Hydrogeology and WIPP Compliance - 11658

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ABSTRACT

The hydrogeology of the geologic formations that impact the long-term (10,000 years) performance of the Waste Isolation Pilot Plant (WIPP) have been characterized, tested, and simulated for more than thirty years, resulting in a high degree of confidence in present hydrologic understanding. The WIPP repository is located more than 300 m below the Culebra Member of the Rustler Formation in bedded halite of the Salado Formation. In performance assessment (PA), the Culebra is considered the most likely groundwater radionuclide pathway away from WIPP, in scenarios where human intrusion breaches the repository.

This paper describes the conceptual model for flow and transport through the Culebra. The model includes multirate diffusion in a dual-domain medium, which has the effect of greatly retarding radionuclide movement away from a potential release point. The implementation of Culebra radionuclide transport in the current PA only accounts for single-rate matrix diffusion and dual porosity, which is a conservative approximation. Data collected from seven large-scale tracer tests, approximately 100 hydraulic tests, and continued analysis of high-frequency pressure data from monitoring wells support and validate the role the Culebra plays in the WIPP PA.

This paper summarizes how the hydrogeology of the Culebra has historically contributed to WIPP compliance using data collected at a multitude of scales. It also considers how data collection and long-term monitoring contribute both to conceptual model validation and the continued compliance of WIPP.

INTRODUCTION

The hydrogeology of the geologic formations that impact the long-term (10,000 years) performance of the Waste Isolation Pilot Plant (WIPP) have been characterized, tested, and simulated for more than thirty years, resulting in a high degree of confidence in present hydrologic understanding. The hydrologic characterization and modeling effort at WIPP is ongoing, as the conceptual model of the system is refined 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 near-surface Dewey Lake Formation, and the deep Bell Canyon Formation) are much less permeable and therefore 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].

WIPP PERFORMANCE ASSESSMENT

Geologic and hydrologic data collected from the Culebra have been used to construct conceptual and numerical flow and radionuclide transport models, and these models comprise components of the overall WIPP performance assessment (PA) repository model. The US Environmental Protection Agency (EPA) regulates WIPP compliance. PA-predicted release probabilities and their corresponding uncertainties have been utilized to justify the regulatory compliance of WIPP in its 1996 compliance certification application and subsequent compliance re-certification applications (CRA-2004 and CRA-2009). PA considers several potential release mechanisms over the regulatory life of the repository, all of which involve releases due to future human intrusion through oil and gas drilling. Underground site characterization efforts have shown the Salado formation has hydraulic properties favorable to the objectives of PA [3], and therefore conditions that undisturbed radionuclide transport from the closed repository to the accessible environment is considered extremely unlikely. Future human intrusion is required for radionuclide transport to have an impact on compliance; intrusion connects the repository with high-pressure brine pockets in the underlying Castile Formation, and provides possible pathways to the Culebra and surface environment.

