IMPORTANT NOTICE: The current official version of this document is available via the Sandia National Laboratories WIPP Online Documents web site. A printed copy of this document may not be the version currently in effect.

SANDIA NATIONAL LABORATORIES
WASTE ISOLATION PILOT PLANT

AP-150

Analysis Plan for the Analysis of Observed Water Level Fluctuations

Task 1.4.2.3

Effective Date: 06/14/10

Authored by:	Kristopher L. Kuhlman	*Original signed by Kristopher Kuhlman*	*6/14/10*
	Print Name	Signature	Date
Reviewed by:	Richard L. Beauheim	*Original signed by Shelly R. Johnsen for*	*6-14-10*
	Print Name Technical Reviewer	Signature	Date
Reviewed by:	Mario J. Chavez	*Original signed by Mario Chavez*	*6/14/10*
	Print Name Quality Assurance Reviewer	Signature	Date
Approved by:	Christi D. Leigh	*Original signed by Christi Leigh*	*6/14/10*
	Print Name Department Manager	Signature	Date

© 2010 Sandia Corporation

Table of Contents

1 Introduction and Objectives 3
1.1 Introduction 3
1.2 Objectives 3
2 Approach 4
3 Software List 4
4 Tasks 5
4.1 Task 1: Assembly of Data 5
4.2 Task 2: Regression Analyses 5
4.3 Task 3: Time Series Analyses 6
4.4 Task 4: Physical Model Analyses 7
4.5 Task 5: Report Preparation 8
5 Special Considerations 8
6 Applicable Procedures 8
7 References 8

1 Introduction and Objectives

1.1 Introduction

In 1996, the Department of Energy (DOE) completed a performance assessment (PA) for the Waste Isolation Pilot Plant (WIPP). The PA was part of the Compliance Certification Application (CCA) submitted to the Environmental Protection Agency (EPA) to demonstrate compliance with the radiation protection regulations of 40 CFR 191 and 40 CFR 194. As required by the WIPP Land Withdrawal Act (Public Law 102-579), DOE is required to submit documentation to EPA for the recertification of the WIPP every five years following the first receipt of waste in order to continue operation of the site. The Culebra Member of the Rustler Formation is a key hydrologic component in the understanding of the system that surrounds the WIPP repository. The Culebra is extensively monitored using high temporal resolution (sampling at least hourly) pressure transducers; the Magenta Member of the Rustler Formation is currently also monitored to a lesser degree. These transducers were initially used to monitor specific well-testing events, but are currently used to monitor water levels between well tests and in quiescent periods of no well testing.

1.2 Objectives

This analysis plan (AP-150) describes the programmatic-level analysis (see NP 9-1, Appendix A) and methods that will be used to investigate observed water level fluctuations in monitoring wells at and near the WIPP site. Pressure data have been collected at numerous locations over several nearly continuous years (see Figures 1 and 2). Anomalies in observed water levels can be more easily characterized – and sometimes explained or associated with a likely cause – by analyzing high-frequency data, compared to analyzing observations collected only at weekly or monthly intervals.

Water level fluctuations can be roughly categorized by their temporal duration and their physical extent. Some changes in water levels dissipate quickly (i.e., hours to days) and are spatially localized (e.g., spikes due to nearby oil or gas well construction). Other water level changes dissipate a bit slower (i.e., days to weeks), and are more regional in space (e.g., quick responses to precipitation events). Still other water level changes are of large spatial scale and long (i.e., weeks to years) time scale (e.g., general rises and declines in water levels potentially correlated to precipitation or other unknown events).

The high-frequency data collected at the WIPP has the potential to be used for two different types of analyses. First, a larger amount of data at a higher frequency means the potential cause of the water level oscillations can be identified. Different sources have different characteristic profiles or behaviors in time.

Second, as a by-product of the analysis to understand observed long-term records of water level fluctuations and barometric pressure, we can potentially estimate hydraulic properties, using statistical approaches, physical models, or methods analogous to passive seismic interpretation techniques. The driver for this analysis is the understanding and potential explanation of observed water level fluctuations (e.g., multi-year rise and fall, intermediate time scale response to precipitation events, and short-term response to barometric and earth tide fluctuations); to properly explain observed anomalies, the effects of known physical processes must be removed from the observed signal. Because the analysis will be using real-world data collected from WIPP, both sources of fluctuations must be dealt with appropriately during the course of the analysis.

