Santa Paula Basin Hydrogeologic Characterization and Safe Yield Study Ventura County, California

Prepared for **United Water Conservation District**
Santa Paula, California

May 25, 2017

RICHARD C. SLADE & ASSOCIATES LLC
CONSULTING GROUNDWATER GEOLOGISTS

Daniel B. Stephens & Associates, Inc.
3916 State Street, Suite 1A | Santa Barbara, California 93105

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Gregory Schnaar, Ph.D.
Daniel B. Stephens & Associates, Inc.

PROFESSIONAL GEOLOGIST
STEPHEN J. CULLEN
No. 7399
STATE OF CALIFORNIA

Stephen J. Cullen, Ph.D., P.G.
Daniel B. Stephens & Associates, Inc.

Richard C. Slade, P.G., C.E.G.
Richard C. Slade & Associates LLC

Anthony Hicke, P.G., C.Hg.
Richard C. Slade & Associates LLC

PROFESSIONAL GEOLOGIST
ANTHONY
S.
HICKE
CERTIFIED
HYDROGEOLOGIST
No. 858
STATE OF CALIFORNIA

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Foreword from Santa Paula Basin Technical Advisory Committee

This *Santa Paula Basin Hydrogeologic Characterization and Safe Yield Study* (Safe Yield Study) was prepared at the request of United Water Conservation District (United) in 2014 as part of a coordinated effort by the Santa Paula Basin Technical Advisory Committee (TAC) to determine safe yield of the Basin and to explore alternatives that could be implemented to enhance Basin yield. The Superior Court of the State of California for the County of Ventura entered a stipulated judgment to establish pumping allocations and establish a management plan for the Santa Paula groundwater basin (*United Water Conservation District vs. City of San Buenaventura,* original March 7, 1996, amended August 24, 2010 [hereinafter "Judgment"]). The Judgment provided for the creation of a TAC with equal representation from United, the Santa Paula Basin Pumpers Association (SPBPA), and the City of San Buenaventura. Under the Judgment, the TAC is required to monitor hydrogeologic conditions in the Basin and to:

> *"…undertake or cause to be made studies which may: assist in determining the amount of water which can be taken from the Basin without causing overdraft; assist in determining whether surplus or temporary surplus water exists, and if so, to what extent; identify additional replenishment sources for the Basin; develop programs for the conjunctive use and operation of the Basin; and provide such other information as may be useful in developing a management plan for operation of the Basin. The Technical Advisory Committee shall also consider and attempt to agree upon the safe yield of the Basin."*

The goal of this Safe Yield Study was to estimate safe yield of the Basin with available information and using conventional analytical methods. In initiating this Safe Yield Study, the TAC recognized that there may be limitations in such an approach or with available data, but the study could still contribute to informed Basin management until a comprehensive, numerical groundwater flow model is developed. In parallel with planning and execution of the Safe Yield Study, the SPBPA initiated a study to identify additional replenishment opportunities and develop programs for enhancing the operating safe yield of the Basin (Practical Measures/Yield Enhancement Options Study). Together, the Safe Yield Study and Practical Measures/Yield Enhancement Options Study are expected to further the ability of the TAC to guide basin management efforts that will help in "meeting the reasonable water supply needs of the parties, including protection for historic users, without harm to the Basin" as stated in the Judgment.

Respectfully submitted,

Santa Paula Basin Technical Advisory Committee

Executive Summary

Daniel B. Stephens & Associates, Inc. (DBS&A), in association with Richard C. Slade & Associates, LLC (RCS) performed this hydrogeologic investigation and safe yield study of the Santa Paula Subbasin (the Basin) for the United Water Conservation District (UWCD). Basin safe yield was last considered in 2003 by the Santa Paula Basin Expert Group, who concluded that extraction of 26,000 acre feet per year (ac-ft/yr) is sustainable based on "relatively stable or small declines" in groundwater elevation during the study period. However, since that time data have indicated long-term groundwater elevation decline within the Basin despite average annual groundwater extraction of approximately 26,000 ac-ft/yr.

The objectives of this study were to estimate safe yield of the Basin based on available hydrologic data and standard methods and improve conceptual hydrogeologic understanding of the Basin to support the safe yield analysis and groundwater management planning.

The Basin is oriented along a northeast-southwest direction within the Santa Clara River watershed of Ventura County, California. The Basin is located within a Mediterranean-type climatic zone characterized by long dry summers and short mild winters; annual average precipitation ranges from 17 to 19 inches per year along the Basin floor. Surface water is drained from the Basin primarily by the Santa Clara River, which flows from northeast to southwest along the southeastern Basin boundary. Santa Paula Creek, the largest tributary of the river within the contributing subwatershed, drains a large portion of the Sulphur Mountain foothills, the Topatopa Mountains, and Santa Paula Ridge to the north.

Water-bearing formations include Holocene and Pleistocene undifferentiated alluvium and the underlying San Pedro Formation. In general, the alluvium is divided into two basic units: the younger alluvial channel deposits along the Santa Clara River (maximum thickness 80 to 100 feet), and the older alluvium (200 to 300 feet thick). Significant low-permeability layers have been identified within the alluvium, correlated with Holocene alluvial fan deposits. The San Pedro Formation is of Pleistocene age, unconformably underlies all alluvial sediments in the Basin, and is exposed at ground surface along the hillsides north of Santa Paula. The reported thickness of the San Pedro Formation is as great as 4,000 feet.

Aquifer properties (transmissivity, hydraulic conductivity, and storativity) were compiled from previous reports, municipal supply well aquifer tests, and UWCD well database specific capacity values. Near the northeastern Basin boundary hydraulic conductivity of active channel deposits, undifferentiated alluvium, and San Pedro Formation were estimated to be 300 feet per day (ft/d), 126 ft/d, and 118 ft/d, respectively. Near the southwestern Basin boundary, average hydraulic conductivity for the active channel deposits and undifferentiated alluvium were assumed to be 300 ft/d and 94 ft/d, respectively. Structural complexities in the southwestern boundary region (including the Country Club fault and Oak Ridge fault zone) are assumed to at least minimize hydraulic communication and groundwater flow across the southwestern Basin boundary within the San Pedro Formation.

Available Basin storativity values range from 1×10^{-4} to 9×10^{-3}, and these values are considered representative of the confined and/or semiconfined aquifer units. The general direction of groundwater flow is toward the southwest, and the hydraulic gradient was estimated to range from 0.001 to 0.006 feet per foot, based on groundwater elevation contour maps that were prepared with respect to the geologic strata in which the wells are perforated.

Hydrologic groundwater balance estimation was conducted to provide a basis for safe yield determination and to improve understanding of relative Basin inflow/outflows for ongoing groundwater management planning. Groundwater balance component magnitudes were estimated based on available data and using standard methods (e.g., Fetter, 2001; Freeze and Cherry, 1979), consistent with the DBS&A proposed technical approach (DBS&A, 2013). The hydrologic base period used for the groundwater balance was water years 1999 through 2012 (i.e., October 1, 1998 through September 30, 2012). Recharge by deep percolation of irrigation and precipitation was estimated in part by application of an advanced watershed model developed by DBS&A, known as the Distributed Parameter Watershed Model (DPWM). The change in groundwater storage in the Basin was based on statistical trend analysis of 64 wells throughout the Basin.

Average annual groundwater inflows over the base period were estimated to be 37,260 ac-ft/yr, and average outflow was estimated to be 37,313 ac-ft/yr. The principal groundwater inflow component was lateral underflow from the Fillmore Basin (25,244 ac-ft/yr, 68 percent of the total inflow), with the remainder attributable to deep percolation of precipitation (6,549 ac-ft/yr, 18 percent of the total inflow), deep percolation of irrigation (3,879 ac-ft/yr, 10 percent), Santa Paula Creek percolation (1,105 ac-ft/yr, 3 percent), and percolation from wastewater effluent and septic systems (483 ac-ft/yr, 1 percent). The principal outflow component was groundwater extraction (25,505 ac-ft/yr, 68 percent), while the remaining outflow was attributed to natural outflow, that is, the combination of lateral outflow, discharge to surface water, and riparian evapotranspiration (11,808 ac-ft/yr, 32 percent). Groundwater inflow increases significantly in wet years relative to that in dry years; however, the groundwater balance analysis indicates that most of the increased inflow exits the Basin as natural groundwater outflow in the wet years rather than increasing long-term groundwater storage in the Basin. The net decline in the amount of groundwater stored during the hydrologic base period was estimated to be 53 ac-ft/yr, with a possible range of 42 to 1,477 ac-ft/yr based on a sensitivity analysis. Although numbers are reported to the nearest acre-foot per year, the authors are not asserting that level of accuracy in the findings of this Study

Uncertainties in the groundwater balance are due to data limitations and necessary assumptions inherent to Basin-scale hydrologic analyses, and are typical of similar studies in arid and semi-arid environments. Data gaps and limitations include the relatively short base period (fourteen years), limited gage data for Santa Paula Creek and the Santa Clara River, lack of Basin-specific storativity values representative of the unconfined or semiconfined undifferentiated alluvium, and the generally poorly understood conditions that govern outflow to the Mound and Oxnard Forebay Basins. In addition, the DPWM incorporates simplifying assumptions necessary for Basin-scale watershed modeling, including the assumption of constant annual irrigation rates and land use over time during the base period, and homogenous properties (e.g., vegetation, soil-type) within each 295-ft x 295-ft model grid cell.

Annual average safe yield of the Basin was defined as the maximum quantity of water that can be withdrawn annually without causing an undesirable result such as gradual lowering of groundwater levels. Safe yield of a groundwater basin should not be taken simply as the sum of all groundwater inflows; rather, sustainable groundwater extraction is limited to less than long-term annual recharge because of natural system discharge. Therefore, safe yield of the Basin was estimated based on the sum of groundwater inflows minus natural groundwater outflow, which is also assumed equal to the sum of historical groundwater extraction and change in groundwater storage. Groundwater level decline and Basin storativity were identified as the most significant potential sources of error impacting the safe yield estimate. A sensitivity analysis was conducted to calculate an acceptably conservative safe yield range given uncertainty related to those parameters. Based on this analysis, a current safe yield range of 24,028 to 25,463 ac-ft/yr is recommended. Therefore, despite limitations in the groundwater balance, this sensitivity analysis indicates that the range of uncertainty in the resulting safe yield estimate is approximately 1,500 ac-ft/yr (average percent difference of 6 percent).

1. Introduction

At the request of United Water Conservation District (UWCD), Daniel B. Stephens & Associates, Inc. (DBS&A) in association with Richard C. Slade & Associates, LLC (RCS), conducted a safe yield study for the Santa Paula Subbasin (the Basin) located in Ventura County, California (Figure 1). The objectives of the study were to update the safe yield of the Basin based on available hydrologic data and standard methods and to improve hydrogeologic conceptual understanding of the Basin to support groundwater management planning. The safe yield study is being conducted concurrently with an operational study being led by the Santa Paula Basin Pumpers Association. The operational study is evaluating alternatives for augmenting Basin supply and increasing safe yield.

The remainder of this section provides background information and a general Basin description. Section 2 summarizes the results of previous major studies of the Basin that were reviewed as part of this study. Section 3 of this report provides a hydrogeologic description of the Basin. Section 4 provides water balance calculations, including significant groundwater inflow and outflow components. Section 5 presents the methodology and determination of Basin safe yield.

1.1 Background

UWCD is authorized to conduct groundwater management activities within the Basin. In March 1996 a stipulated judgment by the Superior Court of the State of California created a Technical Advisory Committee (TAC) composed of UWCD, the City of Ventura, and the Santa Paula Basin Pumpers Association. The TAC monitors groundwater levels and quality, groundwater pumping, Basin inflow and outflow, changes in stored groundwater, and determines the safe yield of the Basin (UWCD, 2014a).

Basin yield was last considered in 2003 by the Santa Paula Basin Expert Group (SPBEG). The SPBEG reported that the average pumping rate during the base period for their evaluation (1983 through 1995) was approximately 26,000 acre-feet per year (ac-ft/yr), and concluded that this extraction rate is sustainable based on “relatively stable or small declines” in groundwater elevation during the study period (SPBEG, 2003). Since that time, UWCD has documented declines in groundwater levels within the Basin over various evaluation periods (UWCD, 2013a), including recent years (e.g., 1999-2011), and over the longer historical period (e.g., 1944-2005), despite pumping volumes that averaged 26,000 ac-ft/yr. Therefore, the Basin yield analysis is being updated such that future groundwater extractions at the revised value, and under current water balance conditions, would not result in continued long-term decline in groundwater levels.

1.2 Basin Description

The Basin is located in the lower elevations of the 1,613-square mile Santa Clara River watershed (Figure 1). The Basin is located in Ventura County, California, and includes the City of Santa Paula, the town of Saticoy, and portions of the City of San Buenaventura (City of Ventura).

UWCD reports (e.g., UWCD, 2015) typically include two separate Basin delineations (Figure 2):

- Based solely on the extent of alluvial deposits and extending to the approximate boundary with the Sulphur Mountain, South Mountain, and Santa Paula Ridge foothills.

- Based on the Basin Settlement boundary as determined in the March 1996 Superior Court of the State of California stipulated judgment establishing a management plan for the Basin (*United Water Conservation District vs. City of San Buenaventura*, March 7, 1996), which includes the extent of Basin alluvium and extends further northward into the South Mountain and Santa Paula Ridge foothills to include outcrops of additional formations, primarily the San Pedro formation.

For the purpose of this report, the Settlement Basin Boundary is used as the Basin boundary. As defined by the Settlement boundary the Basin is oriented along a northeast-southwest direction and is approximately 10 miles long and 36 square miles in area. The Basin is bordered to the north by the low-permeability bedrock units of the Sulphur Mountain foothills, Santa Paula Ridge, and the Topatopa Mountains, on the south by the South Mountain foothills, on the northeast by the Fillmore Basin, and on the southwest by the Mound Basin and the Oxnard Forebay Basin.

The subwatershed contributing to Santa Paula Basin (excluding Santa Clara River flow from upgradient areas of the watershed) was defined based on geographic information system (GIS) subwatershed delineation data provided by UWCD. The subwatershed has an area of 115 square miles and includes the Santa Paula Creek subwatershed (extending to the Topatopa Mountains) and the Sulphur Mountain foothills to the north of the Basin (Figure 2). The subwatershed is bordered on the west by the Ventura River watershed, on the east and southwest by the remaining portions of the Santa Clara River watershed, and on the southeast by the Calleguas Creek watershed.

Land use within the Basin includes high-slope mountain foothills of Sulphur Mountain and South Mountain with minor agricultural development, significant agricultural areas on the basin floor, and urban developments within the cities of Santa Paula and Ventura and the community of Saticoy. Major agriculture in the Basin includes citrus, avocados, row crops, and strawberries (UWCD, 2013b).

