COLLECTION AND INTEGRATION OF GEOSCIENCE INFORMATION TO REVISE THE WIPP HYDROLOGY CONCEPTUAL MODEL

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Introduction

The Waste Isolation Pilot Plant (WIPP) is the U.S. Department of Energy (DOE) deep geologic repository for transuranic (TRU) and mixed waste. The repository was constructed 655 m below ground surface in bedded halite of the Permian Salado Formation in southeastern New Mexico (Figure 1). Site-characterisation activities began in 1974, and WIPP became a licensed, operating repository in March 1999. The Culebra Dolomite Member of the Rustler Formation (Figure 2) is the most transmissive fully saturated unit above the WIPP repository horizon and the most likely groundwater pathway for radionuclides released from the repository by potential inadvertent human intrusion. Consequently, the Culebra is the focus of groundwater monitoring at WIPP. On-going monitoring has shown that Culebra heads are rising and that they respond to discrete, present-day events, an apparent contradiction of the original conceptual model for the Culebra which envisaged steady-state, or slowly declining, heads. Accordingly, the WIPP regulator, the Environmental Protection Agency (EPA), has requested that the DOE undertake additional studies of the Culebra and develop a revised conceptual model consistent with recent observations.

Figure 1. **Location of the WIPP site**

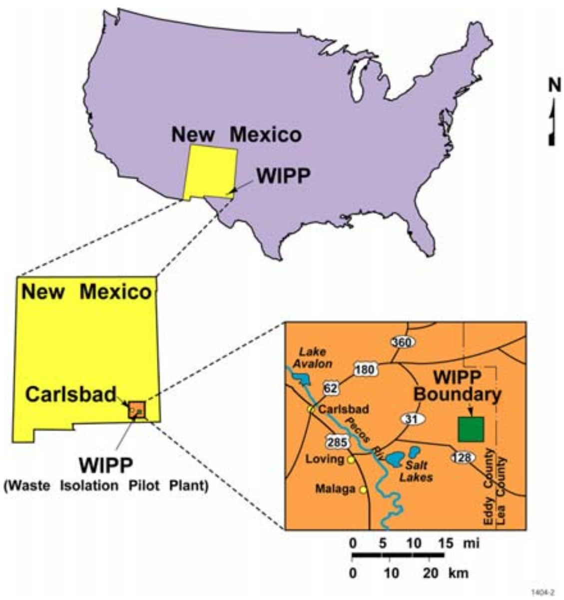
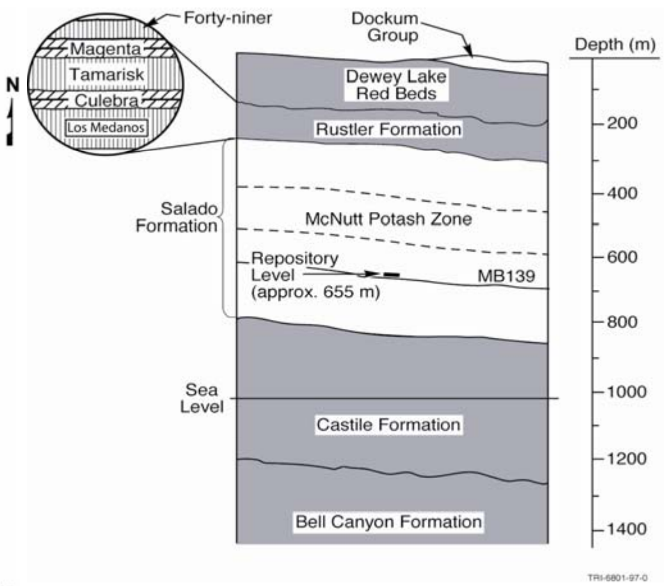


Figure 2. **WIPP stratigraphic column**



Role of conceptual models and peer review at WIPP

Conceptual models play an important role in the licensing process for WIPP. According to the EPA [1]:

- Conceptual models provide a broad overview of the disposal system, including processes that may occur during the regulatory time frame at the WIPP, and they incorporate simplifying assumptions regarding the behaviour of the disposal system.
- The conceptual models used at WIPP should represent those characteristics and attributes of the WIPP disposal system that reasonably describe the disposal system's performance.

In addition, by regulation, all conceptual models for WIPP must undergo independent technical peer review. As defined by the U.S. Nuclear Regulatory Commission [2], a peer review is an in-depth critique of assumptions, calculations, extrapolations, alternate interpretations, methodology, and acceptance criteria employed, and of conclusions drawn in the original work, performed by peers who are independent of the work being reviewed. The fundamental question that peer review should answer is, "Do the final conceptual model(s) and the subsystem components used in the compliance application represent a reasonable approximation of the actual disposal system?" [1].