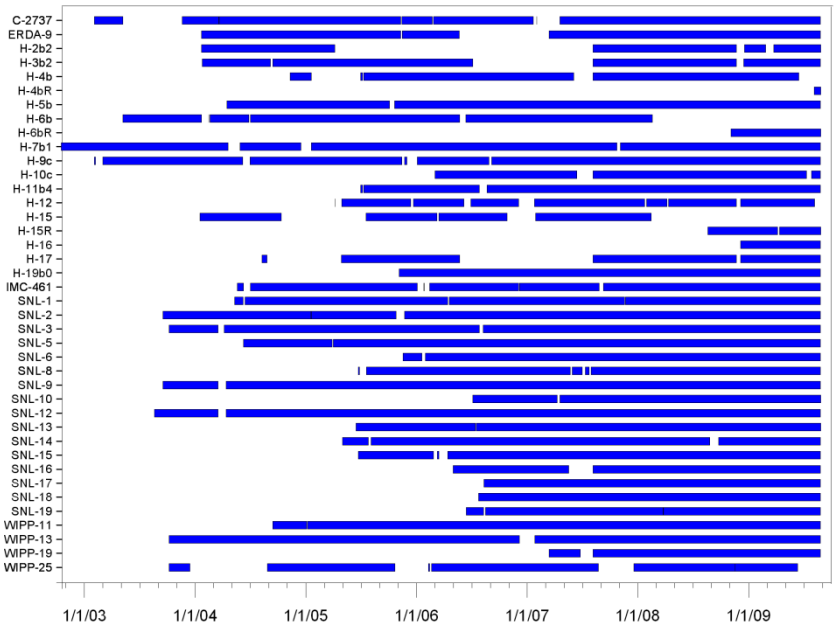

Figure 1. Culebra pressure transducer installation history through August 2009

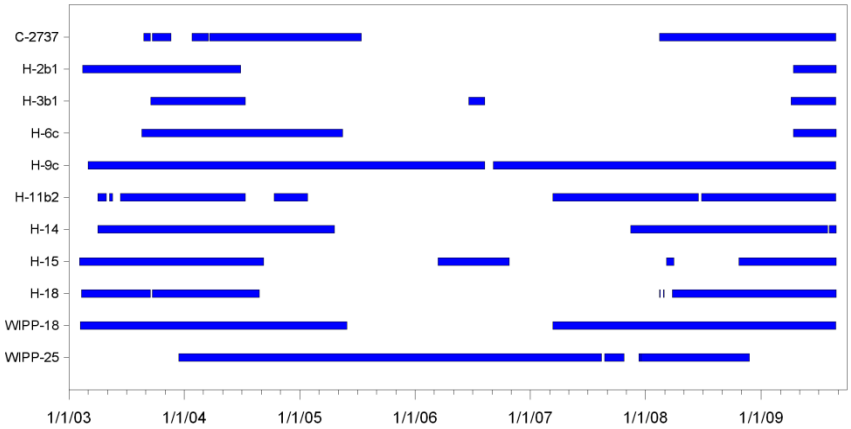

Figure 2. Magenta pressure transducer installation history through August 2009

2 Approach

This analysis depends on the water level, barometric, and precipitation data that are available. Each of these data sources must be acquired from a quality-assurance (QA) verified source (e.g., a WIPP database with qualified data) or they must be individually qualified for this analysis. The databases that may be used in this analysis are not fully qualified at this time, but it is believed that they will be utilized in this analysis once ready. Once the qualified data are obtained, they will be analyzed using a variety of approaches. Any scripts, software, or algorithms developed as part of this analysis will be subject to QA documentation in the associated Analysis Report that will summarize and document the work.