The Basin is located within a Mediterranean-type climatic zone characterized by long, dry summers and short, mild winters. Nearly all precipitation occurs in the winter months. Precipitation rates are variable, and cyclic patterns occur, sometimes with sub-average rainfall over several consecutive winters (droughts). Annual average precipitation rates over the last 30 years (1981-2010) increase moving from south-to-north, averaging from 17 to 19 inches per year (in/yr) along the Basin floor to 36 in/yr at the mountain peaks north of the Basin boundary (Figure 3). The 1890 to 2011 water-year average precipitation for the Basin floor is 17.51 inches (UWCD, 2013e).

The Basin is drained primarily by the Santa Clara River, which flows from northeast to southwest along the southeastern Basin boundary (Figure 2). Santa Paula Creek is the largest tributary of the Santa Clara River within the contributing subwatershed and drains a large portion of Sulphur Mountain, the Topatopa Mountains, and Santa Paula Ridge to the north, reaching its confluence with the Santa Clara River near the eastern Basin boundary.

2. Previous Studies

Various groups within the Santa Clara River watershed have studied hydrogeologic conditions in the Basin. Several previous studies that were reviewed as part of these water balance calculations and updated safe yield determination are summarized in Sections 2.1 through 2.9. In addition to those studies listed below, DBS&A was provided two recent studies in September 2015: (1) a preliminary evaluation of historical changes to the Santa Paula Creek channel and potential effects on Basin recharge (Hopkins, 2015) and (2) an independent underflow assessment between Fillmore and Santa Paula Basins (Bachman, 2015).

2.1 1993 Santa Paula Basin Water Resource Evaluation

Law-Crandall (1993) performed a water resource evaluation of the Basin on behalf of UWCD. A groundwater budget was performed with a base period of 1956 – 1990, which was recognized as a relatively ‘dry’ period. The study concluded that the Basin was recharged primarily by surface-water percolation and subsurface inflow from the Fillmore Basin; most groundwater exited the Basin by extraction, with a lesser amount attributed to subsurface outflow. The average net pumpage demand from the basin was 22,000 ac-ft/yr. The total safe yield of the Basin alluvium was determined to be 20,000 ac-ft/yr based on the Hill method; and it was stated that an additional 800 ac-ft/yr was being “mined” from the San Pedro Formation. From 1956 to 1990, groundwater extraction and drought were estimated to result in a cumulative loss of 27,000 ac-ft of groundwater in storage, and the report concluded that the Basin was likely in a threatened state of overdraft at that time.

2.2 USGS Groundwater/Surface Water Study

This U.S. Geological Survey (USGS) study focused on quantifying surface water/groundwater interaction in the Piru, Fillmore, and Santa Paula basins (Reichard et al., 1999). Field data collected included surface water gaging, groundwater level monitoring from nested wells, water quality sampling and isotopic analysis, and aquifer “slug” tests for hydraulic properties. Analytical modeling was also used to evaluate time series data of shallow groundwater levels and Santa Clara River levels.

Surface water gaging along the Santa Clara River within the Santa Paula Basin from 1993 to 1995 indicated a net surface water gain, and this was attributed to discharge of groundwater from the shallow alluvial aquifer to the river. Eight gaging measurements were conducted, six during releases from Lake Piru (Figure 1) and two during “zero-release” conditions.

Two sets of nested groundwater monitoring wells were constructed within the eastern portion of the Basin; locations are shown on Figure 4, along with hydrographs for each well. For the 03N21W15G01/-02/-03/-04/-05 monitoring well series (referred to as SP-1 in the USGS report) a 120-foot-thick low-permeability unit was observed in geophysical logs from 100 to 220 feet below ground surface (ft bgs). Groundwater level hydrographs for this nested well indicated that the 120-foot-thick low-permeability unit acts as a confining unit and hydraulically separates the shallow alluvial groundwater (50 to 100 ft bgs) from the deeper alluvial and San Pedro Formation units (greater than 250 ft bgs) at this location.

The 03N21W16H05/-06/-07/-08 monitoring well nest (referred to as SP-2 in the USGS report) is located approximately 4,000 feet west of the 03N21W15G monitoring well series (Figure 4). At this location, a 60-foot low-permeability unit was logged from ground surface to 60 ft bgs, and a 20-foot-thick low-permeability unit was logged from 80 to 100 ft bgs. Groundwater level trends for monitoring wells at all depths in this location responded similarly to seasonal pumping patterns.

Aquifer slug tests were conducted at all depths for both of the monitoring well nests in the Basin. Resulting hydraulic conductivity values ranged from 18 to 100 feet per day (ft/d) for depths representative of the alluvial aquifer and from 15 to 68 ft/d for depths representative of the San Pedro Formation (based on formation depths reported by UWCD [2013a]).

Stable isotope analysis of groundwater samples (delta-deuterium and delta oxygen-18) for the deepest interval at 03N21W16H05S, the deepest well at this location (530-500 ft bgs) and 03N21W16H08S, the shallowest well at this location (50-70 ft bgs) reflects recharge from local runoff from mountains to the north. Results of stable isotope analysis for the remaining groundwater samples for both nested wells were consistent with recharge from the Santa Clara River. Radioisotope (tritium and carbon-14) analyses indicated groundwater ages of 300 to 400 years old in the deepest intervals of both nested monitoring wells (Reichard et al., 1999).

2.3 2003 Investigation of Santa Paula Basin Safe Yield

Previous safe yield analysis of the Basin attempted two approaches: (1) Modified Hill Method, which is based on a statistical regression between groundwater levels and annually extracted groundwater volumes and (2) change in groundwater levels over a base period, which compares groundwater levels at the beginning and end of a base period to determine if groundwater extraction has caused a net decline (SPBEG, 2003).

The SPBEG study used 1983 to 1995 as a base hydrologic period, and groundwater pumping over this period averaged 26,000 ac-ft/yr. The Modified Hill Method reportedly did not result in an adequate correlation and therefore could not be used. The study stated that over the base hydrologic period, water level measurements for 14 wells with adequate data indicated an average decline of 4.9 feet, with more pronounced decline in the western portion of the Basin as compared to the eastern portion. However, the authors also stated that the “small amount of drop in water levels indicates that there is no apparent overdraft (i.e., long-term lowering of water levels) in the Basin, with the exception of the very west end of the Basin where it appears that water levels have fallen somewhat over the period which was considered.” Based on this interpretation, the authors concluded that Basin extraction of 26,000 ac-ft/yr is “sustainable” and would not adversely affect the Basin.

2.4 Santa Clara River Flow Percolation Investigation

In August and September of 2010 and 2011 UWCD staff conducted flow gaging of the Santa Clara River to estimate river percolation within the Basin (UWCD, 2013c). UWCD field monitoring in 2011 was more extensive compared to 2010 and provided the primary basis for the UWCD study’s conclusions. Streamflow measurements were collected using a handheld acoustic Doppler velocimeter (Sontek Flowtracker) at transects including an upstream location (Willard Road) and downstream location (Orr Rd) (Figure 5). Pressure transducers were also set at these locations, and flow was then estimated as a function of river stage. Percolation along the 5.1-mile reach of the river was estimated by the difference in upstream and downstream flow, while accounting for inflow from Santa Paula Creek, surface water diversions, and riparian evapotranspiration.

Average river reach percolation for August-September 2011 was estimated to be 4.0 cubic feet per second (cfs) (ranging from a net gain of 2.3 cfs to a net loss of 8.6 cfs). However, UWCD also concluded that the “error bars” associated with the analysis (e.g., due to uncertainty with diversion volumes and evapotranspiration rates) are “larger than the total percolation calculated for the Santa Clara River reach under investigation.” UWCD also acknowledged that river percolation under high-flow conditions remains undetermined.

2.5 Santa Paula Creek Percolation Investigation

UWCD staff conducted streamflow gaging of the lower reach of Santa Paula Creek from April 2011 to February 2012 (UWCD, 2013d). Handheld acoustic Doppler velocimeter (Sontek Flowtracker) measurements were used to estimate creek flow at two locations located approximately 2 miles apart along the lowest portion of the Creek (Figure 5). Maximum stream reach percolation to groundwater was measured to be 6.4 cfs, which was reported to be within the accepted range of error for the methodology. Gaining conditions were also observed on several dates. UWCD reported field identification of seeps along walls of the creek and attributed this seep flow to localized perched water table conditions caused by low-permeability lenses and percolation of irrigation water at a nearby ranch. Significant discharge was also noted in a drain located along the creek channel leading from a city water supply reservoir. Regional groundwater levels were found to be at least 47 feet below the channel elevation. It was therefore concluded that the channel of lower Santa Paula Creek had not intercepted the regional water table and that regional groundwater was not a source of water resulting in gaining conditions along the reach.

2.6 Santa Paula Basin Groundwater Elevation Trend Assessment

UWCD conducted a detailed analysis of trends in historical groundwater levels within the Basin (UWCD, 2013a). Basin wells were assigned to hydrogeologic depth zone classifications after Mann (1959), based on their screened intervals and generalized geologic cross sections:

- Recent (i.e., Holocene) Alluvium (bottom of the well screen less than 110 ft bgs)
- Older Alluvium (screened between 110 to 300 ft bgs)

- San Pedro Formation (upper screened interval starting at greater than 300 ft bgs)
- Older Alluvium and San Pedro Formation (screened across intervals less than 300 ft bgs and extending to depths greater than 300 ft bgs)
- Wells with unknown construction

Hydrographs were generated for 90 wells and plotted on maps for each depth zone classification. Annual high water levels were also determined for 13 selected wet years during the interval 1944 to 2011. Long-term decline among periodic highs were observed for the majority of the wells over the evaluated time periods (Table 1). Shallow alluvial wells located near the Santa Clara River showed the least annual variability, while wells located in the west and central Basin areas perforated in the San Pedro Formation and/or the Older Alluvium showed the greatest declines. Average groundwater level decline over the period 1944 to 2005 was 13.3 feet or 0.22 feet per year (ft/yr). The period 1983 to 1995, used for the previous safe yield estimate (SPBEG, 2003), exhibited an average net decline of 1.6 feet, or 0.13 ft/yr. More recently, the 1997 to 2011 period exhibited an average net decline of 2.4 feet, or 0.17 ft/yr.

2.7 Infiltration Potential of Precipitation Falling on Developed Lands and the Fate of Applied Groundwater Within UWCD

UWCD conducted water balance modeling for developed areas in groundwater basins within UWCD boundaries for the period 2010 to 2012 (UWCD, 2013b). Water balance modeling considered infiltration and deep percolation of applied irrigation water, runoff and infiltration of precipitation, recharge by wastewater treatment plant (WWTP) effluent, and downward leakage through low-permeability units that act to confine certain portions of the UWCD area. For the purpose of this study, the Santa Paula Basin was considered to be uniformly unconfined.

Modeling of precipitation was based on the U.S. Department of Agriculture Natural Resource Conservation Service (NRCS) Curve Number methodology, which provides an empirical approach for estimating runoff based on mapped land use and soil properties. Precipitation water that did not run off was considered to be available for infiltration into the soil. Evapotranspiration, run-on of water from upland areas of the watershed, changes in soil moisture storage, and deep percolation of precipitation past the root zone were not considered.

Estimation of deep percolation of applied irrigation considered salt leaching and percolation based on non-uniformity of water application and was based on a 2010 study of local irrigation practices by the Irrigation and Training Research Center (ITRC, 2010). Leaching requirements (LR), defined as the percentage of applied water needed to leach salts from the root zone, ranged from 5 percent (sod) to 19 percent (avocado), and the area weighted average was 16 percent. Additional percolation was considered based on non-uniformity within irrigation systems, or the distribution uniformity (DU), defined as “the measure of the uniformity with which irrigation water is distributed to different portions of a field” (ITRC, 2010). DU is largely related to pressure differences present within irrigation delivery networks. ITRC selected a DU value of 0.8 to be representative of local agriculture and suggested that irrigation non-uniformity results most often in the deep percolation of water past the root zone. The percentage of “return flow,” or the amount of applied water that percolates past the root zone, considered both LR and DU and was reported to range from 39 to 42 percent for agricultural areas of unconfined basins.

Return flow in developed areas (municipal, industrial, and domestic) considered recharge from recycled water percolation basins, septic systems, and landscape irrigation (assuming an LR of 0.16 and a DU of 0.8). Return flow percentage for developed areas was 64 percent for all three years considered.

2.8 Santa Paula Basin 2012 Annual Report

The 2012 Santa Paula Basin annual report summarizes Basin conditions and collected data, including precipitation, creek flow, diversions, extractions, water quality, and groundwater levels (UWCD, 2015). Extractions for 2012 totaled 25,824 ac-ft/yr, with 96 percent of total pumping assigned to Santa Paula Basin Pumpers Association individual party allocations. Historical annual pumping (1980 to 2012) ranged from 16,710 ac-ft/yr (1983) to 33,453 ac-ft/yr (1990) and averaged 25,699 ac-ft/yr. Groundwater level trends are documented, as discussed in Section 2.5 (UWCD, 2013a). Primary groundwater quality concerns included sulfate, total dissolved solids (TDS), hardness, iron, and manganese, which are elevated in some cases above secondary maximum contaminant levels (MCLs) and/or micro-irrigation plugging hazard indices. Also included within this report are informative maps documenting extractions by individual wells, and the UWCD-delineated groundwater potentiometric surface was shown to extend throughout the Basin and into the bordering Fillmore and Mound basins.

2.9 Ventura County Watershed Protection District Groundwater Section Annual Reports, 2008 to 2013

Ventura County Watershed Protection District (VCWPD) releases annual groundwater section reports that document results of the County's regional groundwater level and water quality monitoring program and data shared by other agencies, including UWCD. According to the most recent VCWPD (2013) report, water quality in the Basin has not changed substantially since 2007. As also documented by UWCD (2013e), TDS, sulfate, manganese, and iron are elevated above their respective secondary MCLs in some locations within the Basin. Water samples from two agricultural wells were analyzed for inorganics (Title 22 metals), and all were found to be below their respective primary MCLs. A hydrograph is presented for Santa Paula Basin "key well" 02N22W02C01S, showing clear water level declines from 2009 to 2013, consistent with recent drought conditions.

For recent annual reports, potentiometric surface maps are presented for the entire Santa Clara River Valley, including the Basin, for fall and spring. VCWPD potentiometric surface maps reflect flow from northeast to southwest within the Basin, and indicate regional groundwater inflow from the Fillmore Basin and groundwater outflow to the Mound Basin and the Oxnard Forebay Basin.

2.10 Confining Bed Evaluation for Santa Paula Basin

Kenneth D. Schmidt and Associates prepared a confining bed evaluation for the alluvial portions of the Basin on behalf of the Santa Paula Pumpers Association (KDSA, 2015). Well completion reports and geophysical electric logs (E-logs) were used to generate maps and a cross section of low-permeability units within the Basin that are interpreted to confine groundwater (reproduced in Appendix A). Two southwest-northeast and three northwest-southeast trending geologic sections were developed. KDSA designated two primary confining units, termed Confining Bed A and Confining Bed B. Confining Bed A was interpreted to extend laterally through the majority of the alluvium within the Basin northwest of the Santa Clara River, with thicknesses of 140 to 300 feet and extending up to or near land surface. Confining Bed A was absent near most of the reach of the Santa Clara River and decreased in thickness approaching the river from the northwest. Confining Bed B was interpreted to be less extensive and deeper (with the top of the bed occurring approximately 300 to 400 ft bgs and 50 to 130 feet thick), and present only in the northeastern section of the Basin (east of R22W and north of Highway 126). Unconfined groundwater was identified in stream deposits above Confining Bed A and beneath or near the Santa Clara River; groundwater in the Basin was interpreted to otherwise be confined.