Original Culebra conceptual model and subsequent evaluation

The conceptual model for the hydrology at the WIPP site developed for the original 1996 license application assumed that all units below the water-table aquifer were effectively isolated from rainfall and other surface hydrologic processes, and that all heads were slowly declining since the end of the last glacial pluvial period approximately 14 000 years ago. In particular, the original conceptual model for the Culebra assumed that it could be conservatively treated as a fully confined unit with heads that would appear to be at steady state over the operational period of the WIPP. The primary groundwater release pathway for radionuclides released from the WIPP repository by inadvertent human intrusion was thought to be through the Culebra, along a high-transmissivity (T) region in the southeastern portion of the WIPP site. The Culebra has higher T and is fractured where underlying halite has been dissolved. The present-day distribution of solutes in the Culebra was thought to be caused by different flow paths taken by leakage entering the Culebra at different places.

While many aspects of the original conceptual model remain consistent with recent observations, a few aspects have been cast into doubt. On-going monitoring has shown that Culebra heads are, in fact, rising and that they respond, at least locally, to discrete, present-day events such as major rainstorms. Furthermore, calibration of new Culebra T fields for the first recertification of WIPP did not produce the high-T offsite transport pathway through the southeastern part of the WIPP site previously thought to be present. In addition, the original peer review of the Culebra conceptual model criticised it for a lack of geologic understanding of variations in Culebra T.

Consequently, the EPA made a series of requests from 2002 through 2005 that the DOE undertake additional studies of the Culebra and develop a revised conceptual model consistent with recent observations. Specific requests included:

- Justify continued use of the old conceptual model, or revise the conceptual model and subject it to peer review [3].
- Develop new T fields calibrated to current (higher) heads [4].
- Install new wells to understand the reasons for rising water levels [4].
- Enhance the monitoring system [4].
- Install a new well to show if the high-T offsite pathway does, or does not, exist [5].
- Update groundwater geochemistry interpretations and collect new samples for age-dating [6].
- Update the 3-D groundwater basin model [6].

New investigations

In response to the EPA requests, the DOE initiated a variety of geoscience investigations, including:

- Drilling (with selected intervals cored) and hydraulic testing of 19 new wells.
- Large-scale hydraulic testing designed to produce transient responses over tens of km^2.
- High-resolution monitoring of Culebra heads and precipitation.
- Mapping of catchment basins in a nearby dissolution trough (Nash Draw).
- Sampling, age-dating, and geochemical evaluation of Culebra waters.
- Correlation of geophysical logs from hundreds of exploratory potash and oil and gas holes around the WIPP site.
- Refinement of the sedimentological model of the basin.
- Detailed evaluation of post-depositional processes (e.g., dissolution).
- Collection of information on potash industry water usage and disposal.
- Evaluation of borehole plugging and abandonment records.
- Collection of information on recent and on-going oil and gas drilling.
- Modelling of various scenarios that could introduce water into the Culebra.
- Refinement and recalibration of T fields for the Culebra flow model.

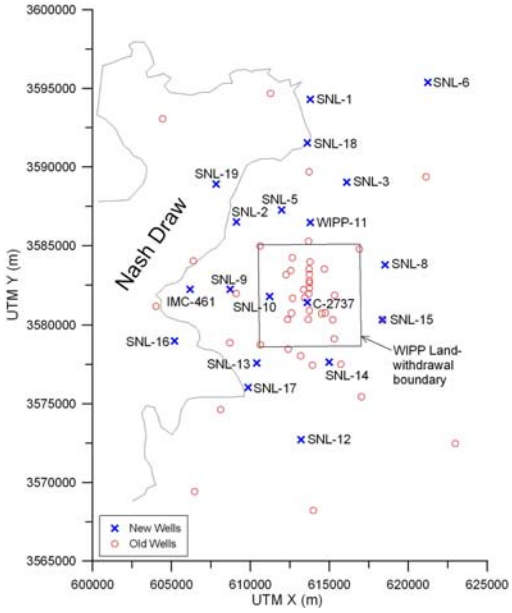
A subset of these investigations are discussed herein.

Locations for new well were selected:

- In areas where modelling shows sensitivity of groundwater travel time to T is high.
- To improve the definition of halite margins in members of the Rustler Formation.
- To verify an inferred correlation between overburden thickness and T.
- To confirm model boundary condition assumptions.
- To identify high-T connections.