3 Software List

Table 1 lists the main computer codes and their minimum applicable version numbers, which will be used for the water level fluctuation analysis. The codes listed in Table 1 are all either WIPP QA qualified or commercial off-the-shelf (COTS) software. Equivalent or newer software versions and programs may be substituted for those listed, based on requirements determined during the analysis.

Table 1. Main computer codes (and minimum version numbers) to be used in analysis

Code	Program Type	Version	QA Status
nSIGHTS	well-test analysis	2.41	Qualified[1]
MATLAB	script interpretation and plotting	R2009	COTS
Python	script interpretation and plotting	EPD 6.1	COTS
Mathematica	script interpretation and plotting	7.0	COTS
PEST	parameter estimation	9.11	Qualified[1]

[1] Qualified software can only be run on qualified platforms, as per NP 19-1

4 Tasks

This analysis will combine several types of data collected as part of the WIPP hydrology program (collected by both Sandia National Laboratories (SNL) and Washington Regulatory Environmental Services (WRES)). The data will be brought together and analyzed using a variety of techniques and approaches. The methods used here will be made general enough to allow re-interpretation of a presumably larger dataset of water levels, precipitation, and barometric pressure at a later time in the future. Aside from the first (data collection) and final (report writing) steps (see Table 2), portions of this analysis may be omitted or expanded, based on the discretion of the analyst and will be documented as a deviation to the analysis plan as called out by procedure NP 9-1 § 2.1.2.

4.1 Task 1: Assembly of Data

Long high-frequency time series of downhole pressure data currently exist, and will continue to be collected in the future under procedures SP 9-7 (pressure data from transducers) and SP 12-7 (water level data collected using sounders). These data will be queried from QA-approved databases (which are currently under development), or will be subject to QA approval for this analysis. Similarly, precipitation time series will be obtained from multiple geographic locations with the same requirements and expectations regarding QA discussed for the downhole pressure data. Precipitation time series are available from the WIPP site as external data, or from dataloggers at the WIPP-30, H-9, and SNL-16 locations under procedure SP 12-3. Barometric pressure data is collected continuously at the meteorological station at the WIPP site and at the SNL “portacamp”. Other potentially relevant time series (e.g., surface deflection from the tiltmeter at SNL-16) or spatial information (e.g., locations of closed surface drainage basins or calibrated Culebra groundwater flow model parameters) may be obtained and utilized in the analysis, once proper QA pedigree has been obtained for the data.

4.2 Task 2: Regression Analyses

Statistical regression analysis between forcing inputs (barometric fluctuations and precipitation) and outputs (changes in observed water level elevation) has been successful in the determination of lumped quantities, such as barometric efficiency (e.g., Clark (1967); Todd (1980); Davis and Rasmussen (1993). This type of analysis typically results in a single parameter (efficiency) for each pairing of well record and atmosphere record. Commonly, this approach is used to clean barometric effects from the data record, not to obtain hydraulic parameters. Beginning with this type of analysis will help to quickly characterize and find possible issues in the data and can be used to compare against results obtained in subsequent tasks.

4.3 Task 3: Time Series Analyses

Similar to purely statistical regression analyses, time series analyses typically do not take physical flow processes into account. Despite this limitation, time series analysis (e.g., Box et al. (1994)) can be more sophisticated than regression analysis, and can potentially incorporate spatial statistics as well (e.g., Schabenberger and Gotway (2005)). Rasmussen and Crawford (1996) developed a deconvolution approach to barometric correction of observed water level data, which is implemented in BETCO (Toll and Rasmussen, 2007) and nSIGHTS. This approach results in a unit response function for each well, which sometimes simplifies to the barometric efficiency case in Task 1. Although the deconvolution approach is not physically based, the resulting response function from this approach (when saved as part of the analysis) can at least qualitatively be related to physical parameters.

A simplified time series analysis has been performed on a small portion of the water level data, to specifically investigate the timing of the response at observation wells to two distinct precipitation events, see Figure 3 from Hillesheim et al. (2007).