3. Basin Hydrogeology

Descriptions below have been interpreted largely from work by California State Water Resources Board (SWRB, 1953), Mann (1959), mapping published by Dibblee (1992), Law-Crandall, Inc. (1993), and RCS E-log correlations and well construction projects in the Basin. A map of surficial geology, presented in Figure 6, shows that the northern portion of the settlement boundary roughly aligns with the outcrop of the Saugus Formation (equivalent to the San Pedro Formation, discussed below), except for the narrow canyons where the boundary follows the geologic contact of the shallow alluvium.

3.1 Electric Log Correlations

Geologic cross section diagrams prepared by RCS are presented in Appendix B. The cross sections were developed based on geophysical E-log correlations, and UWCD provided profiles of the ground surface and scanned/digitized versions of E-logs across the Basin using their Rockworks E-log database.

In order to define the subsurface geology throughout the Santa Paula Groundwater Basin, RCS relied on the availability of water well and oil well E-logs in the region and various published reference materials (described in Section 2) that discuss the surficial and subsurface geologic conditions in the region. Many of the available E-logs for oil and gas wells and water wells in the Basin had already been acquired and reviewed by RCS during the course of prior groundwater studies. Further, UWCD maintains an extensive E-log database for the Basin. Thus, the E-log correlations and the E-log correlation network that were independently established by RCS for prior projects in and around the Santa Paula Basin formed the basis upon which the new and enlarged E-log correlation network for this project was eventually developed using the additional data provided by UWCD.

E-log correlation was necessary for RCS to independently corroborate the interpreted depths of geologic contacts in wells throughout the Basin. This correlation work was useful in determining the contacts between the undifferentiated alluvial materials and the San Pedro Formation in various boreholes in the Basin. E-log correlation work also helped define potential offset along the Country Club fault, which helped to estimate the geometry of the outflow boundary (Section X-X' in Appendix B) used for the outflow calculation (Sections 4.7.2).

Key data sources for the available E-logs included:

- California Division of Oil, Gas and Geothermal Resources (CDOGGR), which has subsurface data (and E-logs) from the numerous wildcat and producing oil and gas wells in the several oil fields in the region

- Pacific Section of the American Association of Petroleum Geologists (AAPG), particularly their cross section CS-30 (Hopps et al., 1995)

- UWCD E-log database and construction reports for water wells in the Basin, including those previously prepared by RCS and those prepared by other consultants

- Interpretation of the E-log signatures associated with the key Fox Canyon member of the San Pedro Formation, as derived from Plate 26 in the work by Mann (1959) (discussed below).

Alignments for the cross sections were chosen by RCS based on E-log availability. Two cross section alignments were ultimately chosen: A-A', which is located near the southern portion of the Basin, and B-B', which lies near the northern end of the groundwater basin; both sections trend in a generally northwest-southeast direction, perpendicular to the longitudinal axis of the Santa Paula Basin. Alignments of the cross sections are shown on the Location Map in Appendix B.

As is standard for development of cross sections from interpretation of E-logs, correlation began with deep E-logs, significantly deeper than the depths of interest for the safe yield study. Vital to defining possible key marker beds on the E-logs and to understanding the overall stratigraphy in the region were the basic oil industry data and reports on shallow and deep stratigraphy. Subsurface locations and alignments for the nearby oil fields, namely the Saticoy Oil Field and the South Mountain Oil Field Area Bridge, were also available on the topographic base maps and in literature for the region. These data and records helped provide the perspective of the oil industry professionals on shallow and deep geologic formations in the region and also provided the basic control on the character of the spontaneous-potential (SP) and the resistivity curves on the various E-logs. These oil field data also help establish the depth to the top and bottom (base) of the San Pedro Formation across the region. In addition, a “type log” for the area was used to help define the subsurface geologic contact between the undifferentiated alluvium and the underlying San Pedro Formation.

The distinctive E-log signature of the “main Fox Canyon Sand” (or Fox Canyon Aquifer, as it is commonly known) within the San Pedro Formation was first defined by Mann (1959, Plate 26; defined in a personal communication between John Mann and Richard Slade in the mid-1970s as the Standard Oil Company, Maulhardt Community No. 101-A, in Section 1 of T1N/R22W of the Oxnard Plain). Previous work by RCS geologists in the Santa Paula Basin identified that distinctive signature on the E-log for an oil well named “S.P.S (North) 2,” and this is considered to be the “type log” for the Santa Paula Basin for the purposes of this report.

E-log correlation began with the logs previously correlated by RCS for prior projects in the region, including the type log well S.P.S. (North) 2. The basic character and the changes in the character of the SP and resistivity curves were examined laterally and vertically throughout the Basin. Perforation intervals, the driller’s terminology, and even the color of the sediments (if provided by the driller on a log) were annotated on each available water well E-log, to be used as additional tools to help understand existing conditions and changes in the lithology relative to the E-log signatures.

Key results of correlation work are as follows:

- Correlation of the San Pedro Formation based on E-Log signatures was somewhat problematic due to the unconformable nature of the contact between that formation and the overlying “Qoa, or basal gravels” deposits shown on the cross sections. Deformation and erosion of the San Pedro Formation prior to deposition of the older alluvium deposits define that geologic contact as an angular unconformity. E-log correlation work suggests that the San Pedro Formation beneath the Basin has been deformed by tectonic forces over geologic time. In general, this deformation is expressed as a synclinal-type structure within the San Pedro Formation within the Santa Paula Basin.

This structure in the San Pedro Formation is corroborated by analysis of the outcrop pattern along the northern flank of the basin. In general, ground surface exposures of the San Pedro Formation strata in the low-lying foothills of the Sulfur Mountains are parallel to the alignment of the Santa Paula Basin. The pattern of older sediments outcropping at progressively greater distances from the longitudinal axis of the Basin suggests synclinal structure. Geologic mapping by Dibblee (1992; basis for geologic map presented in Figure 6) shows strike-and-dip measurements in the San Pedro Formation (labeled as the Saugus Formation on the 1992 Dibblee map) that strike parallel to the axis of the Santa Paula Basin and dip toward the axis of the basin at angles on the order of 45 degrees.

- The existence of the Country Club fault is confirmed by the correlation work. Although the offset along the Country Club fault is distributed among numerous fault splays and correlation across the fault is difficult, the estimated total offset along the fault is roughly 500 to 1,000 feet. The geologic materials on the northeast side of the Country Club fault appear to be downthrown relative to those on the southwest side of the fault.

- The base of fresh water (based on interpreted low TDS concentration), as interpreted by E-log correlation work, is shown on both cross sections. In the central part of the Basin, that contact is deeper than the total depth of the two cross sections.

- On the southwestern side of Section B-B’, geologic contacts are shown to truncate against the fault without significant deformation. It may be that the geologic formations have been dragged upward along the fault and a synclinal feature is formed, but definitive evidence for such structure is lacking.

- No evidence for a laterally extensive confining low-permeability layer that extends across the entire Basin has been observed in the E-log data, as discussed in Section 3.3. However, as discussed in Section 3.3, relatively fine-grained deposits are present across much of the Basin at varying depths. Furthermore, available storage coefficients in the Basin are typical of confined or semiconfined aquifers. Therefore, despite the lack of evidence in E-log data for a single confining low-permeability unit that extends across the Basin, it appears that confining or semiconfining layers are present across much of the Basin.

Using the E-log correlation data described above, schematic cross sections were constructed at the interpreted inflow (Section Y-Y') and outflow (Section X-X') boundaries; these cross sections are shown in Appendix B. The simplified sections were created using the E-Log correlations shown on Sections A-A' and B-B' and expanding that correlation work to E-logs in the area of the flow boundary calculations. Although not illustrated on Section X-X', data from Saticoy Well 3 (2N/22W-2H2, projected onto Section X-X') was used to estimate the bottom contact of the San Pedro Formation. For section Y-Y', the "Deepest Well Near Boundary" (Well 3N/21W-1N3) and Well 3N/21W-11F4 (the "Deepest Well in Area") were used to help define the effective depth of the San Pedro Formation for the purposes of the groundwater inflow calculation discussed in Section 4.

3.2 Water-Bearing Units

Major water-bearing formations in the area include the Quaternary alluvium and the underlying San Pedro Formation. In general, the undifferentiated Quaternary alluvium is divided into two basic units: the younger alluvial channel deposits (Holocene alluvium) and the older alluvium (Pleistocene alluvium). The younger alluvium generally consists of young gravel and sand layers deposited by the Santa Clara River; maximum thickness of this unit is on the order of 80 to 100 feet. Underlying the younger river alluvium are alluvial fan deposits (Qht) and older sediments (Qoa) deposited by the ancestral Santa Clara River; together, these units are described as "older alluvium." The thickness of the older alluvium is reported to range between 200 and 300 feet (Mann, 1959). Law-Crandall, Inc. (1993) recognizes two principal facies within the older alluvium: the alluvial fan facies and the fluvial deposits. The alluvial fan facies is reported to consist of alluvial fans and mudflows that lie in the northern and far western portions of the Basin, whereas the fluvial facies reportedly consists of older fluvial deposits. These older deposits are coarser in grain size and, as a result, are considered to be more permeable than the younger alluvium, and they occur largely within the central and southern portions of the Basin.

Water-bearing sediments underlying all younger and older alluvium have been designated as the San Pedro Formation by the California Department of Water Resources (SWRB, 1953) and later by Mann (1959). However, Dibblee (1992) has designated the underlying formation as the Saugus Formation. Work conducted by Law-Crandall, Inc. (1993) supports designating this unit the San Pedro Formation in the Basin, consistent with SWRB (1953) and Mann (1959). In this report, the unit is referred to as the San Pedro Formation.

The San Pedro Formation is of Pleistocene age and unconformably underlies all alluvial sediments in the Basin. San Pedro Formation strata are exposed at ground surface in an east-west direction along the hillsides north of Santa Paula and are shown by Dibblee (1992) to be steeply dipping toward the Basin. Reportedly, the upper portions of the formation consist of continental deposits, whereas the lower portion consists of near-shore marine deposits. The formation is composed of gravel, sand, clay, and poorly consolidated conglomerate and sandstone. Thickness may be as great as 4,000 feet (Law-Crandall, 1993). The water-bearing zones within the San Pedro Formation yield significant amounts of groundwater to wells in the region.

3.3 Low-Permeability Units

Previous investigators have noted the presence of an extensive and laterally continuous low-permeability layer of fine-grained material (clay and silt) in near-surface portions of the alluvial sediments of the Basin (e.g., Reichard et al., 1999; KDSA, 2015).

A laterally extensive confining layer that extends across the entire Basin has not been observed in the E-log data, although there are limitations related to the E-log data. The density of available E-log information is sparse in certain areas of the Basin and the majority of E-logs do not include near-surface data. Water well E-logs available for this Study show resistivity data beginning at depths ranging from 20 ft to 50 ft bgs. For oil well E-logs available for this study, although a couple of logs have data beginning at depths of 80 ft bgs, the remainder of those E-logs begin at depths of 500 ft bgs or greater. The general extent of confining materials observed on E-logs is generally in agreement with the KDSA (2015) findings, although the lateral continuity of the confining layers as illustrated in the KDSA (2015) report is subject to some uncertainty as it is based primarily on subjective interpretations in drillers' logs. Further, KDSA (2015) does not appear to honor the geologic structure of the Basin that is implied by the outcrops and dip angles of the San Pedro Formation on the north side of the Basin.

E-log and driller's log data do support the existence of a high percentage of low-permeability sediment in the alluvial sediments along the northern flank of the Basin and at certain depths in other portions of the Basin, as discussed below. Accordingly, groundwater from a large percentage of the wells in the Basin is considered to occur under semiconfined to confined conditions.

To evaluate whether a thick section of low-permeability sediment (i.e., clay or silt) is continuous in the upper 200 feet of alluvial-type deposits that mantle ground surface across the Basin, RCS evaluated descriptions of the earth materials presented on approximately 220 drillers' logs (i.e., water well completion reports) provided by UWCD. Specifically, RCS analyzed the percentage of low-permeability sediments that were present in the driller's descriptions of the drill cuttings observed at each well. In order to maintain consistency of the analysis from one log to another, a single staff geologist was assigned to interpret the driller's descriptions on each log. The estimated relative percentages of low-permeability sediment (clay and silt) were evaluated in 25-foot depth intervals for each log having the requisite data to a depth of 200 feet. The resulting estimates of low-permeability sediment percentages for each depth interval and the locations for the wells were plotted on a topographic basemap of the area. These maps are presented in Appendix C for each of the selected depth zones.

Drillers' logs are based on subjective interpretations, and therefore the maps of low-permeability sediment percentages are considered illustrative but not quantitative. For example, review of the maps in Appendix C reveals large variability between logs from the same area and depth interval. Generally, high-percentage low-permeability sediment zones (greater than 50 percent) were noted at all depths within the central and western portion of the Basin northwest of the Santa Clara River, whereas the eastern boundary and River deposit areas exhibited generally lower percentages of low-permeability sediment, consistent with KDSA's (2015) findings.

Review of the drillers' logs further indicates that low-permeability sediment zones greater than 50 percent in the shallower intervals (equal to or less than 100 ft bgs) generally tend to correlate with surficial geologic sediments mapped as Holocene alluvial fan deposits (Qhf) by the California Geologic Survey (CGS) (Figure 6), whereas zones with less than 50 percent low-permeability sediment in shallower intervals generally correlate with latest-Holocene stream terrace deposits (Qht) and latest-Holocene alluvial fan deposits (Qhfy), primarily located in the southeastern portion of the Basin, subparallel and adjacent to the Santa Clara River and tributaries. The final low-permeability zone map (Figure 7) was created using those geologic contacts as mapped by CGS (Gutierrez et al., 2008) and is also generally comparable to the extent of confining units as interpreted by KDSA (2015). KDSA (2015) Confining Beds A and B extend to the eastern extent of the Basin, whereas Qhf is not mapped from the eastern portion of the City of Santa Paula to the eastern Basin boundary (Figure 7). In this location the KDSA Confining Beds are located greater than 100 ft bgs (Appendix A).

3.4 Non-Water-Bearing Bedrock

All Tertiary-aged (geologically older) rocks that underlie the San Pedro Formation are generally considered to be non- or low-water bearing for general municipal water supply purposes. Some references refer to these formations as the undifferentiated "Tertiary system."

