HYDROGEOLOGY ASSOCIATED WITH THE WASTE ISOLATION PILOT PLANT

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Hydrologic characterization at the Waste Isolation Pilot Plant (WIPP), near Carlsbad, New Mexico, has historically focused on collection of geologic data, such as cores and borehole geophysical logs, and the estimation of hydrologic parameters from single- and multi-well aquifer tests. These data have resulted in a detailed understanding of the depositional and alteration processes that have affected the hydrologic units of interest at WIPP. The hydrologic conceptual model has been used to create a groundwater flow and radionuclide transport model used in WIPP performance assessment (PA). Long-term monitoring of a large network of monitoring wells between testing events has produced millions of high-frequency, long-duration water level records. Utilizing hydrologic analysis techniques associated with barometric, earth tide, and precipitation signals, these long-term data have the potential to reveal additional insights about the large-scale hydrogeology of the formations near WIPP. This study emphasizes that hydrological and geophysical data and analysis is important on multiple temporal and spatial scales in order to achieve effective characterization.

I. INTRODUCTION

The hydrogeology of the geologic formations that impact the long-term (10,000 years) performance of the WIPP have been geologically characterized, hydrologically tested, and numerically simulated for more than thirty years. The hydrologic characterization and modeling effort at WIPP is ongoing, as the understanding of the system evolves and more data are collected. Although the WIPP repository is located in bedded halite of the Salado Formation more than 300 m below the Culebra Member of the Rustler Formation (see Fig. 1), the Culebra is considered the most likely radionuclide groundwater pathway from WIPP due to the potential future human intrusion of the facility. Other formations at WIPP (e.g., the Magenta Member of the Rustler, the Dewey Lake Formation, and the Bell Canyon Formation) are not considered likely groundwater pathways to the accessible environment in the event of human intrusions, but they have also been studied to a lesser degree to better characterize the entire flow system at WIPP [1,2].

Geologic and hydrologic data for the Culebra have been used to construct numerical flow and radionuclide transport models, components of the WIPP PA. PA has been utilized to justify the compliance of WIPP in certification (1996) and re-certification (2004 and 2009) efforts. The latest version of the Culebra flow model used both steady-state freshwater heads and aquifer test transient drawdown observations to calibrate 100 individual realizations involved in the Monte Carlo simulation of radionuclide transport in PA [3].

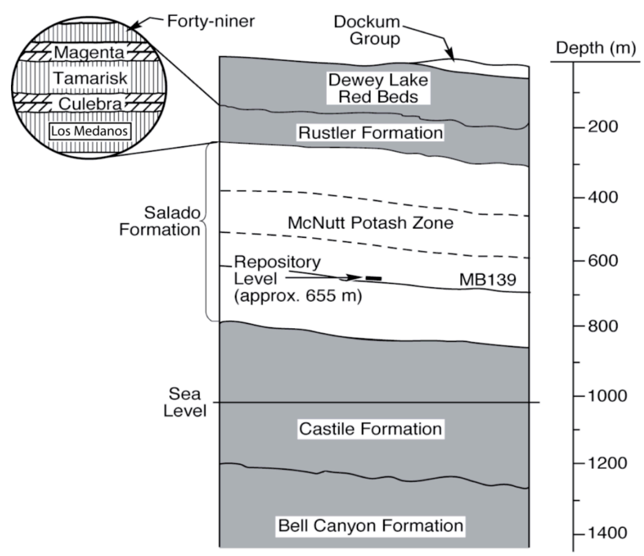

Fig. 1. Generalized WIPP geologic cross section

II. LARGE-SCALE GEOLOGIC INVESTIGATION

The major features of the Rustler geologic model have been defined by extensive stratigraphic data obtained from boreholes and shafts. Four large-diameter shafts have been mined through the stratigraphy overlying the WIPP facility. The excellent geologic information obtained from the construction of the air-intake shaft [4], in particular, provided some of the clearest evidence for the geologic model now used for the Rustler [5].

Over 90 boreholes have been drilled and geophysically logged through the Culebra in the vicinity of the WIPP site for characterization and monitoring purposes; many of these boreholes were cored through key regions (i.e., the Culebra and Magenta members of the Rustler Formation). Geophysical logs from nearby oil and gas wells are used to further constrain stratigraphy and geologic boundaries (see Rustler mudstone/halite margins and Salado dissolution margin in Fig. 2);

petroleum wells are completed outside the WIPP site in deeper formations (i.e., the Bell Canyon Formation and below) [1,2].

