Using Water-Level Models to Conceptualize Groundwater-Flow Systems: Examples from the Nevada National Security Site – 17044

Tracie R. Jackson
U.S. Geological Survey, Henderson, NV, USA

ABSTRACT

Analysis of water-level trends in well hydrographs can be used to better understand and conceptualize a groundwater-flow system. A water-level trend reflects the summation of all natural and anthropogenic stresses acting on the aquifer at the well location. Common stresses include recharge, evapotranspiration, barometric pressure, earth tides, and pumping. A water-level model (WLM) can be used as a tool to distinguish which stresses are affecting the trend and quantify the impact of each stress on the trend.

A WLM is an analytical model that fits measured water levels to a synthetic curve representing the sum of one or more time-series components that explain the water-level trend. Time-series components include recharge pulses simulated with Gamma transforms of precipitation; long-term climatic trends and barometric-pressure responses simulated with moving averages of barometric pressure and water levels in background wells; tidal responses computed from theoretical tidal signals; and pumping drawdown simulated with Theis models. WLM examples are presented to show how to: (1) determine and decompose stresses affecting long-term water levels in wells; and (2) estimate short-term drawdowns in observation wells where drawdown is masked by environmental water-level fluctuations.

INTRODUCTION

Groundwater-flow system conceptualization influences every part of a groundwater study from setting up the problem, to collecting and analyzing data, interpreting results, and formulating conclusions. Groundwater-flow systems are conceptualized based on the interpretation of data. Most groundwater studies involving flow and contaminant transport utilize water-level data in wells. This paper presents two groundwater study examples where water-level models are used to extract useful information from water-level data in order to better understand and conceptualize a groundwater-flow system. The groundwater studies are within the Pahute Mesa—Oasis Valley (PMOV) groundwater basin, which intersects the northwestern part of the Nevada National Security Site.

The first example, herein called “long-term trend analysis”, analyzes multi-decadal water-level trends in well hydrographs within and near the PMOV basin to determine the stresses affecting water levels. A water-level trend reflects the summation of all environmental and pumping stresses acting on the aquifer at the well location. Common stresses include recharge, evapotranspiration, and pumping. WLMs are used to distinguish which stresses are affecting the trend and quantify the magnitude of the effect of each stress on the trend.

The second example, herein called “short-term drawdown analysis”, uses WLMs to estimate small drawdowns in observation wells where the drawdown is masked by environmental water-level fluctuations caused by earth and gravity tides, barometric pressure fluctuations, and seasonal climatic trends. Small drawdowns can be differentiated from environmental noise using WLMs.

LONG-TERM TREND ANALYSIS DATA COLLECTION

Periodic Water-Level Data

Data used for the long-term trend analysis were compiled from the U.S. Geological Survey (USGS) National Water Information System (NWIS) database [1]. The two wells discussed in this paper have quarterly water-level measurements spanning about 20 years. One of the wells, ER-12-1, is a 1,036-meter (m) deep well screened in carbonate rock in the recharge area known as Rainier Mesa. The other well, Beatty Wash Terrace Well, is a 12-m deep well screened in alluvium near a spring discharge area by Beatty, Nevada. The two wells are about 55 kilometers (km) apart.

Precipitation Data

Precipitation and groundwater recharge are temporally and spatially variable in the PMOV basin; therefore, each well used a different precipitation site to estimate recharge patterns near the well. Well ER-12-1 used a precipitation index site on Rainier Mesa and Beatty Wash Terrace Well used a precipitation index site near Beatty, Nevada. The Rainier Mesa precipitation index site has precipitation data from the *A12* and *M40* monitoring stations [2]. The Beatty precipitation index site has precipitation data from the *Beatty 8N* [3] and *Beatty* monitoring stations [4].

Precipitation from wet winters is assumed to contribute to groundwater recharge. Winter months occur from October to March, and wet winters are defined as winters with total precipitation that exceeds the mean of winter precipitation from 1973 to 2016. Precipitation contributing to recharge is defined as a threshold, where winter precipitation exceeds a specified percentage of the long-term winter precipitation, based on visual inspection of water-level responses to recharge. A zero-percent threshold is equal to the long-term mean of winter precipitation. For the Rainier Mesa precipitation site, the threshold is 50 percent (Fig. 1A); that is, winters that are 1.5 times the mean (0.074 m) contribute to recharge. For the Beatty site, the threshold is 100 percent (Fig. 1B); that is, winters that are two times the mean (0.068 m) contribute to recharge.