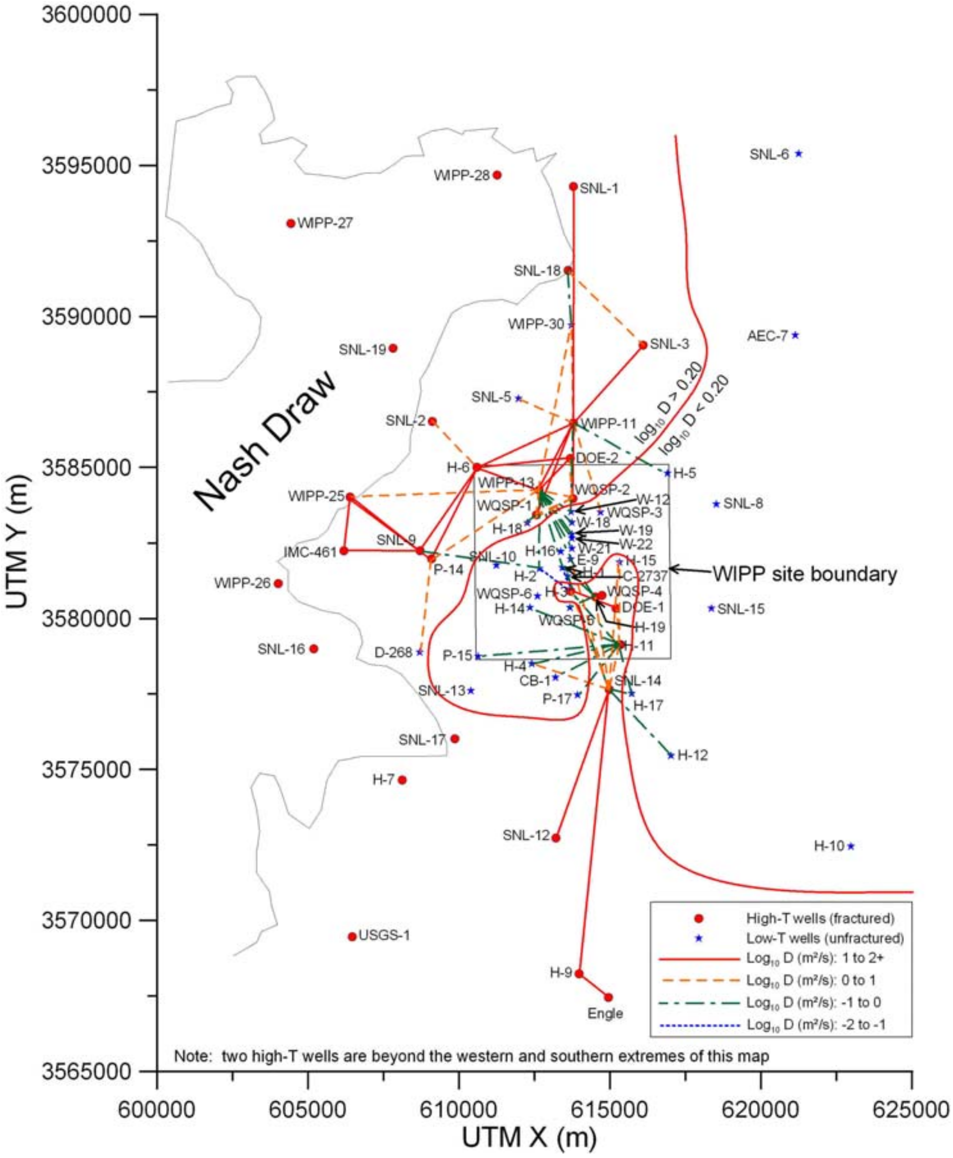
resulting in the well network shown in Figure 3.

Figure 3. **Culebra well locations around WIPP**



An extensive hydraulic testing programme was initiated that included single-well testing in all new wells and long-term (19 to 32 days) pumping tests conducted north, south, and west of the WIPP site that produced responses in observation wells up to 9.5 km away. Interwell diffusivity (D) values calculated from the test responses were used to map fracture connections, based on evidence that $\log_{10} D$ (m^2/s) values greater than 0.2 reflect fracture connections (Figure 4) [7]. This mapping delineated a swath of the Culebra running from northeast to southwest across the WIPP site that appears to lack a network of interconnected fractures, and also clearly showed the presence of a high-diffusivity area in the southeastern part of the WIPP site extending much farther to the south. The transient response data from the long-term tests are also used in new T-field calibration.