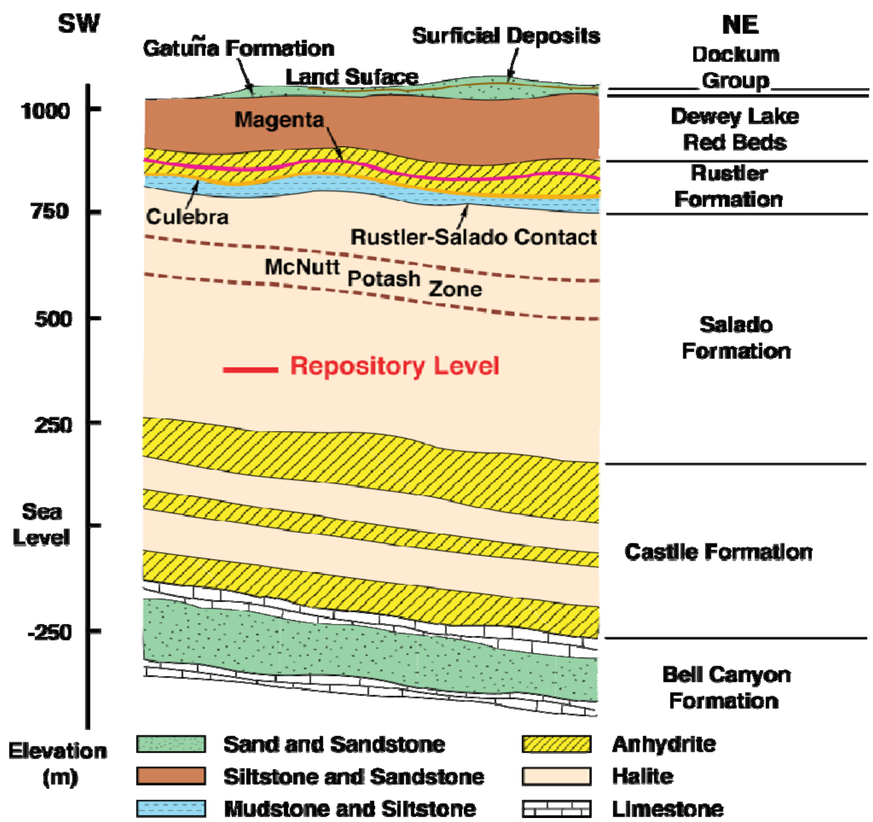

Fig. 1. WIPP geologic cross section

Radionuclide transport to the accessible environment is divided into two main types. The first type, direct releases include the transport of waste to the surface during an intrusion event; see, for example, the cuttings and cavings and direct brine release (DBR) curves in Fig. 2 obtained during 2009 PA recertification calculations. The second type of potential release mechanism in

WIPP PA is long-term release due to human intrusion through Culebra transport to the edge of the land withdrawal boundary (LWB). The LWB is an area of 16 sections surrounding the surface WIPP facilities. The Culebra is at least an order of magnitude more permeable than any other continuous saturated unit that might be encountered in a potential human intrusion, and would therefore be the most likely offsite pathway for contaminants to follow in such a case. The Culebra is the focus of most hydrologic investigations at WIPP, since the initial characterization phase in the 1970s.