The hydrogeology of the Culebra is controlled by depositional facies [7,8] and dissolution of halite from beneath the Rustler in Nash Draw, west of WIPP (see Fig. 2 for locations). The presence of halite in the Rustler above and below the Culebra (see Fig. 3 for stratigraphy and Fig. 2 for map) is associated with extremely low transmissivity (T) in the Culebra; T has been estimated to be 1.0E-11 and 1.3E-13 m^2/s in SNL-6 and SNL-15, respectively [7,8]. Much higher T is observed in wells completed in the Culebra where the Salado shows evidence of dissolution (west of the Salado dissolution margin in Fig. 2); T ranges over ten orders of magnitude across the WIPP site.

The WIPP land withdrawal boundary (LWB) is situated between the region of very low Culebra T to the east in the halite-sandwiched area, and the higher T to the west in Nash Draw. Regression-based modeling has related T to overburden thickness and evaporite presence in the high- and low-T portions of the Culebra [6]. Fracturing and pore-filling evaporites in the Culebra are the primary factors controlling Culebra T in the middle transition zone at WIPP [3]. These processes occur on a much smaller scale that cannot effectively be mapped on the same scale as the facies and broad-scale dissolution.

The presence or absence of fracturing and evaporates in the Culebra is included stochastically in the groundwater flow model using a geostatistical simulation approach (i.e., indicator kriging) [3].