Figure 4. **$\mathbf{Log_{10}}$ D values observed for pumping well-observation well pairs** [6]



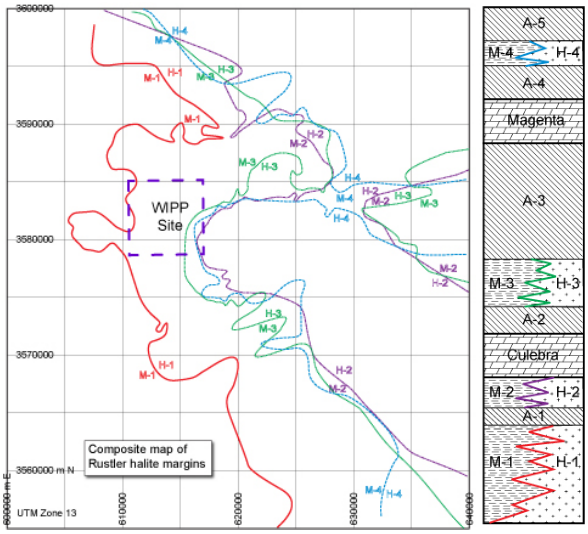
Geologic studies

Geologic studies contribute to our conceptual model of site hydrology, and provide direct input for numerical models. New geologic information was provided by on-the-ground field mapping, examination of cores from new boreholes, and examination of geophysical logs from nearby potash, oil, and gas exploration holes, of which there are an abundance surrounding WIPP (Figure 5).

Recent studies have focused on the distribution of halite in the members of the Rustler Formation [8] and on mapping of rainfall catchment basins in southern Nash Draw [9]. Mudstone and halite are lateral facies equivalents in the non-dolomite members of the Rustler (Figure 6). Deposition (and preservation) of halite in units adjacent to the Culebra is related to the hydraulic properties of the Culebra in several ways. First, when halite was deposited above the Culebra, high-salinity fluids circulated through the Culebra, depositing halite in Culebra pores as well, resulting in extremely low transmissivity. Second, if the Culebra is fractured, allowing high flux, halite immediately below or above the Culebra would probably not survive for millions of years. Therefore, the presence of halite below or above the Culebra can be taken as an indicator of the lack of fracturing in the Culebra. Third, if halite is dissolved from below the Culebra, it could cause fracturing of the Culebra (as Salado dissolution has caused in Nash Draw). As halite is most likely to be dissolved along its depositional margin, the M-2/H-2 margin below the Culebra should be evaluated as a potential location of high Culebra T. Thus, mapping the occurrence of halite in the Rustler members allows us to make inferences about Culebra T in areas where we have no Culebra wells.

Figure 5. **Aerial photograph of WIPP vicinity showing drilling pads for oil and gas well (light dots)**

Figure 6. **Rustler stratigraphy and halite margins**



Additional factors that have found to be related to Culebra T are dissolution of underlying Salado halite, thickness of overburden above the Culebra (less overburden indicates more erosion, causing stress-relief fracturing), and the presence or absence of gypsum cements in the Culebra [10].

Numerous closed drainage basins are present in Nash Draw. To date, only the basins in the southern portion of Nash Draw have been carefully mapped (Figure 7) [9]. The basins drain to sinkholes in Rustler gypsum units above the Culebra. Much of the water entering this gypsum karst discharges into springs in Nash Draw, which have also been mapped. But some portion of it must come into hydraulic communication with the Culebra, at least locally, because Culebra wells in Nash Draw show water-level responses to major rainfall events (Figure 8).