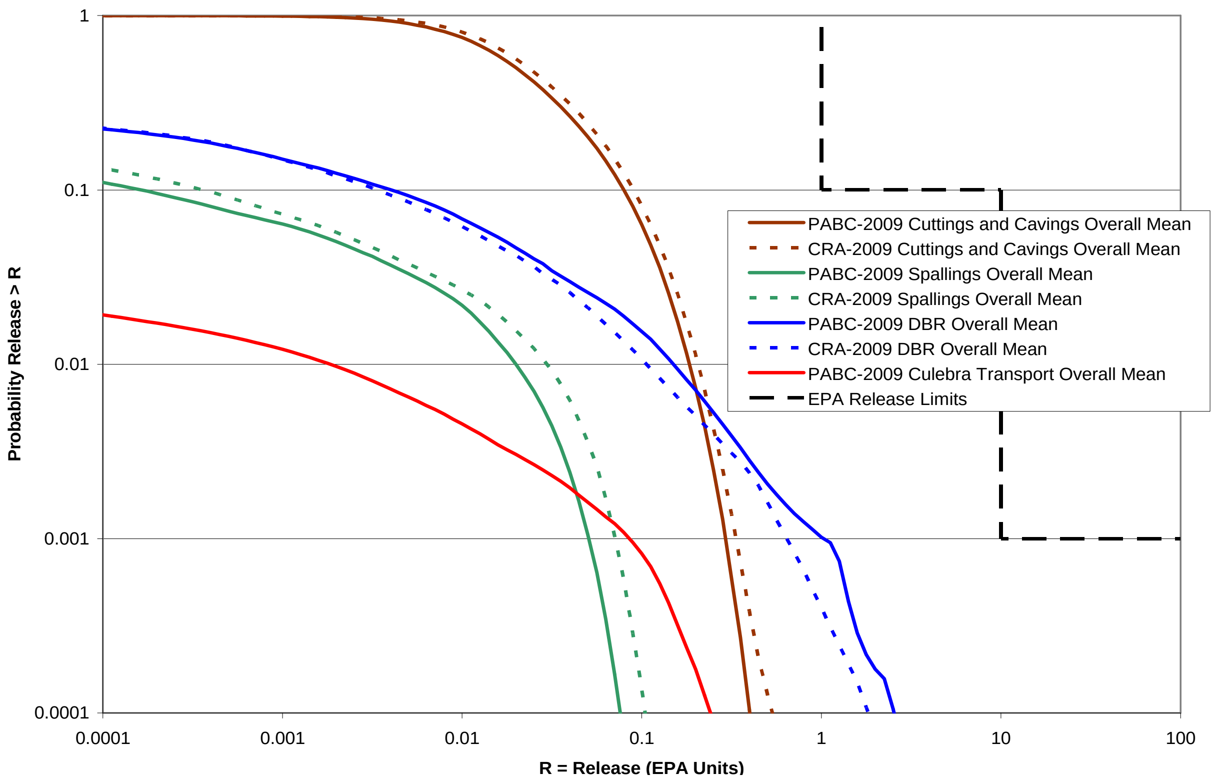

Fig. 2. Release mechanisms in 2009 WIPP PA showing probability (*y*-axis) of a given release size (*x*-axis) as colored curves, while regulatory limits are indicated with the dashed black line. PABC is the PA baseline calculation, with modified parameter values requested by the EPA.

Although the Culebra contribution to total release probabilities predicted in the 2009 performance assessment baseline calculation (PABC) (the normalized sum of all solid curves in Fig. 2) to the accessible environment is relatively small, this is due to the hydrologic flow and transport properties of the Culebra, which are favorable for the objectives of PA. Similar to the characteristics of the Salado, which make undisturbed radionuclide transport away from the WIPP unlikely, the characteristics of the Culebra make long-term radionuclide transport to the accessible environment a small contribution to the overall result.

Culebra hydrology is included in overall PA by simulating steady-state flow across an area 28.4 by 30.7 km, centered on WIPP. An ensemble of 100 flow models are calibrated to observed hydrologic conditions, and used to simulate radionuclide transport away from the release point to the LWB. Uncertainty is included by Monte Carlo of sampling input parameter values across the entire ensemble [4].

CULEBRA CONCEPTUAL MODEL

The major features of the Rustler geologic conceptual model have been defined by extensive stratigraphic data obtained from WIPP-related 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 [5] in particular, provided some of the clearest evidence in support of the geologic model now used for the Rustler [6].

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 the Culebra and Magenta. Geophysical logs from hundreds of nearby oil and gas wells are used to further constrain stratigraphy, create isopach maps, and locate geologic boundaries, including the Rustler mudstone/halite margins and Salado dissolution margins. Petroleum exploration and production wells are completed outside the WIPP LWB in the Bell Canyon Formation and below [1,2].