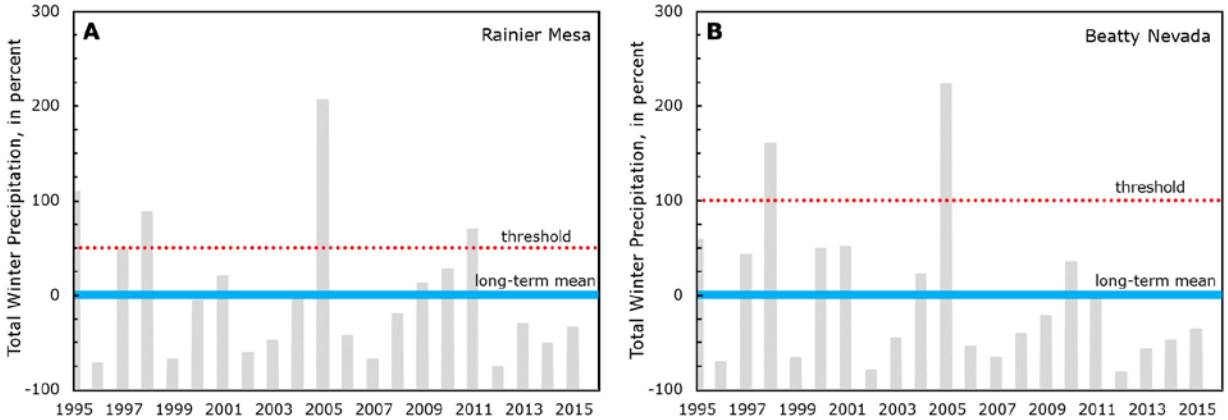

Fig. 1. Precipitation records for the Rainier Mesa (A) and Beatty Nevada (B) precipitation index sites. Zero-percent winter precipitation is equal to the long-term mean winter precipitation.

Groundwater Withdrawals

Groundwater withdrawals have occurred from 7 municipal wells that supply water to Beatty, Nevada [5]. About 6.4 billion liters of groundwater have been withdrawn from these municipal wells between 1996 and 2015. Beatty Well No. 1 produced about 614 million liters between 1996 and 2015.

SHORT-TERM DRAWDOWN ANALYSIS DATA COLLECTION

The ER-EC-11 multiple-well aquifer test in Pahute Mesa was conducted by Navarro Nevada Environmental Services (NNES) in 2010 [6]. Well ER-EC-11 produced water from welded-tuff aquifers and was pumped in April and May 2010 [6, 7]. During aquifer testing, continuous water-level data were collected from an observation well (ER-20-7), located about 1.7 km from the pumping well. Additionally, continuous water-level and barometric pressure data were collected from a background well (ER-20-6 #3), which was assumed to be unaffected by aquifer testing. The observation and background wells are screened in lava-flow and welded-tuff aquifers. There were two constant-rate pumping periods in ER-EC-11 during the aquifer test, in which discharge rates averaged about 20 L/s [6, 8].

METHODS

Water-Level Modeling

WLMs were used to either: (1) differentiate stresses affecting water-level trends; or (2) estimate drawdowns in observation wells masked by environmental noise during aquifer testing. WLMs were used to fit water-level data to a synthetic water-level curve. In the long-term trend analyses, the synthetic curve is the sum of one or more time series components that likely explain all water-level fluctuations in water-level trends [9]. Time series components include Gamma transforms of precipitation, Fourier transforms of evapotranspiration, and Theis [10] transforms of groundwater pumping. For the short-term drawdown analysis, the synthetic curve is the sum of all environmental and pumping stresses that occurred during the period of aquifer testing. Environmental stresses were approximated using time series of computed tidal signals, and measured barometric pressure and water levels from a background well. Theis [10] transforms were used to transform pumping rates into water-level drawdown responses.

A Theis [10] analytical model was used to transform groundwater withdrawal rates from pumping wells into water-level changes (Fig. 2), based on the distance from the pumping well to the observation well and assumed hydraulic properties of the aquifer. Transmissivity and storage coefficients in the Theis transforms served solely as fitting parameters and were not representative of hydraulic properties of the aquifer system, because the simplifying assumptions of the Theis [10] analytical model are violated.