Figure 7. **Drainage basins mapped in southern Nash Draw**

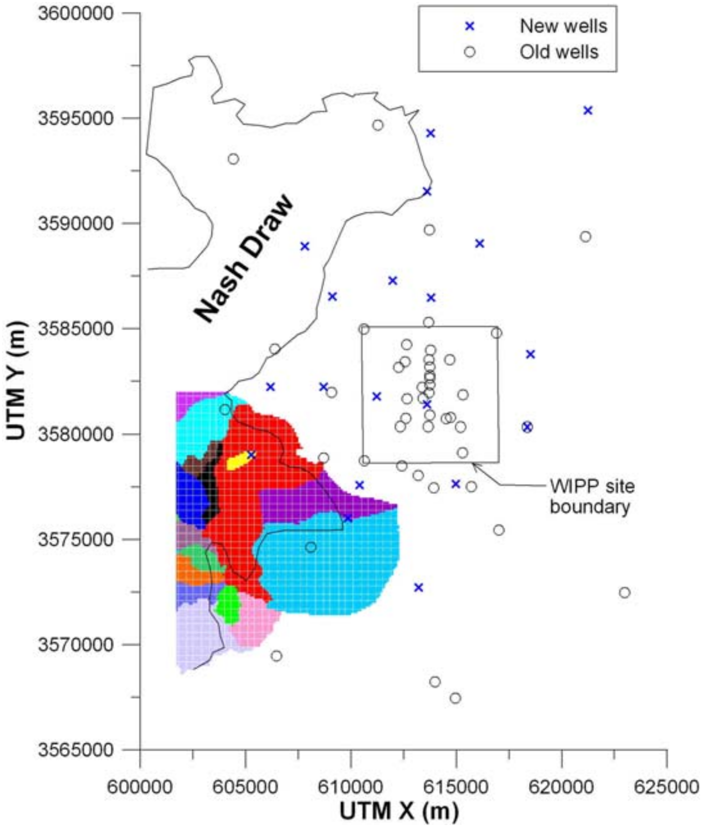
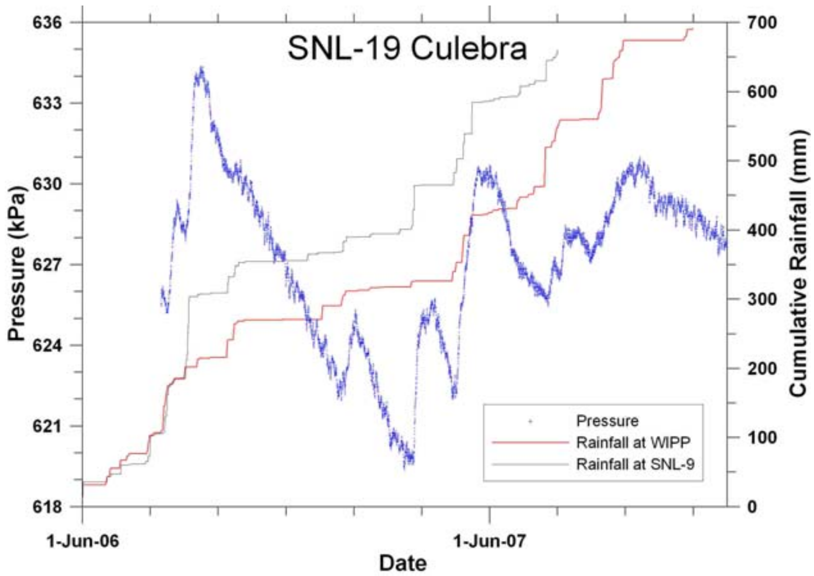


Figure 8. **Hydrograph showing Culebra response in Nash Draw to rainfall events**



Culebra responses to rainfall

Monitoring of water levels (pressures) and rainfall at high temporal resolution has shown that Culebra water levels are much more affected by rainfall than previously believed. Wells in Nash Draw respond within hours to major storms. The increased heads in Nash Draw then propagate to the east (including the WIPP site) over a period of days to months [11]. Whereas water levels in wells in Nash Draw tend to decline shortly after rain-induced rises (Figure 8), water levels in the wells east of Nash Draw appear to be driven primarily upwards, with little decline between rainfall events (Figure 9). With increasing distance from Nash Draw, responses to individual rainfall events are muted, but general trends and major inflections in the trends are preserved (compare the response of SNL-1, adjacent to Nash Draw, to the responses of other wells farther from Nash Draw in Figure 10).

Figure 9. **Hydrograph showing Culebra response adjacent to Nash Draw to rainfall events**

