garber sandstone, a thorough understanding of the hydrogeology is critical for predicting potential future impacts due to existing contamination at the Base and for designing effective remedies. To this end, the Base geologist developed over 130 hand-drawn hydrogeologic cross-sections (Figure 1) beginning in the early 1990's. The lack of key marker beds in the Permian strata necessitated the development of a consistent methodology to correlate sandstone and mudstone lithologies between adjacent boreholes. The methodology includes the following:

- Use of wireline logs (primarily natural gamma) and cores to define downhole lithology
- Use of the published formation structure (strike and dip), the depositional environment (fluvial deltaic), and the Hennessey-Garber contact (in southwest part of Base) to guide correlations
- Use of water level and groundwater quality data in conjunction with wireline logs and cores to define primary HSU boundaries

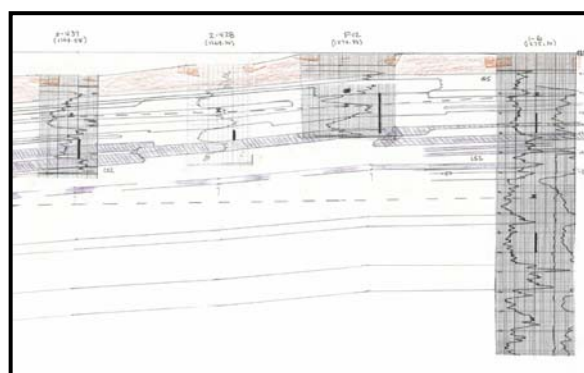


Figure 5. Base geologist's cross-section

- Development of standard unit thickness for HSUs from borings in the northeast quadrant of the Base and application of these rules of thumb throughout the Base.

Although the latter two items refer specifically to HSU boundaries, these are critical elements in identifying the several relatively continuous mudstone lithologic bodies that comprise aquitards within the Garber sandstone.

IMPETUS FOR 3D MODEL CONSTRUCTION

The Base geologist's cross-sections have been an invaluable tool in the groundwater restoration process at Tinker AFB. Construction of a 3D hydrogeologic framework model (HGFM) from these cross-sections captures the interpretations and institutional knowledge of the Base geologist in an integrated, dynamic model that can flexibly support ongoing Base restoration. Traditional 2D mapping products (cross-sections and plan-view maps) can be produced from this 3D model in an automated fashion, and the model supports a range of activities from drilling to numerical model construction to stakeholder communication.

DATA DEVELOPMENT AND MANAGEMENT

The foundation of the 3D HGFM is sandstone versus mudstone lithologic determinations made in 1-ft intervals at nearly 1000 boreholes distributed across the Base. Lithology is assigned using gamma log data and supplemented by the interpretation on the Base geologist's cross-sections. Thus, additional information available to the Base geologist, such as lithologic core data, contributes to the lithology assignment. A total of 927 gamma logs are interpreted. Gamma data are from digital files in 477 cases. The remaining 450 gamma logs were available only in hard-copy format and were manually digitized using a structured workflow that ensured accuracy, efficiency, and traceability. Where multiple gamma runs are available for a given well, a composite log is spliced from the open-hole portions of each run to avoid signal degradation introduced by the well casing. Lithology is assigned to two categories: sandstone (including siltstone) and mudstone (including shale).

Hydrostratigraphic unit picks are also essential to construction of the 3D HGFM. Draft picks for five HSU horizons were made from the HSU interpretations on the Base geologist's cross-sections. These were refined via inspection of 2D contour maps developed from these horizon picks and analysis of the 3D HGFM developed from the HSU and lithology picks. For wells not included on the Base geologist's cross-sections, HSU picks were made with the assistance of 2D contour maps and temporary cross-sections cut through the 3D HGFM.

Other important data in the 3D model include topography, potentiometry, well construction details, and the locations of surface features. The topography is developed from a LIDAR DTM and is warped to honor available surveyed ground surface elevation data. Potentiometric data and existing potentiometric surfaces (available as 2D grids) from a representative monitoring event are incorporated into the 3D framework. Well construction data including filter packs and screened intervals are from a Tinker AFB well database or original well construction diagrams. Surface features such as water bodies, roads, buildings, airfield, and property boundaries are incorporated from a GIS maintained by Base Civil Engineering.

Data is managed in a Microsoft SQLServer 2005 database, with a suite of data interfaces and import/export tools permitting efficient data insertion, editing, and exporting for model construction. These tools encompass critical steps in the workflow and allow the database to be used both as a reliable container and a dynamic device for tracking data updates. The underlying data manipulation is built into the database as stored procedures and accessed via push-buttons in simple front-end applications.

MODEL CONSTRUCTION

The 3D model is constructed using Dynamic Graphics® earthVision® software and reflects lithologic interpretations (sandstone versus mudstone/shale) within six HSUs. Mudstone/shale is differentiated from one HSU to the next, yielding a total of six mudstone/shale 'categories'. Sandstone is not differentiated across HSUs. Thus, the model includes a total of seven categories. Input data for these seven categories are generated by assigning each mudstone/shale lithologic pick to one of six HSU-based categories (depending upon where lithologic picks lie vertically relative to the HSU picks for that well) and assigning each sandstone pick to a seventh category. Next, for each input data point, a data field is generated for each of the seven categories. These data fields are indicators; for example, if a given data point is sandstone, then the sandstone field value is 1, otherwise it is 0.