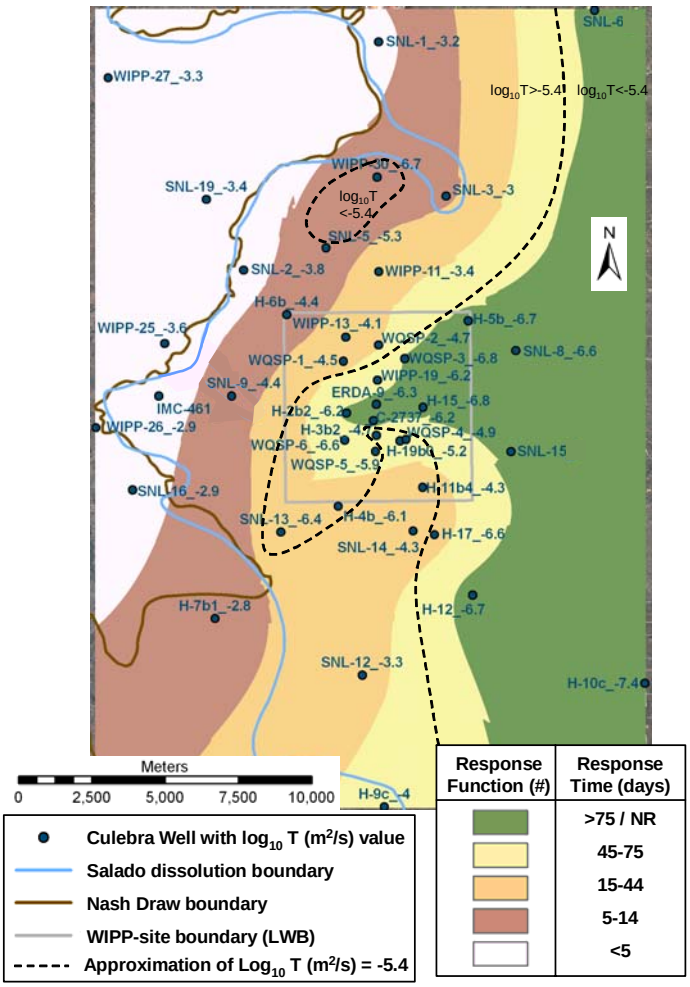

Figure 3. Map of Culebra response lag-time due to large rainfall events (>110 mm in 72 hrs); NR = no response; figure from Hillesheim et al. (2007).

Frequency-based analyses can also be performed on time series data, and often complement analyses done in the time domain or via regression analysis (e.g., Bernard and Delay (2008); Spane (2002); Bras and Rodríguez-Iturbe (1993)). Frequency-domain analyses are most

successful with very long continuous datasets, and may not be applicable to wells with shorter records or irregularities and breaks in the data, without some pre-processing. Frequency-based analyses can be very successful at removing or identifying highly regular signals, such as earth and lunar tide effects.

4.4 Task 4: Physical Model Analyses

This portion of the analysis involves using or developing conceptual and mathematical models that describe the physical characteristics of the system, then fitting the data to these models to interpret hydraulic parameters (possibly using parameter estimation software such as PEST). By predicting, and subsequently removing, the effects of physical processes on the observed water level trends, other un-explained responses may be more fully understood. Many different approaches have been taken in this direction, depending on the configuration and relevant physical processes occurring. Weeks (1979) and Furbish (1991) developed impulse response functions to propagate irregular records of atmospheric loading to the confined or unconfined aquifer of interest. Cooper et al. (1965), Bredehoeft (1967), Bower (1983), and Hsieh et al. (1987) developed models of wellbore/aquifer interactions to earth tides or seismic inputs. Rojstaczer (1988) developed a comprehensive frequency-domain solution from the land surface to the wellbore for analyzing the response of water levels in wells to periodic atmospheric loading.

A survey will be made of existing models; they will be evaluated based on physical applicability to the formation of interest at WIPP. If needed, the models will be modified to include or remove relevant physical processes from models. For example, a dual-porosity type response can be very important in low permeability confined fractured rock formations like the Culebra and Magenta. Incorporating dual-porosity behavior (e.g., Dougherty and Babu (1984); Moench (1984)) into existing models may improve fit of models with observed data. Physical loading of the land surface by precipitation events may also be a mechanism that contributes to water level fluctuations (e.g., Rasmussen and Mote (2007); Domenico and Schwartz (1990, §4.4); van der Kamp and Maathuis (1991); Freeze and Cherry (1979, §6.8)); these types of mechanisms would need to either be included physically in the governing equations, or at least empirically as corrections to eliminate or minimize their effects on other processes being modeled.