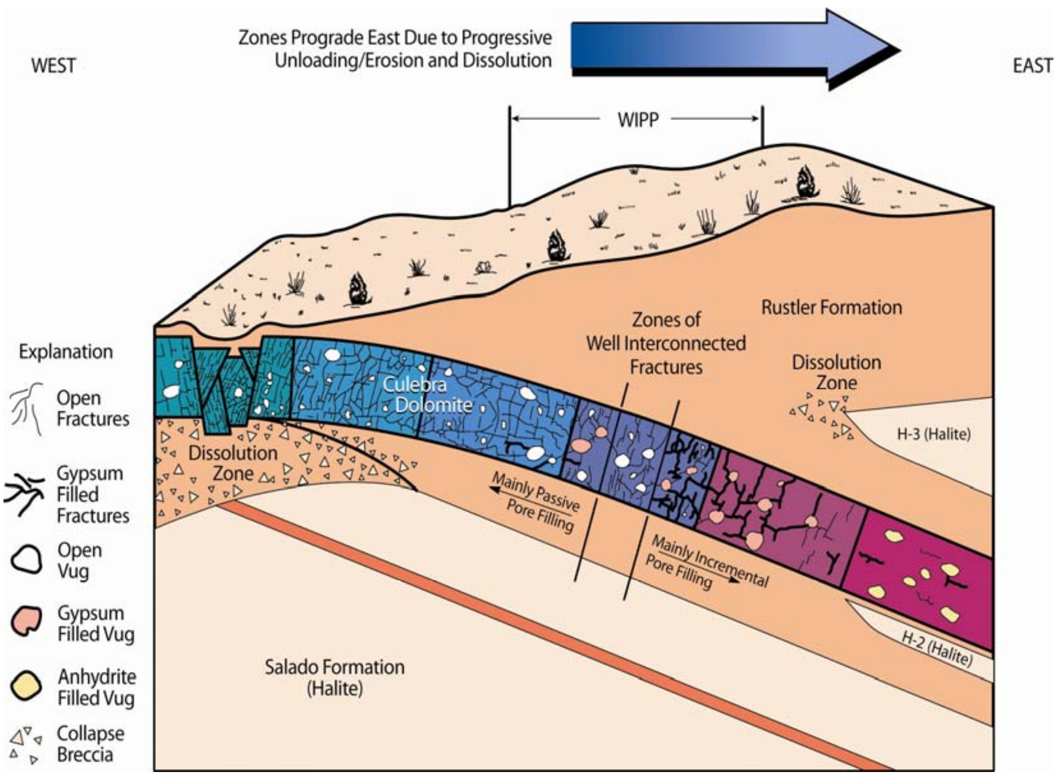

Fig. 3. Diagrammatic cross-section illustrating conceptual model of geologic processes effecting Culebra flow and radionuclide transport at WIPP

The hydrogeology of the Culebra is controlled by depositional facies [6,7] and dissolution of halite from beneath the Rustler (see Salado dissolution in left portion of Fig. 3) in Nash Draw, west of WIPP (see Fig. 4 for location).