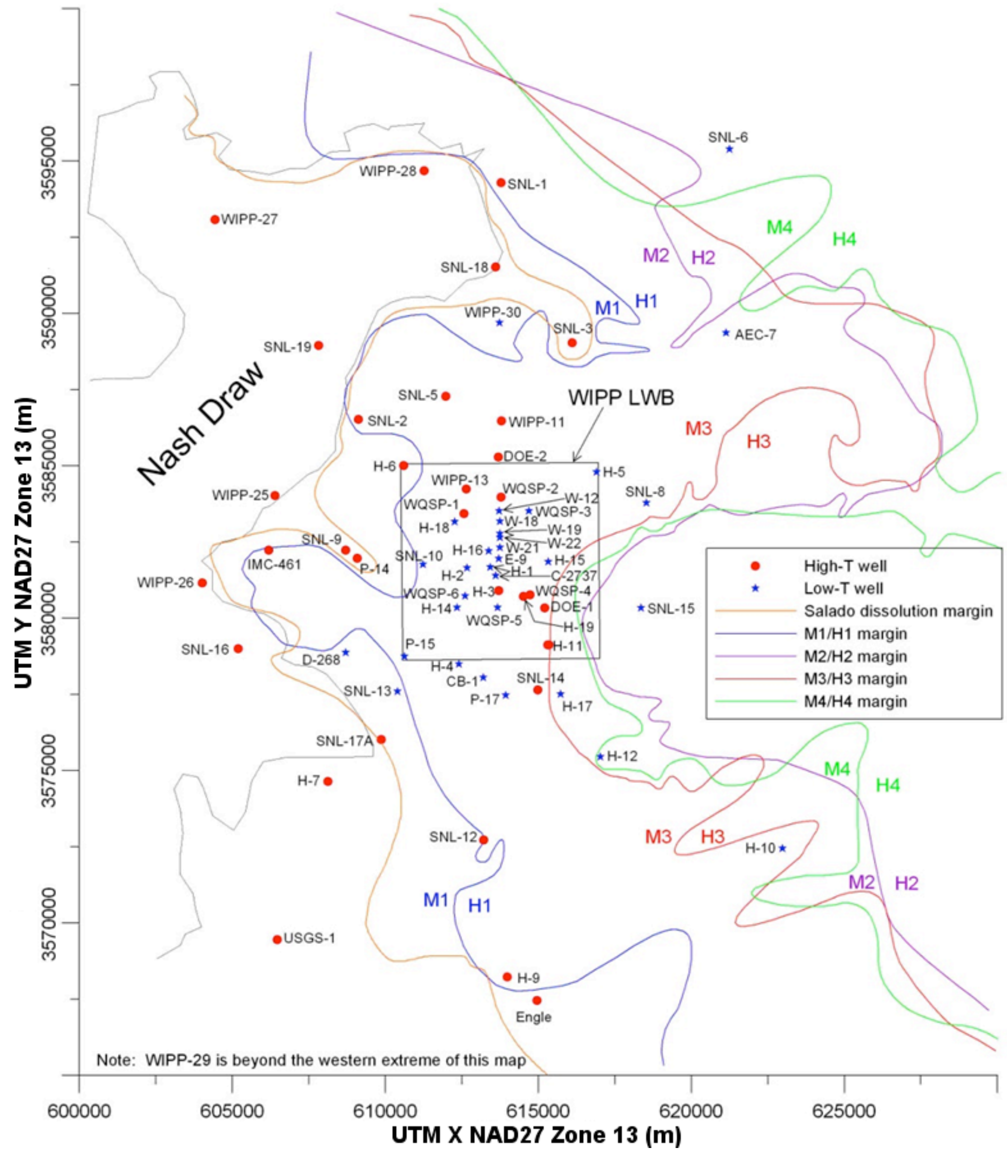

Fig. 2. Map showing Rustler halite margins, Salado dissolution margin, single-well Culebra aquifer test locations, WIPP Land Withdrawal Boundary (LWB), and Nash Draw

Based on a combination of stochastic simulation and simple regression models, a suite of groundwater flow and transport models have been constructed and calibrated. The suite consists of 100 individually calibrated, stochastically generated flow model realizations used to predict flow and transport over the 10,000-year time horizon for regulatory purposes [3].

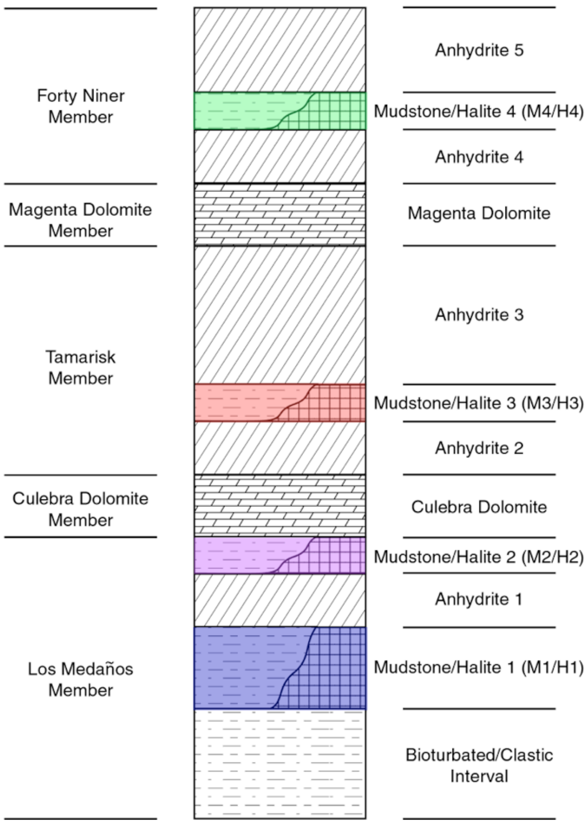

Fig. 3 Stratigraphy of the Rustler Formation; Rustler mudstone/halite facies shown in color (locations in Fig. 2)

III. AQUIFER TESTING

To estimate Culebra hydraulic properties, numerous slug and constant-flowrate pumping tests have been conducted (see red circles and blue stars in Fig. 2). More than 90 tested Culebra wells indicate that single-well Culebra T ranges over at least 10 orders of magnitude and is typically 2 orders of magnitude greater than any other formation [7,8]. Weak pad-scale anisotropy and some pad-scale heterogeneity have been observed in small multi-well test (at the scale of 30 meters) [7]. Additional testing in other units indicates the Magenta Member of the Rustler Formation is the next most permeable unit (>24 tested wells). The upper Dewey Lake formation is somewhat permeable, but it only contains a thin lens of local perched water at the WIPP site.

Single-well aquifer tests are the simplest to perform, but do not provide reliable estimates of aquifer storage properties, and give no information about heterogeneity. Small-scale multi-well tests require nearby wells and more work to perform than single-well tests, but provide more information, including aquifer storage properties and pad-scale heterogeneity.

Eleven large-scale multi-pad aquifer tests (at the scale of hundreds to thousands of meters) have been performed in the Culebra (see green stars in Fig. 4). Multi-well aquifer tests allow for more reliable estimation of hydraulic diffusivity (D) – the ratio of T to storativity – and give an indication of hetereogeneity between well pads at a larger scale.