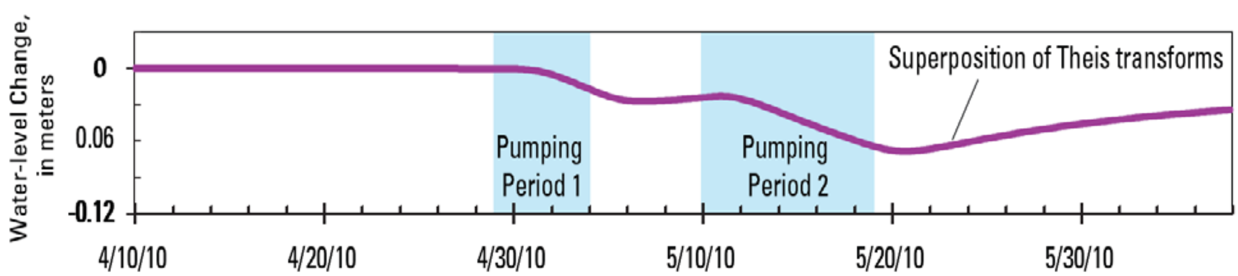

Fig. 2. Example showing superposition of Theis [10] transforms used to transform groundwater withdrawals from pumping in Well ER-EC-11 into water-level drawdown responses in Well ER-20-7.

The Gamma transform was used to simulate groundwater recharge. The Gamma transform accounts for the behavior of recharge with respect to unsaturated zone thickness [11]. As the unsaturated zone increases, the timing of recharge is lagged and the magnitude of recharge is attenuated. Precipitation from wet winters was transformed into a time series using the Gamma probability distribution function (Fig. 3A). The amplitude, scale, and shape of the Gamma transform were adjusted to match water-level data to the Gamma transform. In some cases, two Gamma transforms were used to simulate groundwater recharge (Fig. 3B). Conceptually, the two transforms represent fast and slow recharge pathways in a dual-porosity system, where hydraulically-connected fracture networks provide fast recharge pathways and the rock matrix causes slow dispersed recharge.

Water-level fluctuations due to barometric-pressure were removed using moving averages of continuous barometric pressure data (Fig. 4) and continuous water-level data (Fig. 5) at a background well. High-to-medium frequency

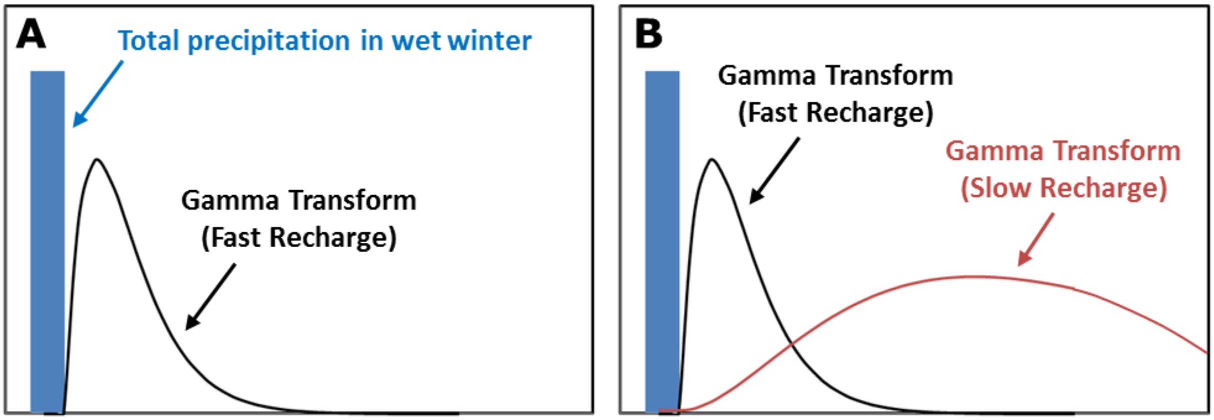

Fig. 3. Gamma transforms of water-level responses to precipitation-derived recharge. (A) Gamma transform representing a “fast” water-level response to recharge. (B) Gamma transforms representing “fast” and “slow” components of recharge in a dual-porosity system.