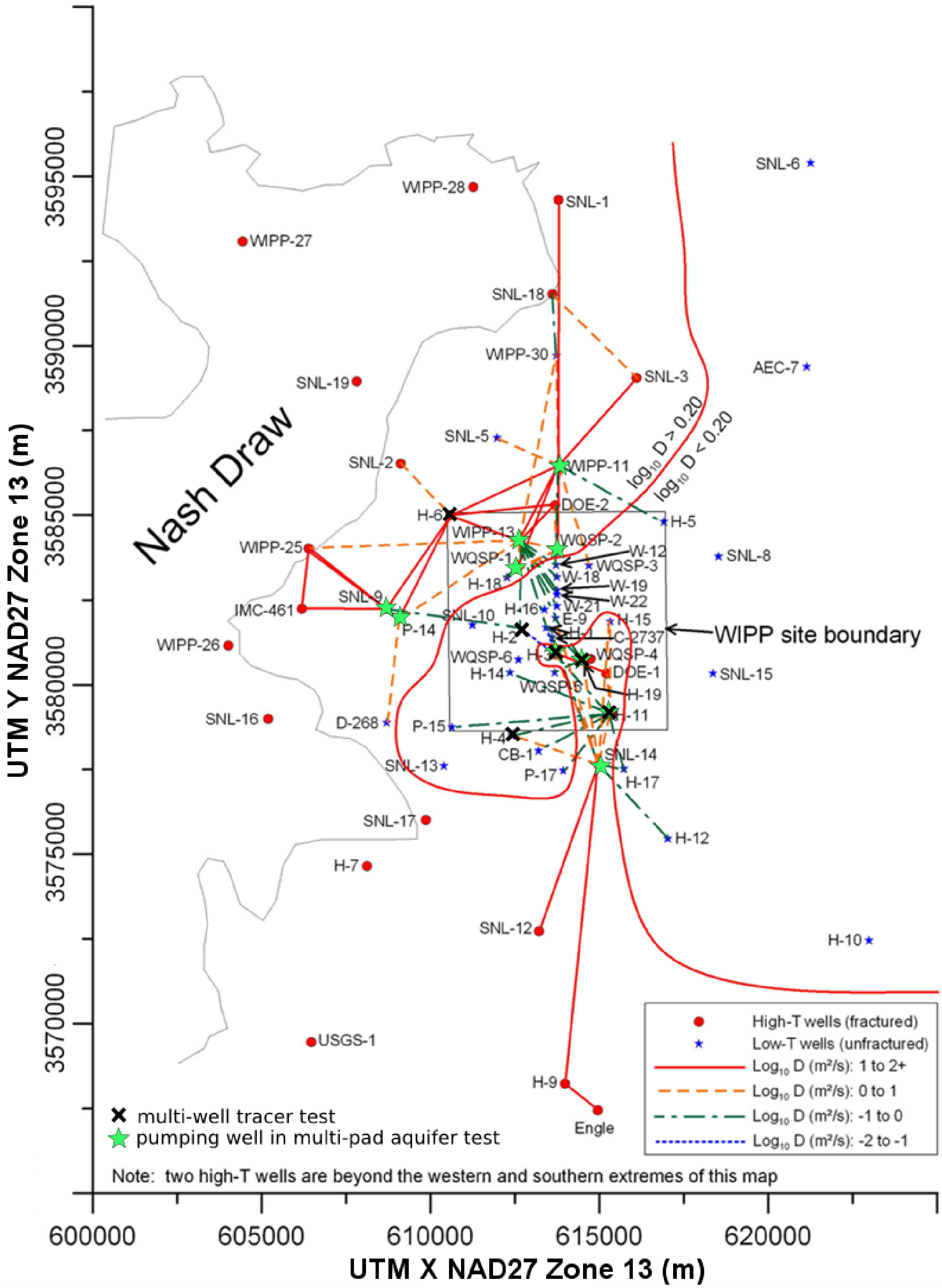

Fig. 4. Locations of WIPP LWB and Culebra wells in relation to Nash Draw, large-scale pumping tests (10 green stars), multi-well tracer tests (6 black crosses), and illustration of hydraulic diffusivity (D) interpreted from multi-pad hydraulic test results (colored lines).

The presence of halite in the Rustler above and below the Culebra (see H-2 and H-3 in Fig. 3), and the presence of anhydrite in Culebra porosity are both associated with extremely low Culebra T. In the eastern Culebra wells SNL-6 and SNL-15 (see Fig. 4 for location), T has been estimated to be approximately $1.0 \cdot 10^{-11}$ and $1.3 \cdot 10^{-13}$ m^2/s, respectively [8,9]. Much higher T is observed in wells completed in the Culebra where the Salado shows evidence of dissolution (e.g., WIPP-26 and SNL-16 have T values of approximately $1.3 \cdot 10^{-3}$ m^2/s). Single-well hydraulic tests reveal that T ranges over at least ten orders of magnitude across the WIPP site.

The WIPP site is situated between the region of very low Culebra T to the east in the halite-sandwiched area, and the region of higher T to the west in Nash Draw. Regression-based modeling has related Culebra T to overburden thickness and evaporite presence in the Rustler [7]. In addition to overburden, fracturing in the Culebra is a primary factor controlling Culebra T in the middle transition zone at WIPP [4]. Interconnected fracturing occurs on a scale that cannot be effectively mapped using cores and geophysical borehole logs, like broad facies and dissolution. The presence or absence of interconnected fracturing in the Culebra is included stochastically in the groundwater flow model using an indicator kriging simulation approach [4].

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 [4]. Conceptual model development and validation require hydrologic testing to estimate likely aquifer parameter ranges for use in numerical models. Transient calibration of the suite of numerical flow models requires pumping tests at scales that can be simulated by the PA groundwater flow model, which has 100-m square model cells.

CULEBRA TESTING

To estimate Culebra hydraulic properties, numerous single-well and multiple-well pumping tests have been conducted (see red circles and blue stars in Fig. 4). More than 90 individually tested Culebra wells indicate that single-well Culebra T ranges over at least ten orders of magnitude and is typically 2 orders of magnitude greater than found from hydraulic tests in any other formation [8,9]. Multi-well hydraulic tests have revealed weak pad-scale anisotropy and some pad-scale heterogeneity have been observed at the scale of 30 meters [8]. Eleven large-scale pumping tests have revealed heterogeneity and produced data for model calibration (see ten green stars in Fig. 4; H-11 has been tested twice). Seven multi-well tracer tests have been conducted in the Culebra (see six black crosses in Fig. 4; the H-11 pad had two tracer tests).