The types of model parameters that would be used would obviously depend largely on the model found to realistically fit the data, and that includes the processes occurring in the relevant formations near WIPP. It is feasible to estimate aquifer storage parameters (e.g., storage coefficients and porosities – Bernard and Delay (2008)), and possibly confining layer and aquifer permeabilities (e.g., Rojstaczer (1988)). These parameter estimates would likely be in the form of a single, uniform parameter estimate for each monitoring well / atmospheric data couple. This would likely result in a distribution of estimated parameters for each well, similar to using a homogeneous well-test solution at each well with a well test.

Another approach, somewhat physical in nature, while also somewhat statistical, is the use of frequency-domain cross-correlation of pressure head responses at different locations to directly derive the Green's function for the domain. The Green's function is a hypothetical "unit injection well" response that accounts for parameter variability and boundary conditions (a Green's function for a homogeneous 2D confined aquifer of infinite extent is essentially the Theis solution). This approach would potentially result in an aquifer diffusivity (permeability/storativity) value corresponding to each pair of wells used in the cross-correlation analysis. This approach has been used successfully in geophysics for seismic wave propagation problems (e.g., Curtis et al. (2006)), but has recently been shown to be possible for diffusive systems as well (Snieder, 2006; Wapenaar et al., 2006). This type of approach could be described as a "passive aquifer test", similar to the "passive seismic" approach used in geophysical exploration. Although this

method has the same pre-requisites as any frequency-based approach (requiring a very long uniform unbroken record), it has potential wide application to datasets such as the ones at WIPP. As given in the literature, this approach would not explicitly require the atmospheric loading time series, but this data may be incorporated into the approach to increase the amount of information available for analysis.

4.5 Task 5: Report Preparation

An analysis report will be written to document the exact approach taken, summarize the results, and to satisfy QA requirements of repeatability and documentation.

Table 2. Task Completion Dates Summary Table

Task	Estimated Time Required	Responsible Individuals
1	4 months	Kris Kuhlman, and others (to be determined)
2	3 months	
3		
4	9 months	
5	2 months	

5 Special Considerations

There are no special considerations.

6 Applicable Procedures

Analyses will be conducted in accordance with the quality assurance (QA) procedures listed below.

Training: Training will be performed in accordance with the requirements in NP 2-1, Qualification and Training.

Parameter Development and Database Management: Selection and documentation of parameter values will follow NP 9-2. The database will be managed in accordance with relevant technical procedure.

Computer Codes: New or revised computer codes that will be used in the analyses will be qualified in accordance with NP 19-1. Qualified codes will be run on the fully-qualified PA Linux cluster, while COTS software may be run on desktop computers.

Analysis and Documentation: Documentation will meet the applicable requirements in NP 9-1.

Reviews: Reviews will be conducted and documented in accordance with NP 6-1 and NP 9-1, as appropriate.

7 References

Bernard, S. and Delay, F. 2008. Determination of porosity and storage capacity of a calcareous aquifer (France) by correlation and spectral analyses of time series, *Hydrogeology Journal*, 16(7), 1299-1309.

Bower, D.R. 1983. Bedrock fracture parameters from the interpretation of well tides, *Journal of Geophysical Research*, 88(B6), 5025-5035.

Box, G.E.P., Jenkins, G.M., and Reinsel, G.C. 1994. *Time Series Analysis: Forecasting and Control*, third edition, Pearson Education.

Bras, R.L. and Rodríguez-Iturbe, I. 1993. *Random Function and Hydrology*, Dover.

Bredehoeft, J.D. 1967. Response of well-aquifer systems to earth tides, *Journal of Geophysical Research*, 72(12), 3075-3087.

Clark, W.E. 1967. Computing the barometric efficiency of a well, *Proceedings of the American Society of Civil Engineers – Hydraulic Division*, HY 4, 93-98.