The results of large-scale pumping tests have revealed strong directional dependence in responses for wells in close proximity to the lower-T zone delineated with a red curve in Fig. 4. For example, the response of SNL-14 (immediately south of the WIPP LWB) showed strong north-south response several kilometers away, while showing no response in nearby wells. This well is located in a region of higher-T surrounded by lower-T. SNL-14 was drilled and tested at this location to confirm the previously inferred high-T pathway in the southeastern portion of the WIPP LWB. The connection of SNL-14 to H-9, almost 10 km away, is clearly evidence of large-scale heterogeneity in the Culebra at WIPP (see Fig. 4). The observed drawdown data in the SNL-14 pumping test were an important calibration target for the groundwater flow model [3]. Large-scale pumping tests and the groundwater model are believed to represent similar scales of flow processes. The drawdown data observed in all the large-scale pumping tests were used as transient calibration target data in the PA groundwater flow model [3]. The drawdown from single-well pumping tests were not included directly in the calibration of the PA groundwater model, due to the disparity in scale between the tests and numerical model, with 100 meter model cells.

In addition to hydraulic tests, seven pad-scale multi-well tracer tests have been performed at six locations in the Culebra [9]. More so than pumping tests alone, tracer tests have revealed the Culebra to be very inhomogeneous, with T controlled by fracturing and geology at an intermediate scale. Tracer tests require a multi-rate transport model to match long tails of tracer concentration observed at very long times in H-19 and H-11 tracer tests [9].

Multi-rate transport is indicative of a multitude of porosity scales with varying rate transfer characteristics in the Culebra, most of which are at the core-scale, and therefore much smaller than those observed in even single-well pumping tests.

IV. WATER LEVEL RECORD INVESTIGATION

During the earlier investigative and licensing phase at WIPP, water levels in monitoring wells were observed at least monthly using only a water level measuring tape.