Hydraulic characterization 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 near the WIPP site (see Fig. 1 for stratagraphic locations of other formations). Most other geologic units at WIPP are considered aquicludes, only contributing to the flow system in Nash Draw where they are highly fractured.

Culebra Hydraulic Tests

Single-well aquifer tests, where pumping and observation are done in the same well, are the simplest to perform. In situations where formation permeability is very low, single-well slug tests might be the only feasible means of testing the hydraulic properties of a formation. Using current well-test analysis approaches, single-well tests do not provide reliable estimates of aquifer storage properties, and give no information about horizontal formation heterogeneity. In fractured rock, a multiple-porosity response (common in the highly fractured part of the Culebra at WIPP [8]) is often only observed in the pumping well itself or in very close observation wells; at larger scales, the network of discrete fractures behave more like a single continuum porous medium. Multi-well tests obviously require nearby wells and are, thus more costly to perform than single-well tests. Multi-well tests provide more information, including aquifer storage properties and pad-scale heterogeneity. At WIPP a distinction is made between pad-scale tests (≤50 m) and multi-pad tests (100 m to 10 km).

Eleven large-scale multi-pad aquifer tests have been performed in the Culebra (see larger green stars in Fig. 4). Multi-pad aquifer tests allow for more reliable estimation of hydraulic diffusivity (D) – the ratio of T to storativity – and give an indication of lateral heterogeneity between well pads at a scale relevant to PA flow modeling. 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. A large-scale pumping test was performed at SNL-14 in 2005 (south of the WIPP site); a pumping rate of 1.9 L/s (30 gpm) was sustained for 22 days. The response of observation wells to pumping SNL-14 showed a very strong north-south trend up to 10 km away, while showing little to no east-west response in nearby wells. SNL-14 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 Culebra high-T pathway in the southeastern portion of the WIPP LWB. A high-D connection is found between SNL-14 and H-9 (red solid rays in Fig. 4), 10 km south, while low-D is inferred from the connection of SNL-14 to nearby H-17 and H-12 (green dash-dot rays in Fig. 4). The SNL-14 pumping test is just one example of observed asymmetries in large-scale Culebra pumping tests.

The observed drawdown data from the SNL-14 pumping test were an important calibration target for the calibration of the PA groundwater flow model [4]. 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 [4]. 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. Estimated values of T obtained from analyzing single-well hydraulic tests were included as fixed pilot point values in the calibration of the T-fields for PA.

Culebra Tracer Testing

In addition to hydraulic tests, seven pad-scale multi-well tracer tests have been performed at six locations in the Culebra [10] (see black crosses in Fig. 4). Five dipole and converging flow tracer tests were initially conducted during from 1980 to 1986. Two sets of single-well injection-withdrawal (SWIW) tests and converging flow tests were conducted later in 1995-1996 at the H-19 and H-11 well pads. Tracer tests are used to estimate transport properties of the aquifer, including advective porosity, dispersivity, matrix diffusion rates, and overall formation heterogeneity (of both flow and transport parameters). Because tracer tests are also hydraulic tests, they provide a large amount of formation characterization information.

The issue of scale is an important factor in the design of tracer tests. SWIW tests involve injecting a pulse of tracer into a well, followed by a chaser of fresh water, then a period of rest. Finally, extraction and sampling are used to estimate the interaction of the tracer with different components of the formation. SWIW tests can give the best information about matrix diffusion rates, because the tracer has long residence time during the rest period to interact with the aquifer matrix. Similar to single-well hydraulic tests, SWIW tests do not provide information about lateral heterogeneity; they are also largely insensitive to advective porosity. Converging flow tracer tests involve a larger portion of the formation by injecting tracer into nearby monitoring wells after a background pseudo-static (Theim regime) converging flow field has been established by the extraction well. Converging flow tests require multiple wells, but give excellent information about advective porosity, and flow system heterogeneity. Depending on the flow rate, they can give good quality information about mass-transfer parameters. A very high flow velocity moves tracer through the fractures too fast to allow it time to interact with the rock matrix.

More so than pad-scale pumping tests, 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 [10].