South of the Santa Clara River, these undifferentiated Tertiary units are comprised, from geologically youngest to oldest, by the Las Posas Sand, the Pico Formation, the Monterey Formation, the Conejo Volcanics, and the Topanga Sandstone. These rocks range in geologic age from the Pliocene to the Miocene, respectively.

The Sespe Formation, which is the oldest geologic unit of the bedrock group, is exposed at land surface in the South Mountain area, just south of the Santa Clara River. The Sespe Formation, along with the stratigraphically higher (younger) units, has been juxtaposed against still younger stratigraphic units (such as the San Pedro Formation) by the Oak Ridge fault. Therefore, that area south of the Oak Ridge fault is deemed not suitable for the siting of water supply wells.

In the hills north of Santa Paula, the undifferentiated bedrock units consist of, from geologically younger to older, the Santa Barbara Formation (Las Posas Sand) and the Pico Formation. These geologic units are of Upper Pliocene-Pleistocene geologic age.

Due to their cemented and/or well-lithified nature, the above “Tertiary unit” rocks possess limited effective porosity and likely contain groundwater only along bedding planes, joints, shears, or fractures. As a result, and because of their structural complexity and low permeability, these rocks are not considered capable of readily yielding groundwater to wells. Moreover, they have a very limited storage capacity, and their ability to provide long-term sustained yields to wells is unpredictable. Thus, these cemented and/or lithified sedimentary rocks are not considered part of the groundwater reservoir within the Santa Paula Basin.

3.5 Groundwater Interaction with Santa Clara River

The Santa Clara River within the Basin exhibits perennial flow and is influenced by releases from Lake Piru (UWCD, 2013c). UWCD reports rising groundwater conditions beneath the river near the Fillmore/Santa Paula boundary (UWCD, 2013c). The Santa Clara River within the Basin has been previously documented as primarily a gaining reach (receiving groundwater discharge) based on stream gaging from 1993 to 1995; however, losing conditions were also observed (Reichard et al., 1999). Surface water gaging reported in the USGS study (Reichard et al., 1999) were not always taken on the same day, and estimated gaining/losing conditions based on these data may be in error because of changing flow rates caused by releases from Lake Piru (UWCD, 2013c).

UWCD stream gaging in 2010 and 2011 measured a range of conditions along the river at different times, including gaining conditions (2.3 cfs) to losing conditions (8.6 cfs), and UWCD concluded that “error bars” associated with the analysis (e.g., due to uncertainty with diversion volumes and evapotranspiration rates) are “larger than the total percolation calculated for the Santa Clara River reach under investigation” (UWCD, 2013c). Similarly, UWCD (2013c) states that during releases from Lake Piru, “the difference between the upstream and downstream flow measurements in Santa Paula is commonly within the ±5 percent error of the method used to measure flow.”

UWCD has stated that percolation under high-flow conditions remains undetermined, but that these conditions exist only over a few days each year. California Department of Water

Resources (DWR) flow data for 1929 to 1932 indicated that more percolation was measured during drier months when flow in the Santa Clara River was lower (UWCD, 2013c).

Groundwater and surveyed surface water elevation data collected adjacent to the Santa Clara River throughout the Basin are sparse, making interpretation of the direction of groundwater/surface water interaction difficult. Available groundwater elevation data collected from monitoring wells located near the Santa Clara River were compared to the surface water elevation of the Santa Clara River nearest to the well. Surface water elevations at each location were obtained from GoogleEarth Pro, which includes digital elevation data of comparable accuracy to digital datasets published by the USGS and other scientific agencies (Rusli et al., 2014).

The USGS-installed depth-discrete monitoring well nest 03N21W15G01/02/03/04/05S is located adjacent to the Santa Clara River in the northeastern portion of the Basin (Figure 4). River stage is greater than observed groundwater elevation at this location, indicating that the river recharges underlying shallow alluvium (Reichard et al., 1999). Analytical modeling relating groundwater elevations at the shallowest interval of the depth-discrete monitoring well to river stage indicated a strong hydraulic connection over a horizontal distance of 300 feet (Reichard et al., 1999). However, further vertical recharge of streambed percolation from the shallow alluvial sediments to deeper production zones of the Basin alluvium is limited in this location by the presence of the 120-foot-thick low-permeability layer from approximately 100 to 220 ft bgs, as noted by the USGS during installation of the monitoring well (Reichard et al., 1999) and consistent with the KDSA (2015) confining-bed interpretation in this location (Appendix A).

The Santa Paula Water Recycling Facility (SPWRF) is located adjacent to the Santa Clara River in the central portion of the Basin. Shallow groundwater elevation data are collected on a monthly basis as a component of the Waste-Discharge Requirement (WDR) monitoring program at the facility, and these data were obtained from WDR annual reporting (GSI, 2016). The nearest SPWRF monitoring well to the river with continuous monitoring data is SPWRF-MW-5, and data from this well are plotted relative to approximate river stage at this location on Figure 4. Groundwater elevations observed at SPWRF-MW-5 have fluctuated above and below the approximate river stage since 2005, indicating that groundwater may discharge to the river during relatively wet periods (e.g., 2005, 2010) and the river may recharge groundwater during dry periods (e.g., 2015).

SPWRF annual compliance reports (FugroWest, 2011; GSI, 2016) consistently report net groundwater flow toward the west and away from the river (indicating river recharge to groundwater); however, few monitoring wells at the facility are located between the river and the percolation ponds to constrain the estimate of groundwater flow in this area, and localized mounding conditions could result in radial groundwater flow away from the percolation ponds, including toward the river. The SPWRF facility is located in an area mapped with a thin-to-absent confining layer (Appendices A and C; KDSA, 2015), and therefore, there is likely a direct connection between the saturated river alluvium and deeper production zones in this location.

Low-permeability confining units are generally absent along the remaining reach of the Santa Clara River in the Basin (Appendices A and C; KDSA, 2015). Three shallow monitoring wells (03N21W32C-a/b/c) are located adjacent to the river in the middle portion of the Basin, approximately 1 mile northeast of the river's exit from the Basin into the Oxnard Forebay (Figure 4). At this location groundwater elevations are generally slightly greater than river stage during the majority of the period of record of the available data (1991-2014), other than during the greatest extended drought periods (i.e., early 1990s, 2012-2014), indicating that shallow groundwater discharges primarily to the river in this location. It should be noted, however, that these wells are located near the Freeman Diversion Dam, which exhibits a degree of control over groundwater elevations in the shallow stream-channel alluvium in the area.

In summary, available data indicate that river stage is greater than groundwater elevation in the eastern portion of the Basin; however, recharge to the deep production zones may be limited by the presence of low-permeability strata that separate shallow alluvial groundwater from deeper alluvial zones and the San Pedro Formation. Moving toward the southwest, low-permeability strata are thin or absent, allowing for direct connection of shallow saturated alluvium and deeper zones. At the SPWRF, groundwater elevations fluctuate above and below the approximate river stage, whereas nearer to the river's exit from the Basin at the location of 03N21W32C-a/b/c, groundwater elevations appear to be slightly greater than river stage throughout the majority of the available period of record.

3.6 Aquifer Transmissivity, Hydraulic Conductivity, and Storativity

RCS reviewed available reports from municipal supply well pumping tests and specific capacity data available in the UWCD GIS database to compile data regarding Basin transmissivity, hydraulic conductivity, and storativity (Appendix D).

3.6.1 Specific Capacity Data

The UWCD GIS well database lists specific capacity values for a number of wells in the Basin. As reported by UWCD, the database was originally constructed by the USGS and has been only minimally updated. Specific capacity values were primarily derived from water level and pumping data listed on drillers' logs, and therefore the dataset is subject to the typical uncertainty associated with such logs.

Based on these data, transmissivity values (T) were calculated using the empirical relationship:

$$T = X * [\text{Specific Capacity}] \qquad [\text{Eq. 3-1}]$$

The value of X is dependent on the type of aquifer: 1,500 for unconfined aquifers, 1,750 for semiconfined aquifers, and 2,000 for confined aquifers (Driscoll, 1986). For this equation, specific capacity must be reported in gallons per minute per foot of water level drawdown (gpm/ft ddn) and the resultant T is in units of gallons per day per foot (gpd/ft). RCS assigned each well a value for X based on the perforation intervals in the data set compared to RCS's subsurface hydrogeologic interpretations. Wells perforated only in undifferentiated alluvium were assumed to be unconfined (X=1,500), whereas wells perforated in both the undifferentiated alluvium and the San Pedro Formation were assumed to be semiconfined (X=1,750), and wells perforated within the San Pedro Formation only were assumed to be confined (X = 2,000).

After transmissivity was determined, the transmissivity was divided by the total listed perforated length for each well (assumed to be continuous between the reported top and bottom of perforation information) to provide an estimate of lateral hydraulic conductivity. By dividing the transmissivity equally among the perforated sections in a well, this method of estimation assumes that each of the water-bearing zones perforated by the well have equal hydraulic conductivities.

Table D-1 (Appendix D) presents specific capacity-derived lateral hydraulic conductivity values for the geographic areas of the Basin based on the specific capacity data available in the UWCD database. Basin areas (i.e., Santa Paula Creek Area, East Santa Paula Basin, Middle Santa Paula Basin, Saticoy Area, West End Santa Paula Basin) as defined by UWCD are shown in Appendix E. Large variability in lateral hydraulic conductivity values is observed within the Basin areas:

- For the Santa Paula Creek/East Santa Paula Basin area, hydraulic conductivity ranges from 11 to 4,086 gallons per day per square foot (gpd/ft^2), with a geometric mean value of 509 gpd/ft^2.

- For the West End Santa Paula Basin/Saticoy Area, hydraulic conductivity ranges from 158 to 1,330 gpd/ft^2, with a geometric mean of 740 gpd/ft^2.

- For the Middle Santa Paula Basin area, the range is 36 to 1,900 gpd/ft^2, with a median of 459 gpd/ft^2.

- For the fault area/south, the range is 30 to 1,750 gpd/ft^2, with a geometric mean of 240 gpd/ft^2.

Across all geographic areas of the Basin, the lateral hydraulic conductivity values for the different units are:

- Undifferentiated alluvium: Values range from 36 to 4,086 gpd/ft^2 with a geometric mean of 489 gpd/$ft^{2.}$
- San Pedro Formation: Values range from 84 to 1,333 gpd/ft^2, with a geometric mean of 508 gpd/ft^2.
- Wells perforated within both formations: Values range from 11 to 1,377 gpd/ft^2, with a geometric mean of 177 gpd/ft^2.

City of Santa Paula Well No. 12 was constructed in 1991 and has louvered perforations placed continuously between the depths of 260 feet and 700 feet. Based on these depths, RCS interprets that for the total 440 feet of louvers in this well, 40 percent are within the undifferentiated alluvium geologic materials and the remaining 60 percent are within the San Pedro Formation. As part of RCS's work for the City of Santa Paula in 1995, available specific capacity test data that existed then for City of Santa Paula Well No. 12 were summarized. Specific capacity measurements from the years 1991 and 1992 were available for City of Santa Paula Well No. 12 for seven pumping rates ranging from 1,170 gallons per minute (gpm) to 4,000 gpm; the duration of each of the pumping periods is unknown. Based on the geometric mean of those data, and using Equation 3-1, a transmissivity value of 269,300 gallons per day per foot (gpd/ft) was derived for the seven pumping rates. Because no depth-discrete pumping (spinner log) information is available, no reliable method for determining the separate transmissivities of the alluvium and the San Pedro Formation is possible. For this reason, hydraulic conductivity values for this well were not included as part of the Basin inflow calculation.

3.6.2 Supply Well Aquifer Test Reports

Transmissivity, lateral hydraulic conductivity, and storativity values were also compiled from available municipal and irrigation supply well aquifer test reports (Table D-2). Available well testing reports included City of Ventura Saticoy Wells No. 2 and No. 3, City of Santa Paula Well Nos. 12, 13, and 14, and Farmers Irrigation Company (FICO) Well Nos. 10 and 12. Average hydraulic conductivity values were calculated for each well test and ranged from 588 to 1,130 gpd/ft^2. Storativity (S) values were calculated from aquifer tests of those supply wells for which a separate observation well was available to be monitored. Resulting S values ranged from 10^{-4} to 9×10^{-3} (Table D-2).

Representative specific yield values for unconfined aquifers can be difficult to determine from standard aquifer tests due to the effects of "delayed drainage" (Kasenow, 2001). To adequately determine the specific yield of an unconfined aquifer, the aquifer test must be sufficiently long to overcome delayed drainage; a pumping test continuing for multiple days may be required (Kasenow, 2001). Hence, aquifer tests for wells in unconfined aquifers in the Basin would likely display storativity values consistent with semiconfined to confined conditions due to the relatively short durations of those tests (i.e., generally ±24 hours).

Review of data and information from previous aquifer tests are discussed in the following subsections. Locations for each of the wells discussed below are highlighted on Figure 2.

3.6.2.1 City of Santa Paula Well No. 13.

This well was subjected to a four-point step drawdown test and a subsequent 29-hour constant rate pumping test immediately following its construction in December 1995. The well was provided with casing to a depth of 690 feet and contains Moss louvers between the depths of 320 feet and 350 feet and between 400 feet and 670 feet. Based on the step test rates of 1,350 to 2,800 gpm, the calculated short-term specific capacity values for this well ranged from 118 gallons per minute per foot of water level drawdown (gpm/ft ddn) at the higher step rate to 134 gpm/ft ddn at the lower step rate (the static water level was at a depth of 84 feet).

Based on pumping the then-new well at 2,400 gpm for a continuous period of 29 hours, the longer-term specific capacity was calculated to be 121 gpm/ft ddn. Groundwater pumped by this well could be considered to occur under confined aquifer conditions for three reasons: (1) the well is considered to be perforated in sediments of the San Pedro Formation, (2) water levels were measured to be 236 feet above the depth to the uppermost perforations, and (3) clay materials were observed in the drill cuttings in the portion of the borehole above the perforated interval in this well. As a result, the theoretical transmissivity of the aquifers perforated in this well could be estimated using the empirical relationship of Equation 3-1; the resulting transmissivity value for this well is 212,000 gpd/ft.

Using water level drawdown data from the constant rate test of this well, a transmissivity value of 254,000 gpd/ft was determined for the early-time data (the initial 100 minutes of pumping), whereas a transmissivity value of 522,000 gpd/ft was calculated for the late-time data (after the initial 100-minute pumping period); the water level drawdown curve for this test appeared to change its slope after 100 minutes of continuous pumping. This change in slope (or “flattening” of the time drawdown curve) could suggest that the cone of depression created during the pumping test reached a recharge boundary or is being affected by a leaky aquitard. Graphical analysis of the water level recovery measurements for this pumping well revealed a transmissivity value of 268,000 gpd/ft.