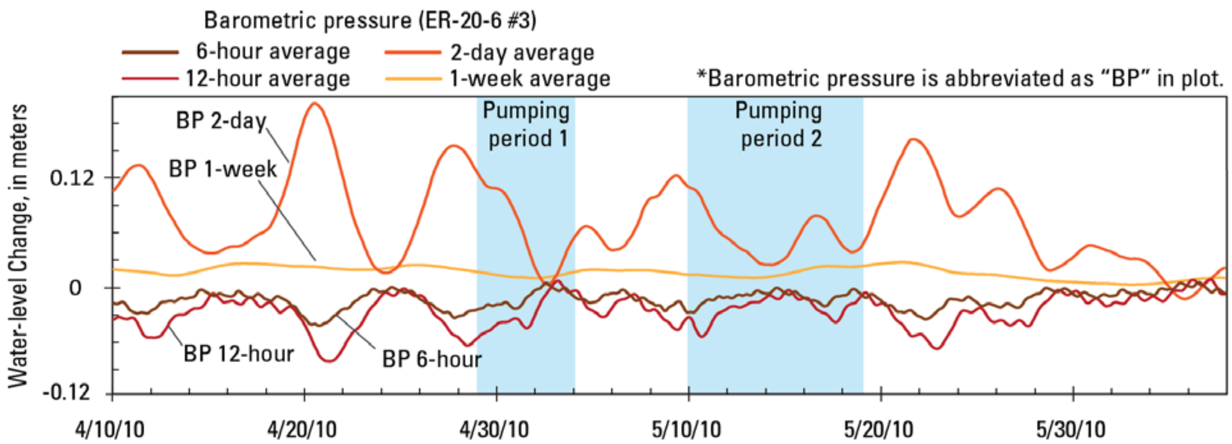

Fig. 4. Moving averages of continuous barometric pressure at background Well ER-20-6 #3 during aquifer testing at ER-EC-11.

(hours to months) fluctuations in barometric pressure affect water levels in confined aquifers. Barometric pressure at land surface propagates through the well casing to affect water levels screened in the open interval of the well. The amplitude and phase of multiple moving-average time series of barometric pressure and background water-level data were used to remove different signal frequencies and were adjusted to match measured and synthetic water levels.

Water-level fluctuations due to seasonal climatic trends were removed using moving averages of continuous water-level data at a background well (Fig. 5). Water levels in background wells are unaffected by pumping, but are assumed to exhibit similar climatic trends as the observation well. The majority of water levels in the PMOV basin have long-term rising trends due to groundwater recharge from

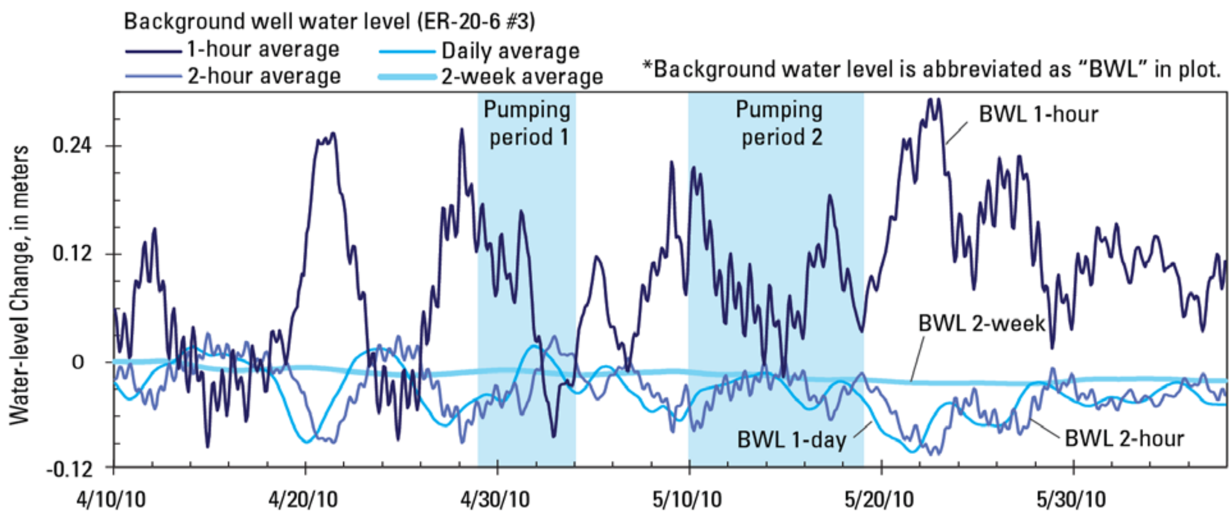

Fig. 5. Moving averages of continuous water levels at background Well ER-20-6 #3 during aquifer testing at ER-EC-11.

multiple wet winters. The amplitude and phase of multiple moving-average time series of background water-level data were used to remove different signal frequencies and were adjusted to match measured and synthetic water levels.

Groundwater evapotranspiration was simulated using continuous water-level data from a background well (Spring Meadows Well) only affected by evapotranspiration. Continuous water-level data exist for the well from 1995 to 1997 (Fig. 6). Water levels were duplicated for each year from 1997 to 2016 to generate a long-term record that is assumed to represent the pattern of water-level change by groundwater evapotranspiration. The amplitude and phase of the groundwater evapotranspiration time series were adjusted to match periodic water levels.