Cooper, H.H., Bredehoeft, J.D., Papadopulos, I.S., Bennett, R.R. 1965. The response of well-aquifer systems to seismic waves, *Journal of Geophysical Research*, 70(16), 3915-3926.

Curtis, A., Gerstoft, P., Sato, H., Snieder, R., and Wapenaar, K. 2006. Seismic interferometry – turning noise into signal, *The Leading Edge*, 25(9), 1082-1092.

Davis, D.R. and Rasmussen, T.C. 1993. A comparison of linear regression with Clark's method for estimating barometric efficiency of confined aquifers, *Water Resources Research*, 29(6), 1849-1854.

Domenico, P.A. and Schwartz, F.W. 1990. *Physical and Chemical Hydrogeology*, John Wiley & Sons.

Dougherty, D.E. and Babu, D.K. 1984. Flow to a partially penetrating well in a double-porosity reservoir, *Water Resources Research*, 20(8), 1116-1122.

Freeze, R.A. and Cherry, J.A. 1979. *Groundwater*, Prentice-Hall.

Furbish, D.J. 1991. The response of water level in a well to a time series of atmospheric loading under confined conditions, *Water Resources Research*, 27(4), 557-568.

Hillesheim, M.B., Hillesheim, L.A., and Toll, N.J. 2007. Mapping of Pressure-Head Responses of a Fractured Rock Aquifer to Rainfall Events. *Proceedings of the 2007 EPA/NGWA Fractured Rock Conference. National Groundwater Association, Westerville, OH*, 522-536, SAND2007-6024C.

Hsieh, P.A., Bredehoeft, J.D., and Farr, J.M. 1987. Determination of aquifer transmissivity from earth tide analysis, *Water Resources Research*, 23(10), 1824-1832.

Moench, A.F. 1984. Double-porosity models for a fissured groundwater reservoir with fracture skin, *Water Resources Research*, 20(7), 831-846.

Rasmussen, T.C. and Crawford, L.A. 1996. Identifying and removing barometric pressure effects in confined and unconfined aquifers, *Ground Water*, 35(3), 502-511.

Rasmussen, T.C. and Mote, T.L. 2007. Monitoring surface and subsurface water storage using confined aquifer water levels at the Savannah River Site, USA, *Vadose Zone Journal*, 6(2), 327-335.

Rojstaczer, S. 1988. Determination of fluid flow properties from the response of water levels in wells to atmospheric loading, *Water Resources Research*, 24(11), 1927-1938.

Schabenberger, O. and Gotway, C.A. 2005. *Statistical Methods for Spatial Data Analysis,* Texts in Statistical Science, Chapman & Hall.

Snieder, R. 2006. Retrieving the Green's function of the diffusion equation from the response to a random forcing, *Physical Review E*, 74(4), 46620.

Spane, F.A. 2002. Considering barometric pressure in groundwater flow investigations, *Water Resources Research*, 38(6), 1078.

Toll, N.J. and Rasmussen, T.C. 2007. Removal of barometric pressure effects and earth tides from observed water levels, *Ground Water*, 45(1), 101-105.

Todd, D.K. 1980. *Groundwater Hydrology*, second edition, John Wiley & Sons.

van der Kamp, G. and Maathuis, H. 1991. Annual fluctuations of groundwater levels as a result of loading by surface moisture, *Journal of Hydrology*, 127(1-4), 137-–152.

Wapenaar, K., Slob, E., and Snieder, R. 2006. Unified Green's function retrieval by cross correlation, *Physical Review Letters*, 97(23), 234301.

Weeks, E.P. 1979. Barometric fluctuations in wells tapping deep unconfined aquifers, *Water Resources Research*, 15(5), 1167-1176.

NOTICE: This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness or any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors.

This document was authored by Sandia Corporation under Contract No. DE-AC04-94AL85000 with the United States Department of Energy's National Nuclear Security Administration. Parties are allowed to download copies at no cost for internal use within your organization only provided that any copies made are true and accurate. Copies must include a statement acknowledging Sandia Corporation's authorship of the subject matter.