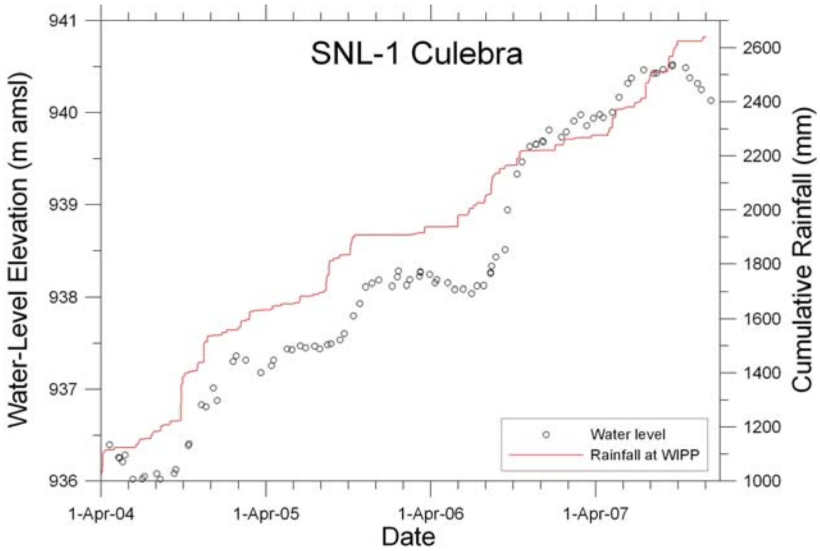
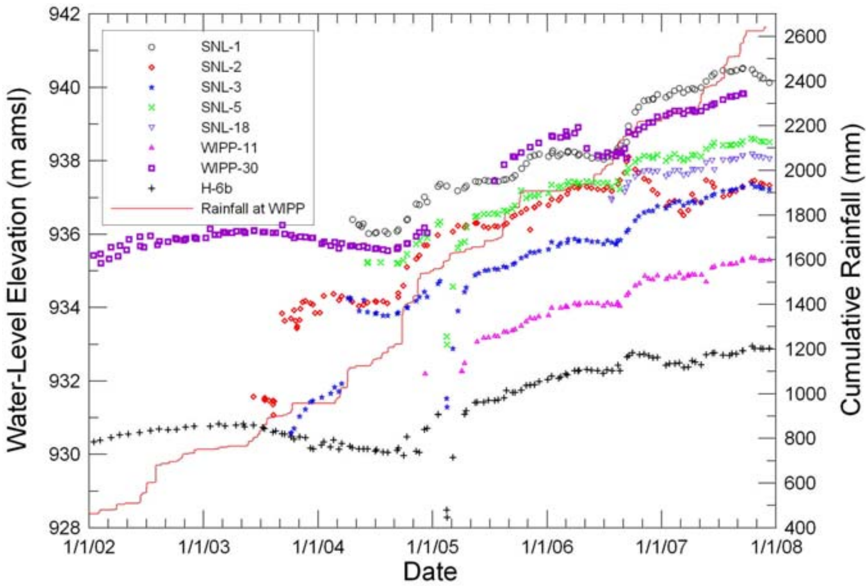


Figure 10. **Hydrograph showing Culebra responses to rainfall propagating away from Nash Draw**



Groundwater chemistry

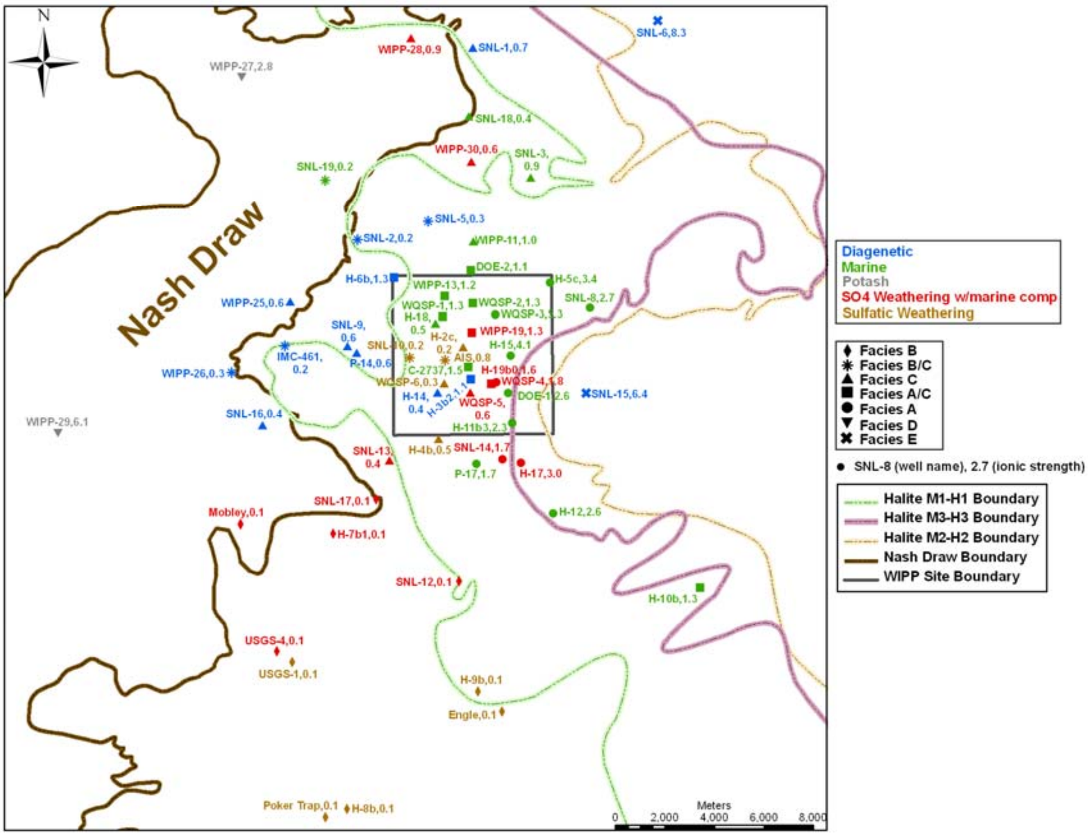
Total dissolved solids (TDS) in the Culebra range from <3 000 to 320 000 mg/L, and TDS decreases in the inferred direction of flow. A credible conceptual model must be able to explain the present-day distribution of solutes and, in this case, a three-dimensional perspective is essential.