In hydraulic tests we observe dual-porosity response, corresponding to the balance of two different types of flow in both fractures and in the porous matrix of the rock. In tracer tests, the response can be much more complex, with multiple mass transfer rates needed to simulate mass transfer between the fast advective flow in the fractures and the slow diffusion into different portions of the rock matrix. Multiple rates of mass transfer between the advective and diffusive domains have been attributed to multiple scales of porosity in the Culebra [11,12]. Large open pores (vugs), inter-beds of silty dolomite, areas of dolomite breccia, inter-crystalline porosity, and inter-particle porosity all exchange tracer mass with the fractures at different rates based on their physical nature and geometry. The superposition of many discrete rates, or a continuous rate distribution can lead to very long-tail behavior in the breakthrough of tracers at observation wells (most easily observed in SWIW tests). Tracer testing results from H-11 and H-19 have revealed the Culebra to clearly follow a multi-rate diffusion model, as opposed to a single-rate model – where only one mass-transfer rate between fractures and matrix exists. PA radionuclide transport modeling has been done so far using single-rate mass transfer between fractures and matrix, as a conservative simplification.

Multi-rate transport is indicative of multiple porosity scales with varying mass transfer characteristics in the Culebra, most of which are at the 0.1-m to 0.001-m scale, and therefore smaller than those observed in most single-well hydraulic tests. Although large-scale hydraulic tests can provide information up to the km-scale, ongoing work with long-term monitoring data collected at WIPP is being done to infer parameters and heterogeneity at even larger scales. At the scale of 10 km, these estimates may be quite appropriate for direct use in large regional groundwater flow models.

WATER LEVEL RECORD INVESTIGATION

During the earlier investigative and pre-licensing phase at WIPP, water levels in monitoring wells were observed typically once a month using a water level measuring tape. Both EPA and New Mexico Environment Department regulations require long-term hydrologic monitoring at WIPP through the current operational phase, and into the post-closure phase. This long record of manual water levels has been and continues to be critical data for the analysis of Culebra state and behavior through time. Long-range changes in water levels that happen over broad areas can be observed solely with this type of data.

Multi-well pumping and tracer tests required the instrumentation of observation wells with pressure transducers for automatic high-frequency observations during periods of pumping and recovery. After completion of testing, most transducers remained in monitoring wells to record pressures, leading us to the conclusion that the monthly water level monitoring was not revealing the whole picture with respect to small time-scale fluctuations. Observed small-scale fluctuations in manual monthly water levels were found to be more than just observation noise. Manual water levels should instead be thought of as a low-resolution sampling of coherent high-frequency water level fluctuations caused by physical processes including fluctuations in barometric pressure and earth tides [13]. Once it was realized that significantly more information may exist in higher-frequency monitoring at existing locations, all observation wells were eventually outfitted with pressure transducers and data loggers.

The many testing and monitoring programs conducted at WIPP have produced a multi-year, 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 at WIPP are largely due to what are often considered only secondary effects. Confined 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 lesser 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 new insight into the complex hydrogeology, such as the level of confinement and connectivity, when compared with observed rainfall, earth tide, and barometric data [14].

SUMMARY

Culebra hydrogeology is used to construct an ensemble of flow and radionuclide transport models that are a key component in overall PA repository 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 hydraulic 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 and the multiple-porosity response due to flow in both discrete fractures and porous rock matrix; multi-well hydraulic tests have provided information about D and heterogeneity. Single-well tracer tests have given strong evidence that multiple mass-transfer rates are needed to accurately simulate Culebra transport. Multiple-well tracer tests have given information about advective porosities, dispersivities, and flow system heterogeneity at the pad scale.

WIPP PA has synthesized the large body of knowledge and data regarding the Culebra into a defensible conceptual model, which is then embodied in an ensemble of numerical flow and solute transport models. The relatively small contribution of the long-term Culebra releases to the overall PA is due to the effect favorable Culebra property distributions have on long-term transport predictions. The current parameter estimates used in PA, and the confidence in the predictions made regarding Culebra hydrology at WIPP exists because of the long history of site characterization efforts.

Analyses continue 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. Mining this existing and ever-growing body of data will provide a new scale of parameter estimates for ongoing modeling efforts.

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