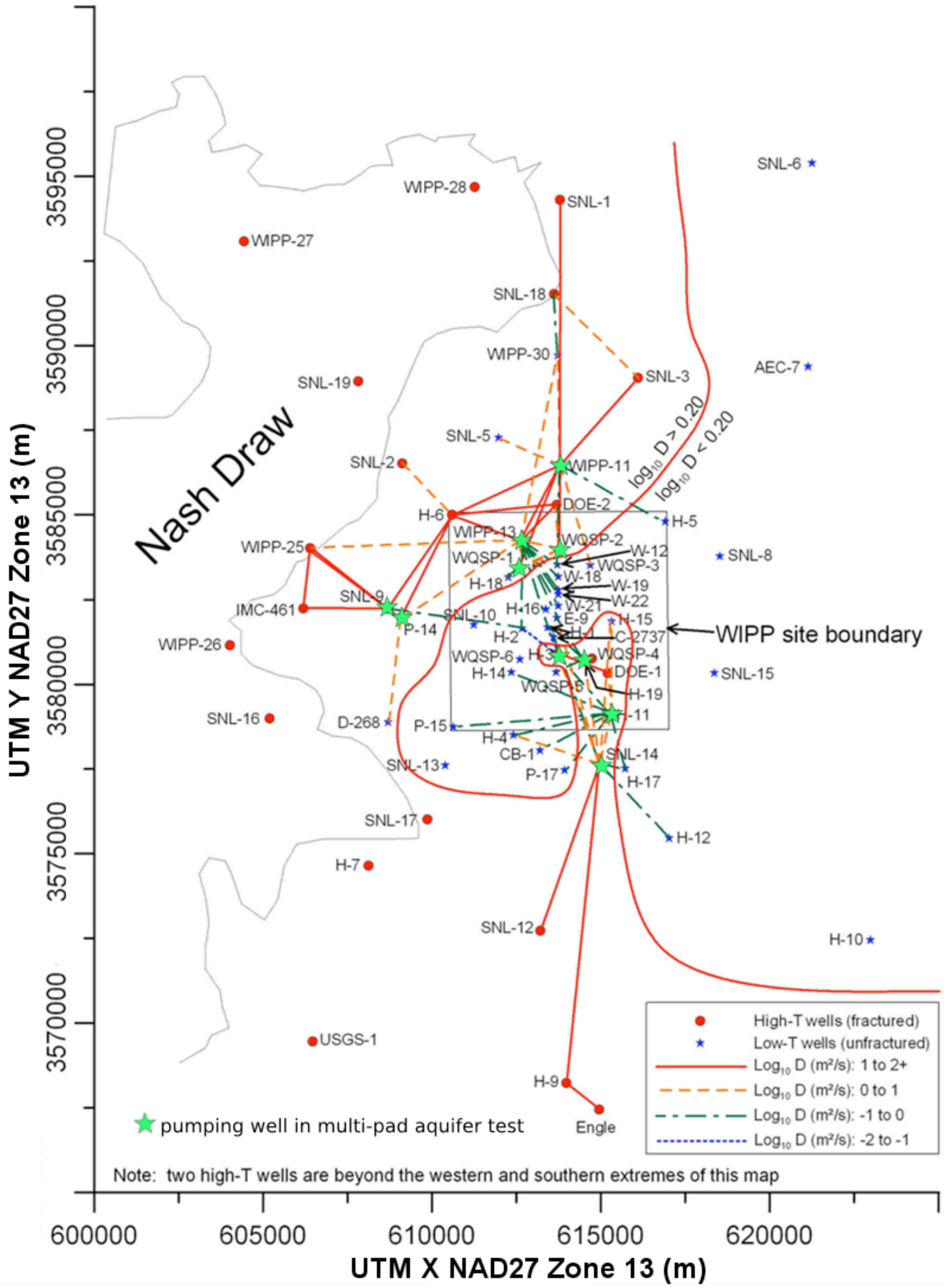

Fig. 4. Multi-pad aquifer tests at WIPP and connections indicated hydraulic diffusivity (D) estimated from observation data. Approximate boundary between high and low D areas shown with red curve.

Multi-well pumping tests required the instrumentation of observation wells with pressure transducers for higher-frequency observations during long periods of pumping and recovery. After completion of testing, most transducers remained in monitoring wells to record pressures, leading to the conclusion that the monthly water level monitoring was not revealing the whole picture with respect to small time-scale fluctuations (compare high-frequency red curve to monthly points in Fig. 5). Observed fluctuations in manual monthly water levels were not simply noise, but were due to coherent high-frequency fluctuations in water levels caused by physical processes including barometric pressure and earth tides [10].

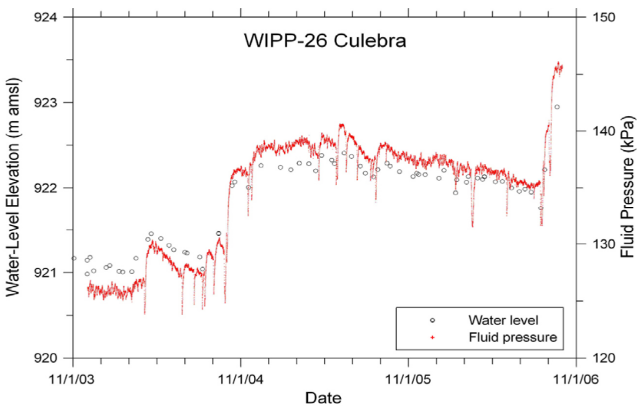

Fig. 5. Comparison of high-frequency pressure transducer data with monthly-scale depth to water measurements

The many testing and monitoring programs conducted at WIPP have produced a long, high-frequency (at least hourly observations) record of water pressure fluctuations in both the Culebra and Magenta formations. In the absence of large-scale pumping for water supply, with only minor livestock watering and environmental sampling, the observed water level fluctuations in WIPP are largely due to what are often considered only secondary effects. Wells respond to barometric loading, earth tides, physical loading due to precipitation, and anthropogenic effects. Human effects do not include municipal groundwater pumping, but rather secondary effects like the drilling of nearby (less than a few kilometers away) oil and gas wells through the Culebra and Magenta, and WIPP-related construction and characterization efforts. The combination of a large pre-existing monitoring network in a relatively quiet groundwater flow system with high temporal-frequency monitoring has allowed unique observations of processes at scales previously unobserved (larger than multi-well tests, but smaller than regional groundwater flow models). These high-resolution water level fluctuations are providing insight into the complex hydrogeology, such as the level of confinement and connectivity, when compared with observed rainfall, earth tide, and barometric data [11].

WIPP is located in the Chihuahuan Desert, and receives on average only 33.0 cm of precipitation annually [12]. Rainfall shows very high inter-annual variability, and a few individual storms may provide the bulk of the precipitation for an entire year. Individual storm events can be highly heterogeneous in space, with rain gages <30 km apart showing high variability. The response of water levels to precipitation events in the confined portions of the Culebra at WIPP, and the unconfined portions of the Culebra in Nash Draw are very different [12].

Figure 6 shows de-trended pressure transducer data (uncorrected for barometric or earth tide fluctuations) collected at four Culebra monitoring locations in or near Nash Draw (see well locations in Figs. 2 and 4), and the weekly precipitation for the same period in 2008 and 2009. The large >3.0-inch rainfall event in October 2008 has a visible correlation with the water level rises observed in SNL-19 and SNL-2, and to a lesser degree, so do the smaller precipitation events proceeding it. The level of confinement at a well and the location and spatial distribution of the precipitation in space both impact how an observation location will respond to a discrete rainfall event.