During this pumping test of City Well No. 13, water levels were also manually measured in two nearby wells: City Well No. 11 (located 760 feet south of Well No. 13) and Farmers Irrigation Company (FICO) Well No. 10 (located 640 feet north of Well No. 13). Curve analysis of water level drawdown data in City observation Well No. 11 revealed a slight decrease in slope in the water level drawdown data at approximately 150 minutes into this pumping test; similar analysis of the water level drawdown data in FICO Well No. 10 showed a slope change at approximately 100 minutes. Similar to the calculations performed for water level drawdown data in the pumping well (City Well No. 13), evaluation of early- and late-time data revealed the following transmissivity values:

- Early-time drawdown data: 285,000 gpd/ft in City Well No. 11 and 491,000 gpd/ft in FICO Well No. 10
- Late-time drawdown: 759,000 gpd/ft in City Well No. 11 and 734,000 gpd/ft in FICO Well No 10.

Notably, because drawdown did occur in the two nearby water level observation wells during the 29-hour pumping test of City Well No. 13, calculations could be made of aquifer storativity. Resulting storativity values were:

- City Well No. 11: 4.1×10^{-4} and 2.36×10^{-6} using early- and late-time data, respectively
- FICO Well No. 10: 4.3×10^{-6} and 7.8×10^{-5} using early- and late-time data, respectively

3.6.2.2 City of Santa Paula Well No. 14.

Immediately following its construction in February 1997, a 4-point step drawdown test, followed by a 26½-hour constant rate pumping test, were conducted on this well. The well is cased to a depth of 820 feet and was provided with Moss louvers continuously between the depths of 370 and 800 feet. Step test rates ranged between 2,255 and 3,454 gpm, and short-term specific capacity values in the range of 171 to 200 gpm/ft ddn were calculated; the static water level was at a depth of 58 feet at the date of the test.

The 26½-hour constant rate test was conducted at a rate of 3,000 gpm, and a longer-term specific capacity for the then-new well was calculated to be 162 gpm/ft ddn from these data. A theoretical transmissivity value for the aquifers perforated by this well, using Equation 3-1, was calculated to be 344,000 gpd/ft for confined aquifer conditions. Using the standard Theis and Cooper-Jacob solutions, transmissivity values of 285,000 gpd/ft and 267,000 gpd/ft, respectively, were calculated in the referenced report using water level drawdown data from the pumping well. Using the short-term (3 hours) water level recovery data, the Theis solution revealed a transmissivity value of 300,000 gpd/ft. Because no nearby wells were available to be used as additional water level observation wells during the pumping test of City Well No. 14, storativity could not be calculated from this test.

3.6.2.3 Saticoy Well No. 2 (Well No. 2W/22W-2K9)

This well, which was constructed to a depth of 420 feet, was interpreted by the well consultant (Staal, Gardner & Dunne, 1988) to have encountered “older alluvium” from ground surface to a depth of 130 feet and then strata of the San Pedro Formation from 130 feet to the total drilled pilot-hole depth of 430 feet. A 4-point step drawdown test was performed in December 1987 at rates of 550 gpm, 1,100 gpm, 1,650 gpm, and 2,200 gpm.

Short-term specific capacity values for this test ranged from 35.9 to 23.6 gpm/ft ddn (the static level was at 18 feet). The 24-hour constant rate test was at 2,200 gpm, and resulted in a specific capacity for the then-new well of about 23 gpm/ft ddn.

During the testing, water levels were monitored in the new pumping well and in an on-site water level monitoring well. Transmissivity values provided in the February 1988 report were 111,700 gpd/ft and 109,600 gpd/ft, depending on method of analysis, for water level drawdown data in the monitoring well, 170,600 gpd/ft for drawdown data from the pumping well, and 135,100 gpd/ft for recovery data from the pumping well and monitoring well. This results in a geometric mean transmissivity value of approximately 129,600 gpd/ft.

3.6.2.4 Saticoy Well No. 3 (Test Well; tentative Well No. 2N/22W-2K12)

This test well was drilled to a depth of 1,005 feet and cased to a depth of 985 feet, with 2-inch-diameter PVC casing; perforations were interspersed with blank casing between the depths of 235 feet and 985 feet. The units interpreted by the site consultant (FugroWest, 1999) were the

"Mugu Aquifer" of the "Upper Aquifer System" (UAS) from 250 to 290 feet and the "Hueneme Aquifer" of the "Lower Aquifer System" (LAS) from 300 to 1,004 feet.

3.6.2.5 Saticoy Well No. 3

Drilled in late 2012 to replace existing Saticoy Well No. 2, this new water supply well was constructed to a depth of 662 feet. Johnson wire-wrapped well screen was placed at the following depths: 312 to 392 feet, 422 to 502 feet, and 512 to 652 feet. The cement sanitary (annular) seal was set to a depth of 251 feet. A step drawdown test conducted in November 2012 was performed at rates ranging from 1,023 gpm to 4,030 gpm and resulted in short-term specific capacity values for the new well in the range of 91.9 to 68.2 gm/ft ddn, respectively (the pre-test static water level was at a depth of 17 feet). The project consultant, Hopkins Groundwater Consultants Inc (Hopkins, 2013) also reported that a 24-hour constant rate pumping test was performed at a rate of 2,990 gpm and resulted in a specific capacity for the new well of 71 gpm/ft ddn. Various analytical methods used by Hopkins identified aquifer transmissivity values in the range of 197,900 to 227,500 gpd/ft. Evaluation of early-time data by Hopkins from a nearby water level observation well (Alta Mutual No. 9, at a distance of 791 feet) resulted in storativity values in the range of 0.0012 to 0.00096. The average of all data sets for transmissivity was 234,000 gpd/ft, whereas the averages of all Saticoy Well No. 3 data sets were transmissivity of 203,000 gpd/ft and storativity of 0.001.

3.6.2.6 Farmers Irrigation Company (FICO) Well 12 (3N/21W-12F7)

Pumping test data were analyzed by UWCD for a step test performed in FICO Well 12. Pumping was performed at rates of 2,000, 3,000, and 4,000 gpm, each for a continuous period of four hours. Water level drawdown data were analyzed by UWCD using curve-fitting software and a variety of analytical solutions, and ultimately resulted in transmissivity values in the range of approximately 183,000 gpd/ft and 290,500 gpd/ft.

Following that pumping test, an "unplanned" pumping period occurred in nearby FICO Well 11 which induced drawdown in FICO Well 12, and water level drawdown data were collected during that pumping period. UWCD also analyzed those data, resulting in a transmissivity value of 276,600 gpd/ft. Ultimately, UWCD suggested that a transmissivity of 290,500 gpd/ft (derived from data collected during the unplanned pumping period of FICO Well 11) was representative of site conditions. Because FICO Well 12 was a water level observation well during the "unplanned" pumping of FICO Well 11, those data were used by UWCD to also determine a storativity value of 1.18 x 10^{-3}.

3.7 Spinner Log Results

Results of known spinner logs (i.e., dynamic flow surveys) previously performed in wells in the Basin are available for City of Santa Paula Well No. 13 (constructed in 1995, with perforations from 320 feet to 380 feet and from 400 feet to 670 feet) and for City Well No. 14 (constructed in 1996 with perforations from 370 to 800 feet). Those results were discussed in separate reports by RCS (in January 1996 and April 1997, respectively), that summarized the drilling, construction, and testing of those two City wells. Spinner log testing confirms that a significant portion of the flow into the tested wells originates from the deeper perforations within the San Pedro Formation and therefore supports the inclusion of underflow into the Basin of the San Pedro sediments.

The spinner log for City Well No. 13 was conducted by Welenco Inc in December 1995, just prior to the termination of the constant rate pumping test of this well (at the time of the survey, the pumping rate was 2,437 gpm). Estimates were made of the groundwater inflow into the upper section of perforations as a group, along with inflow estimates into each successive 45-foot depth interval in the lower section of perforations (from 400 feet to 670 feet). The spinner log revealed the following information regarding inflow rates and depths:

- About 16 percent (386 gpm), of the pumping rate originated from the uppermost perforated interval in the well (between the depths of 320 and 380 feet); these perforations are interpreted to derive water from the undifferentiated alluvial sediments.
- The remaining 84 percent (2,051 gpm) of the pumping rate originated from the lower perforations in the well, which was interpreted to derive groundwater from the San Pedro Formation.

These spinner test data for City Well No.13 were used to determine the transmissivity values for the undifferentiated alluvial deposits and the San Pedro Formation. Applying the relative percentages described above, the transmissivity is 43,200 gpd/ft for 60 feet of perforations in the undifferentiated alluvium and 226,680 gpd/ft for 270 feet of perforations in the San Pedro Formation.

The spinner survey of City Well No. 14 was conducted by Barbour Well Surveying Corporation near the end of its constant rate pumping test in February 1997; the recorded pumping rate was 3,005 gpm at the time of the survey. Reported groundwater inflow percentages and rates were as follows:

- 13 percent (392 gpm) from the 370- to 470-foot depth of perforations
- 74 percent (2221 gpm) from the 470- to 680-foot depth zone of perforations
- 13 percent (392 gpm) from the 680- to 800-foot zone of perforations

These data suggest that flow from the San Pedro Formation is a key contributor to the total flow rate in City Well No. 13 (City Well 14 is perforated entirely within the San Pedro Formation). Further, it is clear that the contribution from the deeper perforated zones in these wells is not as great as the contribution from the shallower perforated zones. While these results are highly dependent on the flow rate at the time of the test and the duration of pumping, the data suggest that groundwater availability (in terms of pumping rates) from these deeper zones in the San Pedro Formation may diminish with increasing depth. Therefore, while constructing wells deeper than 800 to 1,000 ft bgs in the Basin may be feasible (based on E-log interpretation of the base of fresh water), these spinner test data suggest that the flow rates from those deeper zones may be limited and the additional depth therefore may not greatly increase the potential capacity of a well.

3.8 Groundwater Flow Direction and Gradient

RCS created water level elevation contour maps for the Basin using water level data provided by UWCD in combination with water level data available from the California DWR’s CASGEM website (CDWR, 2014). Based on water level data in the UWCD database, depth to water in the Basin typically ranges from 35 ft bgs (25th percentile) to 86 ft bgs (75th percentile), with a median of 53 ft bgs.

Water level data for the years 2000, 2010, and 2012 were examined for wells with data available within 10 days before or after April 1 of each of those years. These years were chosen as they represent the 25th, 50th, and 75th percentile rainfall years (Section 4). April was chosen because it is near the end of the rainy season and occurs before abundant pumping for irrigation might begin in the Basin. Further, water level data for wells in the CASGEM database typically display water level data around the April 1 date, due to the requirements of CASGEM. Wellhead elevation for each well was obtained from the UWCD database.

Available perforated intervals for each well in the water level database (provided by UWCD) for this analysis were derived from GIS data files. Those data files list only the shallowest perforated depth and the deepest perforated depth for each well. They do not include the discrete perforated intervals in each well (i.e., it is unknown whether or not the wells have continuous perforations between the reported shallowest and deepest perforated depths, or if there are blank zones within the listed perforated interval). These perforated intervals were used to evaluate which geologic formation(s) are likely perforated by the well; this was generally accomplished by comparing the depths below ground surface to the geologic map and RCS cross sections. Wells with no listed perforated intervals, but with depths that were considered to cross formation boundaries, were considered to be indeterminate and were not used for creating groundwater elevation contour maps.

As part of the groundwater elevation contour map development process, RCS initially plotted a series of five maps for each of the three water years (2000, 2010, and 2012). Each set of five contour maps was constructed as follows:

- *Map 1.* All data in the data set were plotted, regardless of the depth of the perforations. For nested monitoring wells such as USGS SP-1 (03N21W15G01/-02/-03/-04/-05), water level data from the discrete zone perforated in the undifferentiated alluvial materials were used.

- *Map 2.* Water level data for wells considered to be perforated solely within the undifferentiated alluvium were plotted. Some of the wells in the database have perforations that include both the lower portions of the undifferentiated alluvial sediments and the upper San Pedro Formation; these wells were excluded.

- *Map 3.* For this map, water level data for two types of wells were used: wells considered to have perforations solely in the San Pedro Formation and wells with perforations that cross both undifferentiated alluvium and the San Pedro Formation (in a number of cases, wells perforated across this boundary had a majority of the perforations within the San Pedro Formation).

- *Map 4.* This map is the same as Map 2 (water level data for wells perforated within the undifferentiated alluvium), except that wells perforated across the undifferentiated alluvium/San Pedro boundary were also included.

- *Map 5.* Water level data for wells considered to be perforated strictly within the San Pedro Formation were plotted (wells perforated across the undifferentiated alluvium/San Pedro boundary were excluded).

Ultimately, only Maps 1, 2, and 3 were retained, and only Maps 2 and 3 were used for the determination of hydraulic gradients (Appendix F). Variations in water level elevations and contour patterns between Maps 2 and 4 were not great, but localized anomalies in the contour data resulted in the decision to exclude Map 4. In addition, water level data for Map 5 were very sparse, and therefore the limited contours generated for this map were determined to be unreliable.

To create the contour maps, grids were calculated for each well set using natural neighbor interpolation methods and GIS software. From those grids, contour lines of equal water elevation were plotted in 5-foot contour intervals. The resultant computer-generated water level elevation contour data were then truncated at any location where the contoured data intersected known outcrops of geologic materials other than the San Pedro Formation.

Contour data for all the maps created reveal a groundwater barrier in the western and particularly the southern portions of the Basin (illustrated by a steepening of the water level elevation contours). This barrier appears to exist in the general vicinity of the Country Club fault, as shown on the geologic map by Mann (1959), and as also shown herein on Cross Section A-A' (Appendix B). This barrier appears to be in approximately the same area in which the settlement boundary crosses the Santa Clara River and is otherwise located generally north of the settlement boundary. Subsurface geologic and/or geophysical (E-log) evidence for this fault extending east of Cross Section A-A' was not found by RCS. However, the contour data in the area east of Cross Section A-A' suggests that the barrier extends to the south/southeast of the A-A' cross section alignment toward the Santa Clara River and South Mountain.

Groundwater gradients were calculated for each of three contour map dates (April 2000, April 2010, and April 2012) and for both Maps 2 and 3. Four horizontal hydraulic gradients (feet of groundwater elevation change per foot of horizontal distance [ft/ft]) were then calculated for each map: two on the upgradient side of the inflow boundary, for distances of 5,000 lineal feet and 10,000 lineal feet, and two on the upgradient side of the outflow boundary, for distances of 5,000 lineal feet and 10,000 lineal feet. The gradient calculation locations and the calculations themselves are shown on the groundwater elevation contour maps (Appendix F). The general direction of groundwater flow is toward the southwest. Horizontal hydraulic gradients ranged from 0.001 to 0.004 ft/ft for April 2000, 0.002 to 0.006 ft/ft for April 2010, and 0.002 to 0.006 ft/ft for April 2012.

3.9 Vertical Gradient Evaluation

Two depth-discrete monitoring wells have been identified within the Basin for evaluation of vertical groundwater gradients; locations and hydrographs for each well are shown on Figure 4.