From each of these seven binary fields, a corresponding 3D grid is developed. For example, a sandstone 3D grid is generated by gridding the sandstone field 1's (sandstone) and 0's (not sandstone). A deterministic gridding algorithm is used rather than a geostatistical approach (however, alternate geologic realizations are currently being constructed and explored using transition probabilities geostatistics). A minimum tension gridding algorithm is used, which yields

grids that closely honor the input data without unnatural-appearing predictions in areas lacking input data. The lithologic bodies are conformed to the regional strike and dip throughout much of the Base and to the Hennessey-Garber contact in the southwest portion of the Base. Values in each of the seven category 3D grids range between 0 and 1 and can be thought of as pseudo-probabilities that a given category exists at that location (the term 'pseudo-probability' is used here because a geostatistical approach is not used in developing the 3D grids). A 3D grid representing the combined lithologic-hydrostratigraphic interpretation (Figure 2) is produced by assigning to each grid node the category with the highest value (pseudo-probability) among the seven category grids at that node.

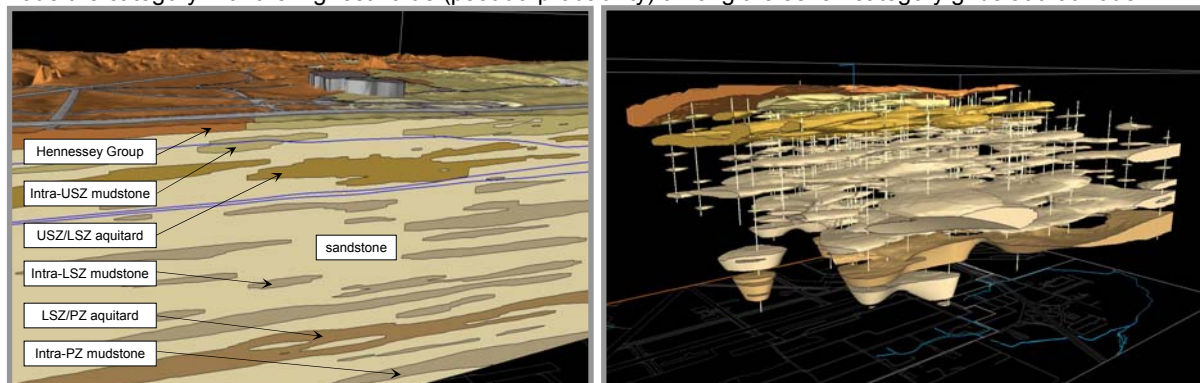


Figure 2. 3D Hydrogeologic framework model in section view (left) and with sandstone removed (right).

The interpreted lithologic and HSU contacts are quality checked via visual inspection of the 3D model, contour maps of the HSU contacts, and cross-sections cut from the 3D HGFM. The model is built iteratively by updating data interpretations and reconstructing the 3D HGFM. Model construction is automated via flexible scripts, freeing project geoscientists to focus on model visualization and analysis rather than model assembly.

Additional data types, including potentiometry and surface features (e.g., roads, buildings, surface water), are integrated into the 3D model to facilitate 3D visualization and analysis with the lithologic and HSU interpretations. The toolset developed for this project allows automated, spatially-accurate placement and labeling of these disparate features on cross-sections cut from the integrated 3D model.

MODEL APPLICATIONS

The 3D HGFM has been and will continue to be used to support Base restoration activities. Applications to-date include:

- The model was used to cost-effectively produce digital versions of the Base geologist's hand-drawn cross-sections, while refining interpretations and ensuring consistency across sections. Cross-sections include lithology, HSUs, potentiometric surfaces, well data (gamma logs, filter packs, screen intervals), surface features (water bodies, roads, buildings), and a polished layout (Figure 3). Custom automation tools allow the production of any desired cross-section in ten minutes.

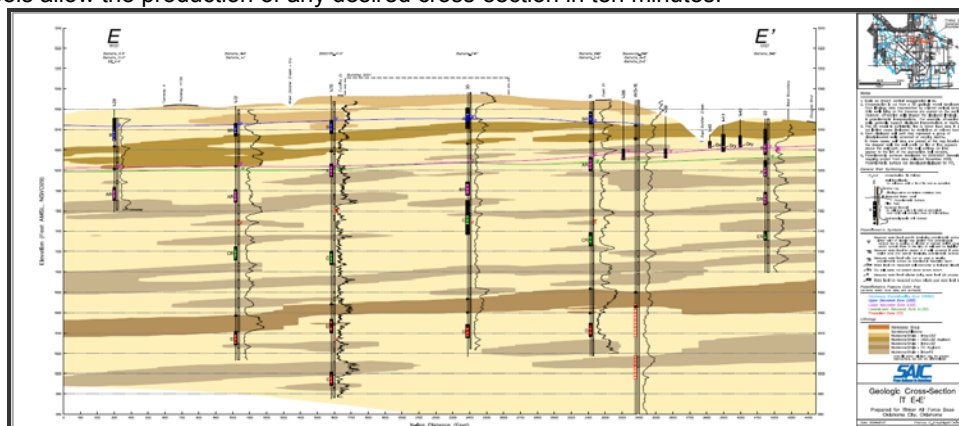


Figure 3. Automated, production-quality cross-section cut from 3D hydrogeologic framework model.