Several approaches have been taken to characterise and understand Culebra groundwater geochemistry. Siegel *et al.* [12] originally defined four hydrochemical “facies” for Culebra groundwater based primarily on ionic strength and major constituents:

- A: 2-3 molal, NaCl brine.
- B: <0.1 molal, $CaSO_4$ water.
- C: 0.3-1.6 molal, variable brine.
- D: 3-7 molal, $K/Na \geq 0.2 \rightarrow$ potash contaminated.

With the addition of samples from the newer wells, transitional A/C and B/C facies can now be defined, as well as a new facies E for high molal (6.4-8.3) Na-Mg Cl brines. The spatial distribution of these facies is shown in Figure 11. Note especially the position of facies E with respect to the Rustler halite margins.

Figure 11. **Hydrochemical facies and SNORM categories of Culebra waters**

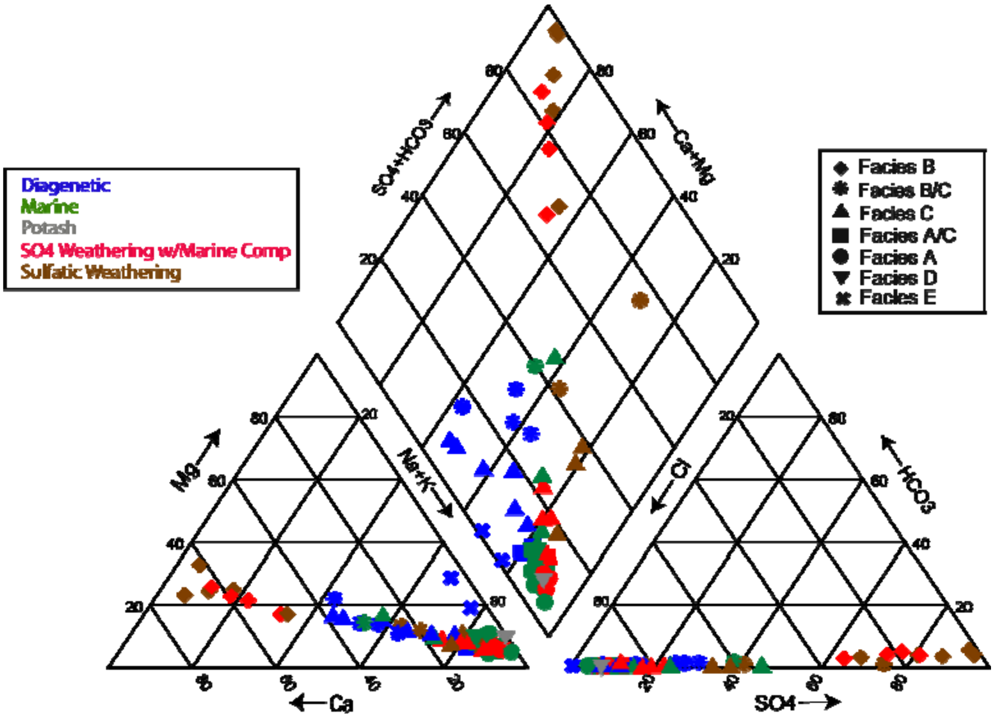


Another method used to characterise the Culebra groundwaters is the salt norm, which is the normative assemblage of evaporite minerals that would result from the instantaneous evaporation of a solution. It is calculated using the SNORM code of Bodine and Jones [13]. Three major solute sources can be identified from the salt norm:

- Meteoric or weathering.
- Marine-derived.
- Diagenetic.