Analysis of the response of monitoring wells is further complicated by the nearby presence of Nash Draw – a well-known karst dissolution feature [13]. Wells completed in Nash Draw (e.g., SNL-19, and IMC-461) show clearer response to precipitation events (see Fig. 7) Fast recharge to the Rustler is happening through sinkholes and other dissolution features in Nash Draw, but the manner in which the surface karst features are connected to and create responses in Nash Draw Culebra is not clear, and is still being studied [12].

V. SUMMARY

Culebra hydrogeology is used to construct a flow and radionuclide transport model that is a key component in PA modeling used to assess WIPP compliance. The hydrologic conceptual model incorporates a wide range of observed geologic data, including cores and borehole geophysical data. Well testing at the WIPP has been used to infer a range of hydraulic property scales: single-well tests have led to small-scale estimates of T; multi-well hydraulic and tracer tests have provided information about D and heterogeneity.

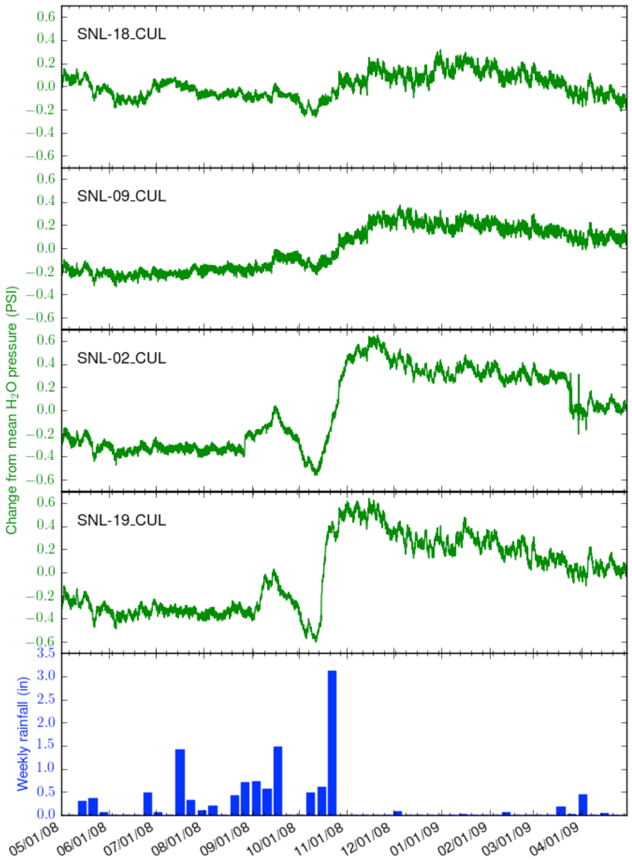

Fig. 6. Data from Culebra pressure transducers (de-trended to remove long-term slope) and weekly rainfall at the WIPP site

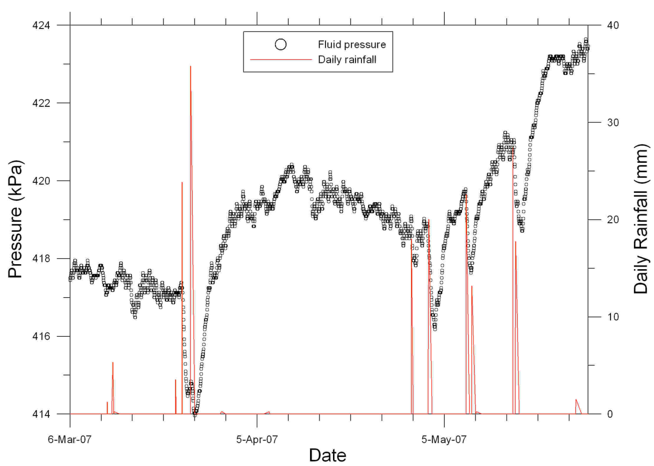

Fig. 7. Data from IMC-461 pressure transducer and daily rainfall at the SNL-9 site.

Analysis now continues on the growing body of data collected at WIPP in what was previously considered "uninteresting" quiescent periods between large-scale pumping tests. Natural stimuli like barometric pressure fluctuations, earth tides, and precipitation events are being used to estimate aquifer T and storage parameters at a scale previously unstudied at WIPP. This information may provide new estimates of parameters for future modeling efforts.

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