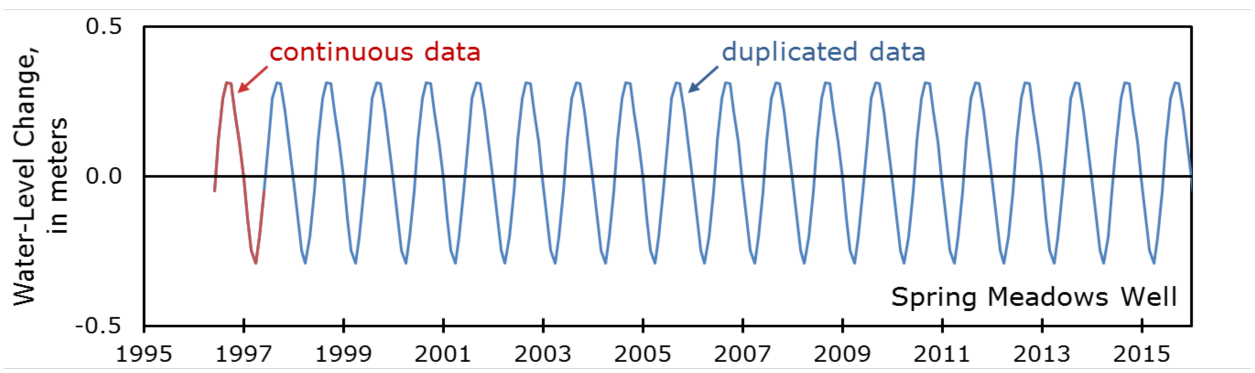

Fig. 6. Continuous water-level data at Spring Meadows Well representing the pattern of water-level change by groundwater evapotranspiration.

Water-level fluctuations due to tidal forces were removed using analytical equations representing theoretical tidal fluctuations (Fig. 7). Tidal forces, which distort the earth's crust through changes in gravitational forces of the Sun and Moon, cause water-level fluctuations in mid-continent wells screened in confined aquifers [13]. Theoretical equations from astronomical and gravitational theory were used to compute earth and gravity tidal forces based on a specified time, and latitude and longitude coordinates within the Harrison [12] model.

Synthetic water levels in WLMs were fit to measured water levels by minimizing the differences with a root-mean-square (RMS) error [9]. Amplitude, scale, and shape were adjusted in each time series that simulated groundwater recharge. Amplitude and phase were adjusted in each time series that simulated environmental water-level fluctuations due to barometric pressure, seasonal climatic trends, and groundwater evapotranspiration. Transmissivity and storage coefficient were adjusted in the Theis models.

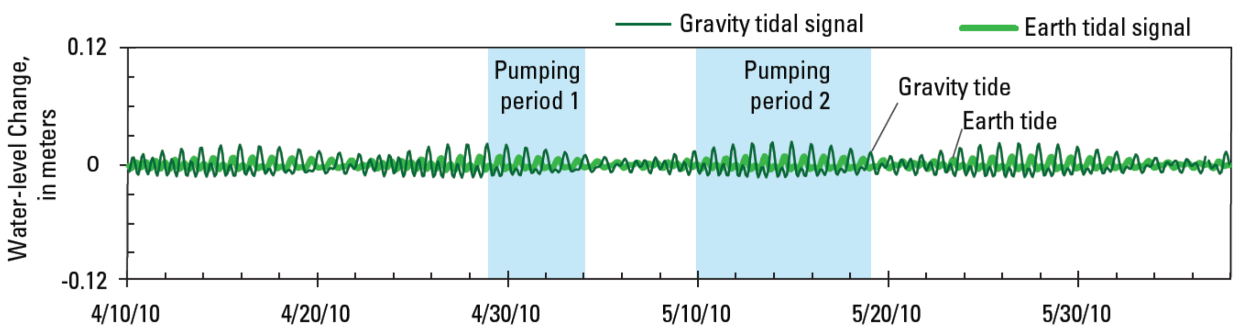

Fig. 7. Computed time series of earth and gravity tides during aquifer testing at ER-EC-11.

RESULTS AND DISCUSSION

Long-Term Trend Analysis

WLMs were used to determine the stresses affecting water-level trends between 1995 and 2016. WLMs are shown for two cases: (1) a well with only steady-state (natural) water-level responses; and (2) a well with transient (pumping) water-level responses.