Well cluster 03N21W16H05S/07S/08S (identified as SP-2 by the USGS [Reichard et al., 1999]) displays obvious differences in water levels between the alluvium and San Pedro. RCS calculated the vertical gradient for the interval from the bottom of the alluvium (well -16H07S) to the shallow San Pedro (well -16H06S, see Appendix D). In all cases, the gradient is downward. The average gradient is 0.0050 based on the water level data from April 2000, 2010, and 2012 and 0.0095 based on the water level data from October 2000, 2010, and 2012.

Well cluster 03N21W15G01S/02S/03S/04S/05S (identified as SP-1 by the USGS [Reichard et al., 1999]) shows minor differences in water levels between the alluvium and the shallow San

Pedro formations as compared to 03N21W16H05S/07S/08S (Figure 4). Gradient calculations for April 2000 and 2012 indicate an upward gradient from the San Pedro (well -15G03S) to alluvium (well -15G04S), whereas those for April 2010 show a relatively small downward gradient. The average gradient for the three April calculations is 0.0001 (upward gradient). For the October 2000, 2010, and 2012 water level measurements, relatively small downward gradients are calculated, and the average is 0.0004.

3.10 Groundwater Quality Character

The groundwater quality character in the Basin was identified by analysis of the general minerals (in equivalents per million), including key cations (calcium, magnesium, and sodium) and key anions (bicarbonate, sulfate, and chloride). Stiff water-quality pattern diagrams were prepared for groundwater sample results previously obtained by others from representative wells. Stiff diagrams are recognized as being a useful method for identifying the character of the groundwater in each well in a groundwater basin and for allowing comparison of the groundwater character in different wells across an entire groundwater basin. Stiff water-quality pattern diagrams were evaluated to determine if there was an obvious distinction in water quality character that could be used to identify distinctly different aquifers. A map showing the Stiff diagrams for wells with available data is shown in Appendix F.

Differences in the groundwater quality character from one well to another across a groundwater basin can reveal variations resulting from differences in well depths, screened zones, or pumping rates and/or pumping levels. Differences in groundwater quality character noted in a single well over time could relate to water quality changes resulting from many different issues that could cause the blending of water entering the well from different aquifers of different water quality. Examples of scenarios that could alter the flow regime in a well are (1) portions of the casing perforations have become plugged over time by biological growths, (2) the pumping rate has increased or decreased over time, or (3) Basin-wide static water levels have declined over time. These types of occurrences would, in turn, possibly reduce the inflow from particular perforated zones into a well.

Changes in groundwater quality character were reviewed to potentially determine whether the Stiff diagrams could be used to determine the geologic formations into which a well was perforated. Review of the diagrams reveal that differences in groundwater quality character in the Basin do not appear to vary greatly with the geologic formation into which a well is perforated, but rather vary by their relative location within the Basin. In general, the groundwater character in a large majority of the wells shown on the map is calcium-sulfate. Two wells located in the middle to southern portions of the Basin display a sodium-sulfate character. Wells in the southern portion of the basin tend to have higher TDS concentrations than wells in the northern portion of the Basin. Based on the available dominant cation and anion data reviewed for this study, there is no clear distinction in groundwater quality character between wells that are perforated in the undifferentiated alluvial sediments versus wells perforated within the San Pedro Formation.

As discussed in Sections 2.7 and 2.8, previous reports have documented groundwater quality impairments in the Basin, including impairment from sulfate, TDS, hardness, iron, and manganese. The concentrations of some of these constituents are elevated, and in some cases, were above their respective secondary MCLs and/or micro-irrigation plugging hazard indices.

4. Groundwater Balance

Hydrologic groundwater balance estimation provides a basis for safe yield determination and ancillary benefits to UWCD and Basin stakeholders in improving the understanding of relative Basin inflow/outflows for ongoing groundwater management planning and updating of the UWCD numerical groundwater model.

Primary groundwater inputs include deep percolation of precipitation including Santa Paula Creek percolation and mountain front recharge (P_p), deep percolation of irrigation (P_i), lateral groundwater inflow (GW_i) from the Fillmore Basin (Figure 1), percolation of recharge from the SPWRF (WWTP) and recharge from septic systems (Se). Groundwater outputs include groundwater extraction (E), lateral groundwater outflow to the Mound Basin and Oxnard Forebay Basin, and potentially net groundwater discharge to the Santa Clara River. For the purpose of the groundwater balance, natural groundwater outflow (i.e., all groundwater outflow from the Basin besides extraction from production wells [O_{nat}]) is considered to be primarily due to lateral groundwater underflow, with lesser contributions by riparian groundwater consumption and net groundwater discharge to surface water. The groundwater balance is given by:

$$\Delta GW_s = [P_p + P_i + GW_i + WWTP + Se] - [E + O_{nat}] \qquad \text{[Eq. 4-1]}$$

where ΔGW_s = The change in groundwater storage

As discussed in Section 2.5, groundwater elevations exhibit inter-annual fluctuation and long-term decline, indicating a net loss of groundwater in storage (i.e., negative value of ΔGW_s).

Groundwater balance component magnitudes have been estimated based on available data and using standard methods (e.g., Fetter, 2001; Freeze and Cherry, 1979), consistent with the DBS&A proposed technical approach (DBS&A, 2013). Components of the water balance that are determined to vary substantially from year-to-year (e.g., recharge from deep percolation of precipitation) are calculated for representative precipitation conditions, including the average (over entire base period), median, 25th percentile, and 75th percentile conditions. Although numbers are reported to the nearest acre-foot per year, the authors are not asserting that level of accuracy in the findings of this Study.

There is uncertainty regarding the net effect of groundwater interaction with surface water in the Santa Clara River over time, and throughout its reach within the Basin, as discussed in Section 3.5. However, the limited available data suggest that groundwater discharging to the Santa Clara River in the west part of the basin may be the dominant interchange between surface water and groundwater. Therefore, the Santa Clara River is generally considered to receive groundwater discharge and not be a net source of groundwater recharge (Section 3.5) and net groundwater discharge to the Santa Clara River is grouped within the natural groundwater outflow term.

4.1 Hydrologic Base Period

UWCD requested an update of the safe yield that reflects current conditions and includes a representative hydrologic base period. Furthermore, UWCD directed that the safe yield analysis be conducted for a period following potentially major hydrologic changes to the Basin, including the development of Freeman Diversion (1991) and U.S. Army Corps of Engineers projects on lower Santa Paula Creek (1998) that may have led to compaction of the streambed channel sediments (Figure 5).

Based on these criteria, the hydrologic base period is from water years 1999 through 2012 (October 1, 1998 through September 30, 2012). VCWPD records for precipitation gage 225 (Wheeler Canyon), which provide a continuous precipitation record over this time period and also extend historically to water year 1967, were used for evaluation of the hydrologic base period. Annual precipitation at VCWPD gage 225, VCWPD gage 175/175A (Saticoy), VCWPD gage 245/245A/245B (Santa Paula), and CIMIS Station #198 are plotted for comparison on Figure 8, and gage locations are shown on Figure 5. Over the entire historical record at gage 225 (1967 to 2013), average and median annual precipitation is 22.7 and 19.0 inches, respectively. In comparison, for the 1999 through 2012 base period, average and median precipitation values were 21.6 and 21.7 inches, which are in reasonable agreement with the longer-term record. Furthermore the hydrologic base period begins and ends with water years with similar precipitation, 11.9 inches for water year 1999 and 12.0 inches for water year 2012.

Water year 1998, the year prior to the beginning of the hydrologic base period, exhibited the greatest precipitation from 1957 to 2014 as measured at rain gages in Saticoy and Ventura (Figure 8). However, review of Basin hydrographs indicates that groundwater levels did not increase to elevations that were significantly greater than those during other periods during the beginning of the 1998 water year (October 1997 to March 1998), and declined by the beginning of the 1999 water year (October 1998). Therefore, by the beginning of the hydrologic base period (October 1998), groundwater elevations were not elevated above historical norms due to the exceptionally wet year in 1998.

Hydrologic balance water components were calculated for average (over the entire hydrologic base period from 1999 through 2012), median, 25th percentile, and 75th percentile water year conditions. During the selected period, the 25th percentile annual precipitation was 12.0 inches (water year 2012), the median precipitation was 21.7 inches (most similar to water year 2000, precipitation of 19.9 inches), and the 75th percentile precipitation was 26.0 inches (most similar to water year 2010, precipitation of 24.8 inches).

4.2 Groundwater Inflow from Fillmore Basin

RCS performed underflow calculations from the Fillmore Basin to the Santa Paula Basin using Darcy's Law:

$$Q = K\ i\ A \qquad \text{[Eq. 4-2]}$$

Where: Q = Underflow from the Fillmore Basin to the Santa Paula Basin [L^3/T]

K = Lateral hydraulic conductivity of the aquifers into which the producing water wells are constructed [L/T]

i = Groundwater gradient within the aquifers into which the producing water wells are constructed [-]

A = Cross-sectional area of the underflow across the boundary between the Fillmore and Santa Paula groundwater basins (i.e., groundwater flow perpendicular to the direction of flow) [L^2]

Lateral hydraulic conductivity (K) of aquifer units at the inflow boundary was estimated based on RCS compilation of available hydraulic conductivity values (Section 3) and a previous study conducted for the SPWRF (FugroWest, 2007), as listed in Table D-3. For the active channel deposits, hydraulic conductivity was estimated to be 300 ft/d based on the FugroWest (2007) study. For undifferentiated alluvium, hydraulic conductivity was assumed to be 126 ft/d based on the geometric mean of (1) the geometric mean of specific capacity-derived values for the Santa Paula Creek/East Santa Paula Basin wells interpreted to produce water from only the undifferentiated alluvium (Table D-1), (2) the geometric mean of data from nine wells reported by FugroWest (2007), (3) data from the Santa Paula Water Company (SPWC) Well No. 13 aquifer test, and (4) data from the FICO Well 12 aquifer test. For the San Pedro Formation, hydraulic conductivity was assumed to be 118 ft/d based on the geometric mean of (1) the geometric mean of specific capacity-derived values for the Santa Paula Creek/East Santa Paula Basin wells interpreted to produce water from only the San Pedro formation (Table D-1), (2) SPWC Well No. 13 aquifer test results, and (3) SPWC Well No. 14 aquifer test results.

Hydraulic gradient at the inflow boundary was obtained for each geologic unit from RCS groundwater elevation contour maps for 2000, 2010, and 2012 (Appendix F). Assumed hydraulic gradient values are listed in Table D-5, and the locations at which gradient measurements were made are shown in Appendix F contour maps.

Cross-sectional areas were based on available geologic maps and RCS-prepared cross sections. For the northern inflow boundary, because no groundwater barriers are known to exist and none were apparent in the groundwater contour mapping work, the settlement boundary between Santa Paula Basin and the Fillmore Basin was selected. The location and schematic cross section of that boundary (Y-Y’) are provided in Appendix B. Cross-sectional depth (850 feet) for the purpose of the inflow calculation was determined using the perforated interval of the deepest producing well in the area (well 3N/21W-11F4, located 4,800 feet southwest of the inflow boundary), and this is considered to be the effective depth of the current water-producing strata in the Basin.

Table D-5 compiles lateral hydraulic conductivity, groundwater gradient, and cross-sectional area information for each polygonal segment of Cross Section Y-Y’ and presents the final calculated groundwater inflow for water years 2000, 2010, and 2012. These total inflows ranged from 22,320 ac-ft/yr for 2012 to 30,909 ac-ft/yr for 2010, with an average of 25,244 ac-ft/yr for all three years. Based on this average value for all three years, approximately 10,000 ac-ft/yr (40 percent of the underflow) is attributed to undifferentiated alluvium and active channel deposits, whereas approximately 15,000 ac-ft/yr (60 percent of the underflow) is attributed to the San Pedro Formation.

4.2.1 Comparison to Santa Paula Basin Pumper's Association Inflow Estimate

Groundwater inflow from the Fillmore Basin into the Santa Paula Basin was estimated by Bachman (2015) on behalf of the Santa Paula Basin Pumper's Association. Bachman presents an average underflow value of 19,700 ac-ft/yr, using Equation 4-2, compared to an average of 25,200 ac-ft/yr used for this study. Below is a discussion of how the Bachman assumptions differ from those used for this study for each of the three variables in the equation. Differences are primarily due to Bachman's application of a lower hydraulic conductivity of 30 ft/d for the San Pedro Formation (with reference to KDSA, 2015, which does not include the 30 ft/d value or specific discussion of hydraulic conductivity) compared to the value of 118 ft/d applied by RCS, and Bachman's assumption that hydraulic gradients in the San Pedro Formation can be assumed to be the same as gradients in the undifferentiated alluvium. Because RCS applied a hydraulic conductivity for the San Pedro Formation based on cited observed test results (Section 3, Appendix D), and independently calculated hydraulic gradients for both the San Pedro Formation and the undifferentiated alluvium using available water level data, the RCS value is considered to be more consistent with available data and is used in the groundwater balance.

4.2.1.1 Hydraulic Conductivity (K)

For the active channel deposits (Layer 1 or shallow aquifer in the Bachman study), the K value used in this study is nearly twice that of the Bachman estimate. The volume of active channel deposits relative to the other geologic formations of the estimation is very small, and therefore the calculation is not highly sensitive to this factor.

For the undifferentiated alluvium (Layer 2 or Oxnard-Mugu Aquifer in Bachman) Bachman applies a K value of 120 ft/d, which was derived by UWCD for FICO Well 12 (UWCD, 2013f). Note that UWCD defined that value as preliminary until further testing could be completed. The present study applied a similar K value of 126 ft/d to the undifferentiated alluvium; that value was derived from the geometric mean of values estimated from specific capacity data, as well as two pumping tests (Table D-1).

RCS estimated a K value for the San Pedro Formation (Layer 3 or Hueneme Aquifer in Bachman) of 118 ft/d; this value is based on measured values, including those from two aquifer tests for two City of Santa Paula wells constructed in the San Pedro Formation. Bachman estimated a much lower value of 30 ft/d, based on the work of KDSA (2015). Review of the KDSA (2015) study reveals no specific discussion of hydraulic conductivity, and therefore, the exact method of determining how KDSA identified a K value is unclear.

4.2.1.2 Gradient (i)

Gradients calculated and presented by Bachman (2015) for the undifferentiated alluvium (or Layer 2) are quite similar to the gradients used in this study (Table D-6). However, those same Layer 2 gradients are applied to Layer 3 in the Bachman report (2015). The present study provided an independent determination of the groundwater gradient in the San Pedro Formation. As described in Section 3.7, three different contour maps were created based on the perforation intervals in the wells from which water level data were collected (these maps are shown in Appendix F). Because there is not an abundance of wells near the eastern settlement boundary, gradient data for the San Pedro Formation were derived from wells located west of the boundary, as illustrated on the Appendix F maps. In this study, groundwater flow gradients in the San Pedro Formation were determined to be roughly one-half of the gradient calculated for the undifferentiated alluvium.