- The model is being used to help underpin a new exit strategy for a contaminated groundwater unit.
 - The 3D HGFM was used to construct the lithology for a multi-phase model that was utilized to simulate TCE vapor migration and to assess soil vapor extraction as a remedial option.
 - Cross-sections were cut through the planned locations of three deep, multi-level wells prior to installation to identify monitoring intervals and evaluate consistency of new field data with the current site understanding. Real time cross-sections facilitated decision-making in the field.
 - Visualization of 3D contaminant models and potentiometric data within the 3D HGFM provided insights into contaminant source area definition, contaminant mass distribution within the subsurface, and potential past and future plume migration pathways.
 - The project database is currently being evaluated to assess the likelihood of continuous sandstones that could act as preferential pathways through the mudstone aquitards.
- An initial phase of 3D modeling of groundwater quality data within the HGFM has been completed (Figure 4). 3D contaminant models can be used to (1) improve communication among stakeholders, (2) facilitate better understanding of the current contaminant distribution and transport pathways at the Base, (3) define initial transport conditions for predictive solute transport modeling, (4) estimate volume of impacted media, (5) estimate mass distribution in system (sandstone versus mudstone), and (6) inform remediation methods and timeframes (remedies may be prolonged if substantial mass has diffused into mudstones, and *in situ* remedies need to be designed around reagent delivery for optimum effectiveness).
- Alternate geologic realizations are currently being constructed and explored using transition-probability geostatistics (TProGS). The data and the streamlined toolset developed during generation of the 3D HGFM provide a solid foundation from which to do this geostatistical analysis. These alternate geologic realizations will be evaluated in an existing numerical flow and transport model, and as such will contribute to understanding of uncertainty in the model predictions.

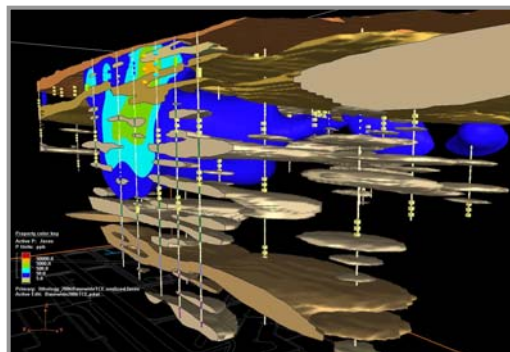


Figure 4. Integrated 3D HGFM & TCE Model.

Next steps include customizing an existing Web portal to allow (1) access to the project database and cross-sections in a GIS framework, (2) visualization of well construction and interpretation details, and (3) dynamic model updates and section generation. Additionally, faults can be included in the 3D model to first understand the relationship between faulting and the underlying geologic structure, and then to test the potential impact of faulting upon groundwater flow and contaminant transport.

CONCLUSIONS

Two-dimensional cross-sections are traditionally used to understand and communicate 3D subsurface conditions for environmental restoration sites. In this case study, the knowledge and interpretations captured on existing 2D cross-sections were readily translated into a 3D HGFM. To-date, the 3D HGFM and the underlying data and toolset have been used to

- cost-effectively produce digital versions of the Base geologist's original hand-drawn cross-sections while refining interpretations and ensuring consistency across cross-sections,
- underpin a new exit strategy for a contaminated groundwater unit via real-time cross-section generation to support field work, identification of contaminant source areas and migration pathways, construction of a multi-phase SVE model, and evaluation of potential preferential pathways through aquitards, and
- initiate development of alternate conceptual lithologic models that contribute to understanding of the uncertainty in predictions from a numerical flow and transport model.

Given current 3D modeling software capabilities, the availability of digital borehole data, and the customized toolset developed here, overall project objectives at new sites can be more efficiently met by developing a dynamic, integrated 3D model than by synthesizing a series of static 2D cross-sections. Data collection for a 3D model involves the same data types as for a single 2D cross-section (e.g., formation strike and dip, key marker beds, formation contacts, lithology, well construction, potentiometry, topography, surface features). Moreover, although this case study uses the lithologic correlations in the existing site cross-sections as the foundation for the 3D model, lithologies

are more efficiently correlated using the fundamental 3D lithologic modeling technique described here. During initial model iterations, a “pure” lithologic model (e.g., sandstone versus mudstone) can be built. Correlations can be visualized and analyzed with this initial model, and the input lithologic data can then be categorized by HSU to efficiently build a combined lithologic-hydrostratigraphic model. The customized toolset and structured data management strategy expedites construction of the 3D model. The tools and methods developed here can be applied readily to other sites to support objectives beyond environmental restoration, including water resource evaluation, resource extraction, and carbon sequestration.