The water-level trend in well ER-12-1 is representative of recharge in Rainier Mesa (Fig. 8). The Rainier Mesa precipitation record was used with a threshold of 50 percent (1.5 times the long-term mean winter precipitation), based on observable recharge responses to the 1995, 1998, 2005, and 2011 wet winters (Fig. 8A). Measured and synthetic water levels compare favorably in the WLM when two Gamma transforms were used to simulate groundwater recharge in

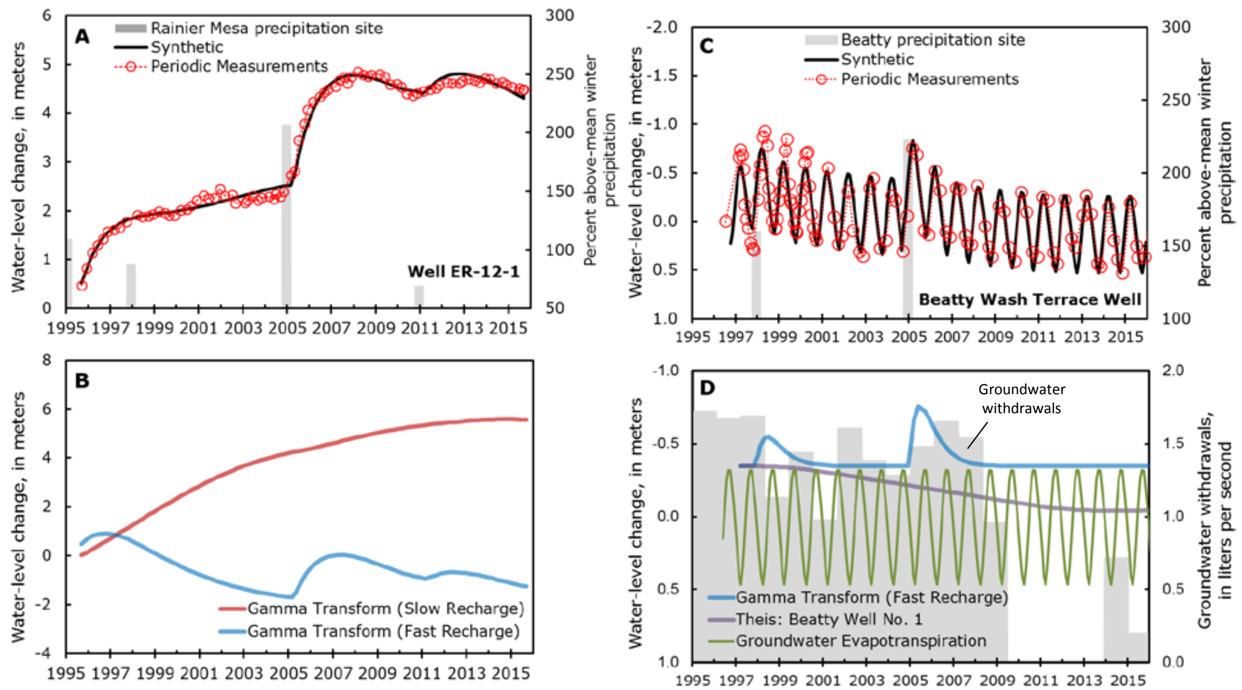

Fig. 8. Water-level model results for Well ER-12-1 and Beatty Wash Terrace Well. (A) Comparison of measured and synthetic water levels in Well ER-12-1; (B) Components of synthetic curve for Well ER-12-1 water-level model; (C) Comparison of measured and synthetic water levels in Beatty Wash Terrace Well; and (D) Components of synthetic curve for Beatty Wash Terrace Well water-level model.

Well ER-12-1 (Fig. 8B). Two Gamma transforms were used to represent fast and slow recharge pathways in a dual-porosity system.

Water levels in Beatty Wash Terrace Well are affected by groundwater pumping in Beatty Well No. 1. Beatty Wash Terrace Well is located near the confluence of Beatty Wash with the Amargosa River and is about 3.2 km northeast of Beatty Well No. 1. Both wells are screened in shallow basin fill. Beatty Wash Terrace Well shows a strong seasonal response to groundwater evapotranspiration because the well is located within a groundwater discharge area (Fig. 8C). Beatty Wash Terrace Well also has strong recharge responses from 1998 and 2005 wet winters superimposed on seasonal groundwater evapotranspiration responses (Fig. 8C). Recharge occurs from the infiltration of streamflow along ephemeral channels during flood events. To determine whether water levels are affected by groundwater pumping, a WLM was used to simulate precipitation (recharge), groundwater evapotranspiration, and groundwater pumping responses. The Theis [10] model estimated a water-level drawdown of 0.3 m from 1997-2015 at Beatty Wash Terrace Well, which is less than the 0.77-m seasonal change from evapotranspiration (Fig. 8D).