To determine the sensitivity of hydraulic gradient, the inflow calculation for this study was re-calculated using the average of the gradients reported by Bachman (2015), with the K values provided by RCS. The result was an average inflow of 35,000 ac-ft/yr, a value that is about 10,000 ac-ft/yr higher than the RCS calculation. Because the Bachman study (2015) used a lower K value for the San Pedro Formation, the assumption that the gradient from the undifferentiated alluvium can be applied to the San Pedro Formation did not have a great effect on the overall inflow calculation. However, the higher K value applied by RCS to the San Pedro Formation, coupled with the larger gradient applied by Bachman to the San Pedro Formation, resulted in a significantly greater calculated inflow value in total and in the San Pedro Formation specifically. In contrast, the calculation of inflow through the undifferentiated alluvium using the RCS-estimated K values and the average of Bachman's groundwater gradients yielded an estimate of 10,000 ac-ft/yr, the same value calculated by RCS as described in Section 4.2.

4.2.1.3 Cross Sectional Area (A)

The cross section provided by Bachman is referenced to the Ventura Regional Groundwater Model. Although not explicitly illustrated in Bachman's 2015 report, the length of his cross section is shown to be roughly 8,500 feet. This includes only the portion of the inflow boundary up to the northern terminus of the alluvial deposits on the Basin flow. It does not include the outcrop portion of the San Pedro Formation in the adjoining hillsides.

Bachman defines a "shallow aquifer" whereas RCS defined only a much smaller "active channel aquifer." For the total cross-sectional area of undifferentiated alluvium (Layers 1 and 2 for Bachman versus active channel and old alluvium by RCS), Bachman calculated an area of roughly 3.4 million square feet (M ft^2), of undifferentiated alluvium, whereas RCS calculated an area of about 2 M ft^2. As shown on Cross Section Y-Y', RCS did not include portions of the undifferentiated alluvium that were interpreted to be within the "High Percent Low-Permeability sediment" Zone."

For the San Pedro Formation, Bachman calculated an area of 2.5 M ft^2, whereas RCS calculated an area for the San Pedro Formation of 5.2 M ft^2. RCS calculation areas G, H, I, and J (shown as the orange-colored regions on the RCS Y-Y' cross section) equal roughly 2.4 M ft^2 and therefore account for some of the discrepancy. If these regions were removed from the RCS calculation, then the inflow across the boundary calculated by RCS would be 18,000 ac-ft/yr.

4.3 Groundwater Recharge from Deep Percolation of Precipitation and Irrigation

The Basin is located within a Mediterranean-type climatic zone characterized by long dry summers and short mild winters. Nearly all annual precipitation occurs in the winter months. Precipitation rates are variable, and cyclic patterns occur, sometimes with sub-average rainfall over several consecutive winters (droughts). Recharge from precipitation is also variable and follows similar trends. Recharge to the Basin is composed of mountain front recharge (recharge within ephemeral washes in the transition zone between the mountain block and the Basin floor), local recharge (along sandy drainages in the interior of the Basin), and diffuse recharge (precipitation that infiltrates on the broad lowland areas between washes and is significantly decreased in developed areas due to the presence of impervious surfaces).

Recharge from precipitation and irrigation is estimated using an advanced watershed model developed by DBS&A, the Distributed Parameter Watershed Model (DPWM). As discussed in Section 4.3.6, recharge of perennial streamflow within Santa Paula Creek was estimated separately from the DPWM based on UWCD field gaging data (UWCD, 2013d).

4.3.1 DPWM Methodology

Application of the DPWM allows for quantitative estimates based on site-specific climatological, geologic, soils, land use, and vegetation factors. DBS&A developed the DPWM based on the MASSIF model developed by Sandia National Laboratories (2007). The DPWM is similar in concept to watershed models used by the USGS (e.g., INFIL [Hevesi et al., 2003]). The model relies on the widely accepted United Nations FAO-56 procedure for computing actual evapotranspiration (AET) from the reference evapotranspiration (ET_0) estimated using the Penman-Monteith method (Allen et al., 1998, 2005). Water budget components accounted for in the model include precipitation, irrigation, bare soil evaporation, transpiration, runoff, run-on, soil water storage, and deep percolation (recharge). Complete documentation of the DPWM is provided in Appendix G.

Precipitation falling on a specific location within the contributing subwatershed may run off (based on rainfall intensity greater than surface infiltration rates) or infiltrate into the soil profile. Runoff may become run-on into other areas, where it may be available for infiltration. Upon infiltration of water into the soil profile, water may be stored and subject to subsequent evapotranspiration. If the soil moisture content increases above soil moisture field capacity, water will be subject to deep percolation at a rate governed by the hydraulic conductivity of the soils and underlying geologic formations. Deep percolation past the root zone is considered to eventually result in recharge of the underlying groundwater.

Within the contributing subwatershed, upland areas north of the Basin are primarily low-permeability Tertiary-aged bedrock units (Figure 6), and precipitation in these areas is likely to lead to significant runoff. Some of the precipitation that falls on the mountain terrain runs off into higher-permeability ephemeral washes and becomes recharge in the transition zone between the mountain block and the sediments at the margin of the Basin floor. This recharge process, termed mountain front recharge (e.g., Wilson and Guan, 2004), occurs in major washes and perhaps hundreds of minor washes that collect water that runs off the mountain block. Recharge to the alluvial washes is likely to contribute to groundwater within the Basin as lateral underflow from the ephemeral washes.

A general schematic of the DPWM is given in Figure 9. The upper DPWM layer (Layer 1) includes bare soil evaporation and transpiration, and its thickness is based on the maximum depth of bare soil evaporation. Layer 1 is divided into two nodes (Nodes 1 and 2).

Node 1 is the bare soil fraction of the cell where evaporation is dominant, and Node 2 is the fraction of the model domain cell surface covered by vegetation canopy, where transpiration is dominant. Bare soil evaporation does not occur in Node 2, but transpiration occurs to some degree in both Nodes 1 and 2.

The second layer (Layer 2, Node 3) represents the remainder of the root zone for the vegetation type; its thickness is the maximum rooting depth minus the thickness of Layer 1. Transpiration is dominant in Layer 2, but some diffuse evaporation also occurs. The final layer (Layer 3, Node 4) represents the thickness of soil below the root zone and allows no transpiration or evaporation. The thickness of Layer 3 is the depth to alluvial sediment or bedrock minus the thicknesses of Layers 1 and 2. In cells with deep alluvium, the thickness is limited to 20 meters minus the root layer thicknesses. Drainage from Layer 3 is limited by the bedrock saturated hydraulic conductivity when it is less than the soil saturated hydraulic conductivity.

Routing of precipitation within the developed areas of the subwatershed is impacted by urbanization, including covering of the land surface with impervious surfaces (i.e., pavement, asphalt, rooftop). The presence of impervious surfaces is generally understood to increase runoff and concomitantly decrease infiltration and deep percolation to groundwater.

For the purpose of DPWM modeling, a "percent impervious surface" is assigned to each model grid cell. The impervious surface portion of each cell in the DPWM model receives no irrigation, contains no vegetation, and accepts all runoff from surrounding areas of the cell. Furthermore, runoff on impervious surfaces within each cell will be routed directly to the impervious surface portion of the next downgradient cell and so on, until reaching the closest mapped surface water channel. In this way, DPWM routing of water in developed areas represents, in an approximate sense, storm flow to storm water drains and then to surface water channels.

4.3.2 DPWM Limiting Assumptions

Although the DPWM provides an advanced and efficient watershed model for estimating recharge, several limiting assumptions are necessary to execute the model over the relatively large subwatershed within the available resources of the overall safe yield project. Key assumptions include:

- All water that percolates past the root zone is assumed to recharge to groundwater.
- Properties (e.g., soil type, vegetation type, percent impervious surfaces) within each model grid cell are constant.
- Soil properties of the vegetated portion of developed areas are not adjusted for the presence of artificial fill or compaction.
- All surface water is routed through the model within a 1-day time step.
- Because all runoff is routed to impervious surfaces when present, focused recharge in developed areas (e.g., from building roofs to vegetated areas) is not accounted for.
- Average representative land use from 2013 was used over the entire time period (1999 through 2012), and changes in land use will not be accounted for.
- Irrigation rates are constant from year to year, an assumption that does not account for inter-annual fluctuations in irrigation as influenced by climate and other factors.

4.3.3 DPWM Domain and Input Parameters

The DPWM model domain covers the Santa Paula Basin and entire upgradient contributing watershed separate from the Santa Clara River (Figure 2) and consists of uniform grid cells 295 feet (90 meters) on a side. The model has been run for the complete base hydrologic period, water years 1999 through 2012, using a daily time-step routine. Model input data were collected from weather stations, site-specific literature sources, and general literature sources, and/or estimated from other properties, as described below and fully documented in Appendix G.

The topography used in the model was derived from USGS digital elevation models (DEMs). The DPWM grids use the slope, azimuth, and elevation and routing of flow as predicted by the DEMs.

Direct climate inputs to the DPWM include daily total precipitation, maximum daily air temperature, minimum daily air temperature, and average daily wind speed. These data were collected from the local VCWPD precipitation gage 225, other local gages, and CIMIS Santa Paula climate station #198 (Figure 5). Daily precipitation data are spatially distributed over the watershed based on the parameter-elevation regressions on independent slopes model (PRISM) estimate of the normal mean precipitation (Daly et al., 1994), as presented in Figure 3.

The spatial distribution of vegetation types in undeveloped areas was obtained from digital land cover datasets provided by the California Gap land cover mapping project (Lennartz et al., 2008).

4.3.3.1 Soils and Impervious Surfaces

Soils data were obtained from the U.S. Department of Agriculture (USDA) SSURGO database, which contains electronic data from field surveys conducted by the USDA. The USDA databases provide soil texture data (percentage of sand, silt, and clay), saturated hydraulic conductivity, and dry bulk density for each soil horizon. Soil water retention characteristics were estimated using soil texture data obtained from SSURGO and input into the widely used Rosetta application, which was developed for this purpose (USDA, 1999). The USDA reports soil depth for depths shallower than 5 feet. For soils specified as greater than 5 feet in thickness by the

USDA, the soil depths are assumed to be far greater than the maximum rooting depth of any vegetation association (20 meters).

Percent impervious surface was assigned for each model grid cell based on 2006 impervious surfaces data available from the USGS National Land Cover Dataset (NLCD) and presented on Figure 10. Recent research has indicated that impervious surfaces exhibit measurable infiltration of water following precipitation events, mostly through cracks in pavements and asphalts (Wiles and Sharp, 2008). Over broad areas, the result may be significant quantities of infiltrated water. The project team has conducted a literature review in order to evaluate the value of hydraulic conductivity assigned to the impervious surfaces in DPWM. Previous studies included double-ring infiltrometer experiments on pavements and asphalts (Wiles and Sharp, 2008), weighing lysimeter experiments of infiltration through fresh-laid asphalt (Ramier et al., 2004), laboratory permeameter testing on new asphalt cores (Huang et al., 1999), and previous urban watershed/climate modeling (Dupont et al., 2006). Based on this review, a hydraulic conductivity value of 1×10^{-5} centimeters per second (cm/s) (0.028 ft/d) was assigned to the impervious surfaces within the model domain.

4.3.3.2 Geologic Units and Alluvial Low-Permeability Sediment Zone

Geologic units underlying the soils of the subwatershed may restrict net infiltration when the saturated hydraulic conductivity of the underlying media is less than the soil infiltration rate and soils are shallow. The distribution of sediment and bedrock types (as mapped originally by Dibblee, 1992) has been obtained in GIS format from the California Geologic Survey (Gutierrez, 2014) and is displayed on Figure 6. The vertical saturated hydraulic conductivities for geologic units were estimated from literature sources in conjunction with the hydrogeologic evaluation conducted and reported herein.

Saturated hydraulic conductivity of the alluvial geologic units was of particular concern because of the presence of low-permeability layers (i.e., clay or silt), which may restrict vertical percolation. As described in Section 3, RCS developed illustrative maps of the percentage of low-permeability sediments based on interpretation of available drillers' logs (Appendix C). Visual inspection revealed low-permeability sediment zones greater than 50 percent generally correlate with surficial geologic sediment mapped as Holocene alluvial fan deposits (Qhf) by the California Geologic Survey (Figure 7), whereas zones with lower percentages of low-permeability sediment correlate with latest-Holocene stream terrace deposits (Qht) and latest-Holocene alluvial fan deposits in the eastern Basin (Qhfy). Therefore, for the purpose of DPWM, geologic units mapped as Qhf were assumed to exhibit relatively high low-permeability sediment content and reduced vertical hydraulic conductivity.

DBS&A searched the State Water Resources Control Board (SWRCB) Geotracker online database for aquifer tests conducted within the shallow low-permeability alluvial sediments. The Geotracker database was considered to be a potentially useful resource, as waste-contaminated sites listed in the database are typically subject to hydrogeologic investigation within shallow sediments (e.g., less than 100 feet). A comprehensive search of the Geotracker database revealed one site located within the low-permeability sediment mapped zone that included aquifer testing: the former ARCO Facility No. 1983, 11005 Citrus Drive (Figure 7). At this site, aquifer slug tests were conducted at three monitoring wells perforated between 3 and 14 ft bgs (Arcadis, 2010). Aquifer test data were interpreted using the AQTESOLV parameter estimation program, and results were 0.1 ft/d for two wells and 0.2 ft/d for the third well. These values were reported to be “reasonable given the documented lithology of the site, which is characterized as sandy to clayey silt and clay with minor interbedded clayey to silty sand” (Arcadis, 2010). Based on these results, for the purpose of DPWM modeling, a vertical hydraulic conductivity of 0.1 ft/d was assigned to the Qhf geologic zones.

4.3.3.3 Agricultural Land Use and Irrigation

Vegetation types in agricultural areas were obtained from GIS coverage provided by the Ventura County Agricultural Commissioner (VCAC, 2013), as presented by UWCD (2013b). Agricultural land use, irrigation rates, and default crop water requirements (e.g., crop factors) for use in DPWM modeling were assigned to be consistent with UWCD (2013b) and ITRC (2010). Recent land-use designations (VCAC, 2013) were assigned for all years within the simulations, and it was assumed that land-use changes (e.g., cropping changes) were not significant over the base period.

The simplifying assumption was made that irrigation rates are constant from year to year. This assumption does not account for inter-annual changes in irrigation rates as influenced by climate and other factors; however, irrigation return flow is expected to be relatively constant as opposed to episodic patterns of rainfall. The amount of irrigation that occurred each month was allocated from annual irrigation rates, proportional to the relative amount of reference evapotranspiration that occurred each month (as determined from CIMIS data).

4.3.4 Areas Contributing Deep Percolation of Precipitation

Model cells assumed representative of areas for which deep percolation of precipitation contributes to Basin recharge are presented in Figure 11. As discussed in Section 4.3.1, upland areas generally north of the Basin (Figure 6) are primarily low-permeability Tertiary-aged bedrock units, and deep percolation to bedrock units is not considered to recharge the Basin. Therefore, as delineated on Figure 11, these areas are not used to calculate DPWM-predicted Basin recharge.