In parts of Nash Draw, potash contamination results in a fourth solute source, while a mixed (sulfatic) weathering and marine source is also recognised in some areas. The spatial distribution of waters categorised with the salt norm is also shown on Figure 11. Figure 12 is a Piper diagram for the Culebra groundwaters, showing both facies and salt norm types.

Figure 12. **Piper diagram of Culebra groundwaters showing facies and SNORM categories**



The Culebra groundwater geochemistry is interpreted as follows: the low ionic strength (≤0.1 molal) sulfatic weathering solutions (facies B) reflect relatively recent recharge through gypsum layers overlying the Culebra in the southern part of Nash Draw. The higher ionic strength (0.3 – 1 molal) brines with differing salt norm signatures (facies C) represent meteoric waters that have dissolved $CaSO_4$, overprinted with mixing and localised processes. The high ionic strength (1.6 – 5.3 molal) brines with marine signatures (facies A) represent old waters (long flow paths) that have dissolved halite and/or mixed with connate brine. The very high ionic strength (6.4 – 8.6 molal) NaCl brines with diagenetic signatures (facies E) represent primitive brines present since deposition of the Culebra.

New T fields

For modelling groundwater flow in the Culebra around WIPP, T fields are created in MODFLOW-2000 [14] using uniform 100 m x 100 m cells. The T fields are calibrated using PEST [15] to adjust T, storativity (S), and hydraulic anisotropy at pilot points to match steady-state heads and the transient responses observed during long-term pumping tests. T's are initially assigned on the basis of a correlation between T and overburden thickness, subject to other geologic controls. Compared to previous models [16], heads are now being set very high (~ground surface) east of WIPP where halite is present above, below, and in the Culebra. Recharge is being implemented in the model southwest of the WIPP site in Nash Draw. Calibration to long-term pumping tests is confirming the presence of the high-T offsite transport pathway extending to the south from the southeastern portion of the WIPP site. In general, the calibration results now being obtained are far superior to those obtained previously.

Revised conceptual model

The new information collected since 2002 has served to confirm many aspects of the original Culebra conceptual model while leading to revision of other aspects. The most significant revision is that the new model stipulates that the strata overlying the Culebra in Nash Draw have lost their effectiveness as confining beds, allowing Culebra heads to respond to rainfall. Head changes in the Culebra in Nash Draw then propagate through the site area where the Culebra remains confined. This likely causes most of the changes in water levels that have been observed over the past 15 years. In addition, short-term, localised changes in Culebra head have been shown to be caused by drilling of nearby oil and gas wells. Additional modelling not discussed herein [17] has shown that the long-term rising trend in Culebra heads may also be plausibly related to leakage into the Culebra through improperly plugged and abandoned boreholes.

The finding of halite in the Culebra east of the WIPP site, combined with extremely low T, high TDS, and high heads, has led to a revised treatment of that area in our groundwater model. The high heads and low T now used in the Culebra model in that region are in better agreement with the 3-D modelling of Corbet and Knupp [18] than the conditions used before.

This revised understanding of Culebra hydrology is consistent with the groundwater geochemistry. A new groundwater facies (E) reflects the syndepositional origin of the brine in the region where the Culebra contains halite. This brine provides solutes, primarily NaCl, to the higher transmissivity facies A region to the west. Rainfall entering the Rustler through gypsum karst in Nash Draw provides the low TDS, primarily $CaSO_4$ waters of facies B found to the south of the WIPP site. The facies C water represents a mixture, with at least one source having an origin to the north of the WIPP site.

Summary and conclusions

As a result of observed changes in water level that were inconsistent with the original conceptual model for the Culebra, the WIPP regulator requested that the DOE undertake a variety of studies. These studies have led to a revised Culebra conceptual model that is different primarily in its understanding of Culebra confinement and recharge in Nash Draw west of the WIPP site, and in its understanding of the Culebra east of the site where halite in the Culebra causes T to be extremely low and head to be very high. New hydrogeochemical data support the revised hydrologic model. The new data have contributed to new T fields that are calibrated better than those that have been produced in the past. The revised conceptual model is more detailed than the model developed for the original WIPP license application but, importantly, continues to support the use of a 2-D confined model to simulate groundwater flow across the WIPP site itself. Our improved, more detailed understanding of Culebra hydrology supports the long-standing conclusion that the Culebra provides an effective barrier to radionuclide transport off the WIPP site.

Acknowledgements

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