Short-Term Drawdown Analysis

A WLM was used to estimate the drawdown in an observation well masked by environmental water-level fluctuations. The drawdown occurred in observation Well ER-20-7 as a result of the ER-EC-11 aquifer test.

Drawdown in Well ER-20-7 was differentiated from environmental fluctuations by fitting synthetic water levels to continuous water-level data in Well ER-20-7. The synthetic curve summed moving averages of continuous barometric pressure in background Well ER-20-6 #3 (Fig. 9A), moving averages of continuous water levels in background Well ER-20-6 #3 (Fig. 9B), earth and gravity tides (Fig. 9C), and Theis models of nearby pumping in Well ER-EC-11 (Fig. 9D). Water levels in background Well ER-20-6 #3 were critical to the WLM because they were affected by tidal potential–rock interaction, barometric pressure, and seasonal climatic trends, similar to observation Well ER-20-7.

Drawdown estimates (Fig. 9E) were the summation of Theis models (Fig. 9D) and residual differences between measured and synthetic water levels (Fig. 9E). Synthetic water levels matched measured water levels with a root-mean-square error of 0.002 m. WLM results indicate that pumping in Well ER-EC-11 induced a maximum water-level decline of 0.07 m in observation Well ER-20-7, which is located about 1,700 m from the pumping well. This compares to weekly fluctuations in Well ER-20-7 of 0.1-0.2 m.

CONCLUSIONS

WLMs are a useful tool for data interpretation to understand environmental and pumping stresses affecting short-term and long-term water-level fluctuations in wells. WLMs can be used to differentiate stresses causing water-level trends and the magnitude of the effect of each stress on the trend. WLMs also can be used to estimate drawdowns in wells where water-level responses to pumping or other applied stresses are masked by environmental water-level fluctuations.

Groundwater-flow conceptualization is dependent on the interpretation of water-level responses to aquifer stresses. For example, water levels may show localized or regional responses to recharge or groundwater pumping, or no response to nearby stresses. Determining water-level responses to stresses provides information on whether the hydrogeologic unit screened in a well is hydraulically connected to or hydraulically isolated from the regional flow system. Misinterpretation or the lack of understanding of stresses affecting water-level trends may adversely impact any study that utilizes the water-level data.

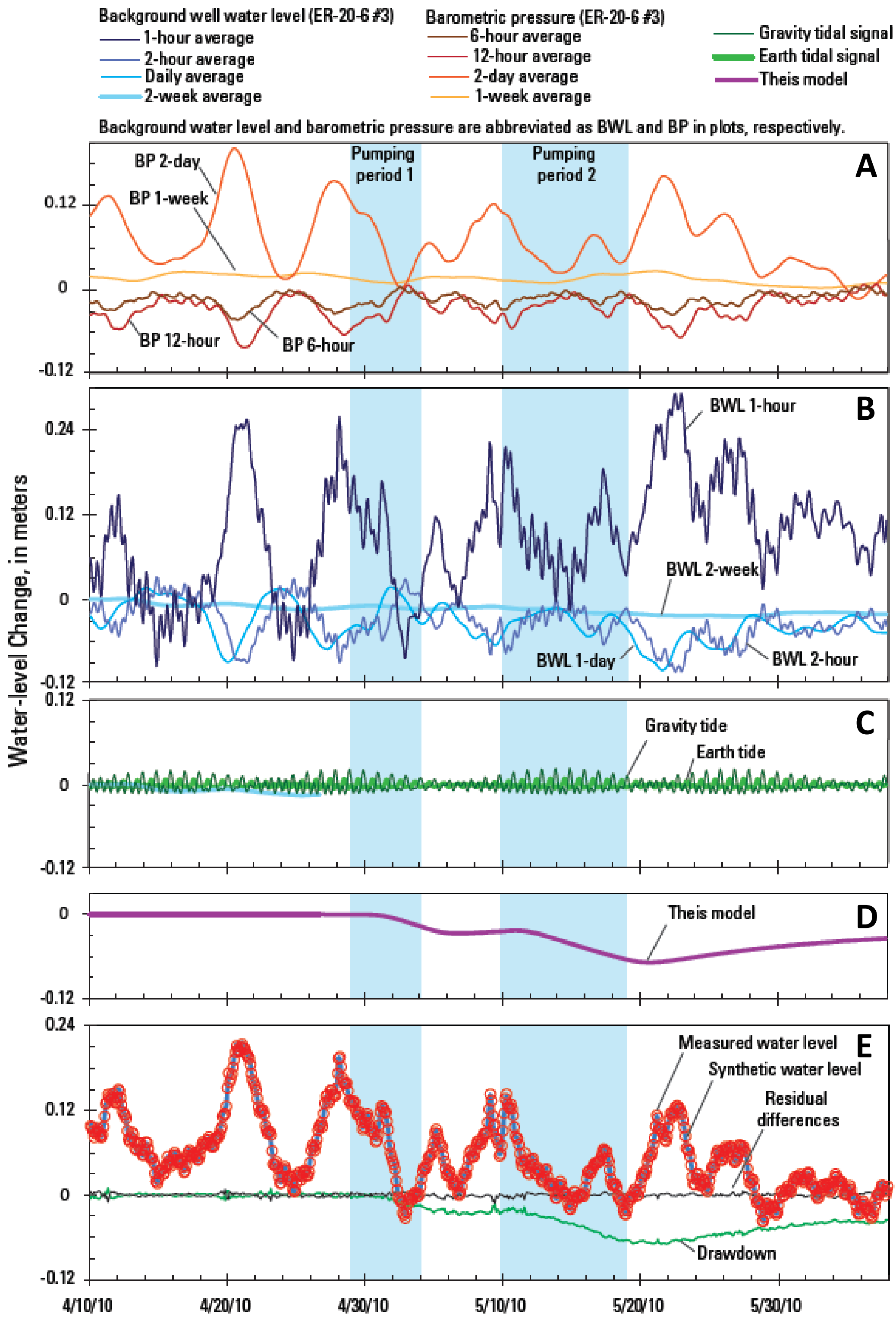

Fig. 9. WLM results for Well ER-20-7. (A) Moving averages of barometric pressure; (B) Moving averages of background water levels; (C) Computed time series of earth and gravity tides; (D) Theis models; and (E) Comparison of measured and synthetic water levels in Well ER-20-7, residuals, and estimated drawdown in Well ER-20-7 in response to pumping in Well ER-EC-11.

REFERENCES

1. U.S. Geological Survey, 2016, USGS Water Data for the Nation: accessed October 2016 at URL http://waterdata.usgs.gov/nwis.
2. National Oceanic and Atmospheric Association, 2016, Air Resources Laboratory / Special Operations and Research Division (SORD): accessed February 2016, at URL http://www.sord.nv.doe.gov/
3. Western Regional Climate Center, 2016, NOAA/NWS Cooperative Observer Network: accessed February 2016, at URL http://www.wrcc.dri.edu/inventory/sodnv.html
4. Community Environmental Monitoring Program, 2016, Community Environmental Monitoring Program data collection program: accessed February 2016, at URL http://www.cemp.dri.edu/
5. Elliott, P.E., and Moreo, M.T., 2011, Groundwater withdrawals and associated well descriptions for the Nevada National Security Site, Nye County, Nevada, 1951-2008: U.S. Geological Survey Data Series 567, 124 p.
6. U.S. Department of Energy, 2011c, Pahute Mesa well development and testing analyses for wells *ER-20-7*, *ER-20-8 #2*, and *ER-EC-11*: U.S. Department of Energy Report DOE/NV–Rev. 1, 163 p., http://www.osti.gov/scitech/servlets/purl/1031914.
7. U.S. Department of Energy, 2010b, Completion report for *Well ER-EC-11*, Corrective Action Units 101 and 102—Central and Western Pahute Mesa: U.S. Department of Energy Report DOE/NV–1435, 146 p., http://www.osti.gov/scitech/servlets/purl/1003755.
8. U.S. Geological Survey, 2016, Nevada Water Science Center Aquifer tests: accessed October, 2016, at http://nevada.usgs.gov/water/aquifertests/index.htm.
9. Halford, K., Garcia, C.A., Fenelon, J., and Mirus, B., 2012, Advanced methods for modeling water-levels and estimating drawdowns with SeriesSEE, an Excel add-In: U.S. Geological Survey Techniques and Methods 4–F4, 28 p.
10. Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, vol. 16, p. 519-524.
11. O'Reilly, A.M., 2004, A Method for Simulating Transient Ground-Water Recharge in Deep Water-Table Settings in Central Florida by Using a Simple Water- Balance/Transfer-Function Model: U.S. Geological Survey Scientific Investigations Report 2004-5195, 49 p.

12. Harrison, J.C., 1971, New computer programs for the calculation of earth tides: Cooperative Institute for Research in Environmental Sciences, National Oceanic and Atmospheric Administration/University of Colorado.
13. Bredehoeft, J.D., 1967, Response of well-aquifer systems to earth tides: Journal of Geophysical Research, v. 72, no. 12, p. 3075–3087.

Approved for public release under Log No. 2016-202.