Because the Santa Clara River is generally considered to receive groundwater discharge and not be a net source of groundwater recharge (Section 4.0), model cells representative of the area of the Santa Clara River are excluded from DPWM-predicted recharge results.

Deep percolation within alluvial washes outside the Basin settlement boundary (Figure 6) is assumed to eventually recharge the Basin as lateral underflow, and therefore, predicted recharge within these model cells are included in DPWM-predicted recharge results (Figure 11).

For the case of the Santa Paula Creek subwatershed, significant groundwater is observed to discharge to Santa Paula Creek in the general location of USGS gage 11113500 near the northern Basin settlement boundary (Figure 5), where the stream is perennial. Some or all recharge within the Santa Paula Creek subwatershed therefore eventually “daylights” as surface water and is unavailable for recharge to the Basin as lateral groundwater underflow.

DBS&A applied digital filtering methods to estimate the proportion of Santa Paula Creek flow attributable to groundwater discharge to surface flow (baseflow) at USGS gage 11113500. Daily streamflow records for USGS gage 11113500 were processed by digital filtering, which is used to estimate the baseflow component of the surface water flow hydrograph (Lim et al., 2005). Results of the baseflow separation are presented for each water year in Table 2, and results are shown graphically for water year 2011 in Figure 12. Observed average total flow at the USGS gage for all water years was 19,585 ac-ft/yr, and the estimated average baseflow component of that was 11,393 ac-ft/yr (58 percent).

Estimated baseflow using the digital filtering analysis (11,393 ac-ft/yr) was greater than the total DPWM-estimated recharge within alluvial channels of the Santa Paula Creek subwatershed (3,337 ac-ft/yr). This indicates that essentially all groundwater recharge to alluvial channels in the Santa Paula Creek subwatershed north of the settlement boundary daylights and discharges to surface water near the boundary. Therefore, the Santa Paula Creek subwatershed area was excluded from the DPWM-predicted Basin recharge results (Figure 11).

Basin recharge resulting from the perennial flow in Santa Paula Creek was estimated separately from the DPWM and is described in Section 4.3.6. Therefore, the area of the Santa Paula Creek channel was also excluded from DPWM-predicted Basin recharge results.

4.3.5 DPWM Results

Table 3 presents average annual DPWM-predicted Basin recharge over the entire study hydrologic base period (1999 through 2012) and for the selected water years 2000 (median), 2010 (75th percentile), and 2012 (25th percentile). Over the entire study hydrologic base period, the average annual total deep percolation of precipitation and irrigation was predicted to be 10,428 ac-ft/yr, including 6,549 ac-ft/yr from precipitation (63 percent) and 3,879 ac-ft/yr from irrigation (37 percent). The majority of precipitation-related recharge (5,430 ac-ft/yr) occurred within the Basin, as compared to alluvial washes outside the settlement boundary (1,119 ac-ft/yr). Importantly, median, 25th, and 75th percentile conditions resulted in less annual precipitation-related recharge as compared to the 14-year average, demonstrating that the average is skewed by the heaviest precipitation years (e.g., 2005).

Figure 11 presents a map of average annual modeled recharge from precipitation and irrigation. Recharge rates for the alluvial portions of the Basin floor generally range from 2 to 10 inches per year (in/yr) on average, compared to 0 to 5 in/yr for the area of the San Pedro outcrop in the northern portion of the Basin. Spatial variability is also influenced by the presence of impervious surfaces in developed areas of the cities of Santa Paula and Ventura (Figure 10).

4.3.6 Santa Paula Creek Recharge

UWCD (2013d) performed stream gaging within Santa Paula Creek in April 2011, May 2011, September 2011, and February 2012 (Section 2.4). Gaging was conducted at Harvard Boulevard and at Bridge Road, which are located 0.55 and 3.1 miles upstream of the confluence with the Santa Clara River, respectively (Figure 5). UWCD estimated percolation between the two locations based on the observed difference in streamflow, assuming that any decrease in streamflow at the downstream location was due to streambed percolation. UWCD (2013d) states that a source of error was the presence of flow into the creek from perched groundwater seeps observed along the west bank of Santa Paula Creek in the vicinity of a surface water reservoir on Wilson Ranch and irrigated orchards near the terminus of Say Road. Increased flow in the seeps at Wilson Ranch is reported following irrigation events at the ranch (UWCD, 2013d). Minor inflows from perched groundwater seeps between the gaging locations were not accounted for in the flow balance calculations.

Figure 12 displays total flow at USGS gage 11113500 for water year 2011, which encompasses most of the UWCD gaging dates that occurred during the same year. April and May 2011 gaging was conducted by UWCD following precipitation in March 2011 and during the resulting baseflow recession. DBS&A compiled UWCD gaging results and corresponding measured flow at USGS gage 11113500 for each day. Percolation of surface water to groundwater between the USGS gage and Bridge Road on each day was taken as the difference in flow at each location. Figure 13 presents a linear regression of estimated percolation within this reach on each date and observed flow at the USGS gage (UWCD data from April 12, 2011 was identified as an outlier and excluded from the regression). Based on this regression, 6.2 percent of surface flow at the USGS gage was estimated to percolate between the USGS gage and the first UWCD gaging location at Bridge Road.

On most gaging dates, UWCD observed greater flow at Harvard Boulevard (downstream) as compared to Bridge Road (upstream), and this is assumed to have been caused by the presence of the irrigation runoff flow entering the channel between the two gaging locations. UWCD (2013d) report that depth to groundwater in the vicinity of the gaging locations has historically been at least 17 feet and therefore there is no groundwater discharge directly to the creek. On the UWCD gaging date that exhibited greatest total flow (April 1, 2011, the date nearest the March 2011 precipitation [Figure 10]), UWCD did calculate a loss of groundwater between Bridge Road and Harvard Boulevard of 6.4 cfs, or 3.0 percent of the flow at the USGS gage on that date. Error introduced by the presence of irrigation runoff is expected to be less during periods of greater flow. Therefore, it was assumed that 3.0 percent of flow at the USGS gage is lost to percolation between Bridge Road and Harvard Boulevard.

Total Santa Paula Creek percolation is assumed to be 9.2 percent (6.2 percent plus 3.0 percent) for the range of total flow exhibited during UWCD gaging dates and included in the linear regression (Figure 13). A percolation rate of 9.2 percent is in the lower range of rates previously estimated for Santa Paula Creek in 1932, 1953, 1971-1972, and 1998, all dates prior to compaction of lower Santa Paula Creek (UWCD, 2013d).

The relationship between total flow and percolation is not expected to be linear for the full range of possible streamflow rates. With increasing total flow, streambed percolation is expected to reach a maximum at some point. Streambed percolation is a function of streambed hydraulic conductivity, wetted area, and vertical hydraulic gradient, and will increase with increasing flow up to a certain flow rate because of increasing wetted width. Streambed hydraulic conductivity is constant, and vertical hydraulic gradient in conditions with pooled surface water overlying unsaturated media is assumed to be 1 under most conditions (Stephens, 1995). Once the entire streambed width is wetted, percolation is not expected to continue to substantially increase with increasing flow rate or increasing height of water.

UWCD gaging was limited to dry weather conditions, and therefore a full non-linear regression is not available across the full range of possible flow rates. Maximum flow at the USGS gage during UWCD gaging dates was 211 cfs (April 1, 2011), compared to a maximum of 7,560 cfs (January 9, 2005) during the hydrologic base period. A total of 97 days during the hydrologic base period exhibited a total mean daily flow at the USGS gage greater than 211 cfs (1.9 percent of all days). For the purpose of the water balance, for all days exhibiting a flow greater than 211 cfs, a maximum percolation of 19.3 cfs was assumed (corresponding to 9.2 percent of 211 cfs). Lack of sufficient wet-weather gaging along Santa Paula Creek is recognized as a data gap.

Daily percolation for all days was estimated as 9.2 percent of measured flow at the USGS gage, subject to the constraint of a maximum percolation rate of 19.3 cfs. Annual total percolation was taken as the summed percolation of all days within each water year. Resulting estimated Santa Paula Creek percolation is given in Table 2. The 14-year annual average is 1,105 ac-ft/yr, and a percolation of 756 ac-ft/yr was estimated for the representative median precipitation condition (water year 2000).

4.4 Wastewater Percolation and Septic Systems

Effluent from the SPWRF has been routed to percolation basins located near the Santa Clara River for disposal since mid-2010 (Figure 7). Prior to construction of the SPWRF, wastewater was discharged to the Santa Clara River via a canal parallel to Peck Road. Wastewater discharge created a discrete tributary of the Santa Clara River within the river bed that ran southwest from Peck Road for approximately 0.6 miles before its confluence with the river. Review of historical aerial photography indicates that this tributary was highly vegetated, and therefore some of the wastewater discharge was consumed via riparian evapotranspiration. Furthermore, the tributary wetted width was relatively narrow (approximately 10 feet), minimizing wetted area and percolation as compared to the SPWRF percolation basins. The Santa Clara River in this location is also likely gaining at least during wet periods, as discussed in Section 3.5. For these reasons, wastewater discharge percolation was assumed to be minor prior to 2010 and was not included in the groundwater balance.

For the purposes of this study it is assumed that SPWRF percolation pond water recharges groundwater and does not readily discharge into the Santa Clara River. SPWRF annual compliance reports consistently report net groundwater flow toward the west and away from the river (FugroWest, 2011; GSI, 2016); however, the facility has few monitoring wells located between the river and the percolation ponds to constrain the estimate of groundwater flow in this area, and localized mounding conditions could result in radial groundwater flow away from the percolation ponds, including toward the river.

Similar to deep percolation of precipitation and irrigation, the presence of low-permeability strata may restrict vertical percolation. The SPWRF facility is located near the Santa Clara River, where continuous low-permeability confining units are mapped as thin to absent (Figure 7). Pre-construction hydrologic evaluation of the SPWRF facility also indicated limited fine-grained media directly beneath the facility as compared to areas north of the facility and farther from the river (FugroWest, 2007). SPWRF records indicate that all percolation pond water is readily recharged into the subsurface. Local ponding conditions, which would be expected if the ponds overlie low-permeability sediment, are not encountered (i.e., a required 5-foot vertical separation is maintained between the ponds and saturated groundwater [GSI, 2016]). Additionally, observed increasing chloride concentrations in nearby irrigation wells following initiation of waste discharge at the SPWRF facility also supports that percolation pond water recharges local groundwater production zones (Malzacher, 2012).

SPWRF waste discharge records were obtained from the SWRCB Geotracker website (PercWater, 2013), and annual total discharge volume is listed in Table 4a. DBS&A identified several additional smaller wastewater disposal sites on Geotracker (Waste Discharge Requirement [WDR]), and discharge volumes for these sites are also listed in Table 4a.

Septic system recharge was estimated using data from the County of Ventura Individual Sewage Disposal System Applications/Permits Database (CVEHD, 2010). This database provides approved septic systems listed by the assessor's parcel number (APN) from 1977 to present. GIS parcel data from Ventura County was used to determine APNs within the boundaries of the Basin. This list was then cross-referenced against the Sewage Disposal System Applications/Permits Database in order to determine the number of approved septic systems within the Basin, which was 464 (Table 4b). The recharge rate for individual septic systems was assumed to be 143.5 gallons per day (gpd), or 0.16 ac-ft/yr, assuming 50 gpd per person based on a study of septic system recharge within southern California (Hantzche and Finnemore, 1992, and an average population of 2.87 persons per household in California (U.S. Census Bureau, 2010). The resulting recharge from all septic systems was 74 ac-ft/yr (Table 4b).

4.5 Groundwater Storage

Historical groundwater levels in the Basin exhibit inter-annual fluctuation and long-term decline (UWCD, 2013a), and therefore the change in stored groundwater is a component of the overall groundwater balance (Equation 4-1). The volume of groundwater that has been released from storage (ΔGW_s) can be estimated from:

$$\Delta GW_s = S \times A \times \Delta h \qquad \text{[Eq. 4-3]}$$

Where: S = Storativity [-]

A = Surface area of the Basin [L^2]

Δh = Groundwater elevation change [L]

The surface area of the Basin (A) was obtained from GIS files provided by UWCD of the Basin as defined by the settlement boundary (Figure 2) and was determined to be 23,077 acres.

UWCD (2013a) trend analyses indicated an average annual groundwater elevation decline of 0.13 to 0.55 ft/yr depending on the time period analyzed and an average decline of 0.18 ft/yr for the time period 1999 through 2011, which most closely matches hydrologic base period for this study (1999 through 2012) (Table 1).

DBS&A performed independent trend analyses of available groundwater elevation data in order to estimate groundwater level decline and loss in stored groundwater. First, Mann-Kendall statistical analysis was used to evaluate the presence or absence of a significant groundwater elevation trend over time (e.g., Wiedemeier et al., 1991; Ofungwu, 2014). Mann-Kendall analysis provides a robust non-parametric statistical test based on a data ranking scheme and is therefore not skewed by the presence of outliers. The U.S. EPA statistical software ProUCL (U.S. EPA, 2010) was used to perform the Mann-Kendall analyses at a statistical confidence level of 95 percent. Mann-Kendall analyses were conducted for groundwater elevations measured at 64 wells identified by UWCD as having available data (UWCD, 2013a). Of these 64 wells, 45 had available data for the entire hydrologic base period of 1999 through 2012.

Trend analysis plots for all wells are presented in Appendix H, and results for all wells are listed in Table 5. Well locations and UWCD-designated Basin areas (i.e., Santa Paula Creek Area, East Santa Paula Basin, Middle Santa Paula Basin, Saticoy Area, and West End Santa Paula Basin) are presented in Appendix E. Table 6 provides a summary of the trend analyses by geographic area as defined by UWCD. For the Basin as a whole, 4 wells exhibited an increasing trend, 30 a decreasing trend, and 11 exhibited no trend at the specified confidence level. Decreasing trends were predominantly observed in the East Santa Paula Basin (16 of 18 wells), Middle Santa Paula Basin (8 of 11 wells) and Saticoy Area (4 of 6 wells), which together represent the majority of the Basin area.

For those wells that were determined to exhibit a statistically significant trend, linear regression analysis was used to estimate trend magnitude or slope (i.e., groundwater elevation change). Linear regression plots for all wells are provided in Appendix H, and results for all wells are listed in Table 5. For those wells determined by Mann-Kendall analysis to exhibit no significant trend over the hydrologic base period, a trend of zero (i.e., no long-term change) was assumed (Ofungwu, 2014).

Table 6 provides summary statistical analysis of computed slope, including the average, median, 25th percentile, and 75th percentile for all wells. Considering all 45 wells in the Basin with available data for the entire hydrologic base period, the average slope was 0.20 ft/yr decrease, median was 0.26 ft/yr decrease, 25th percentile was 0.38 ft/yr decrease, and 75th percentile was 0.00 ft/yr (no change). These statistics are adjusted slightly by an area-weighting scheme based on geographic areas as defined by UWCD (2013a), to an average of 0.18 ft/yr decrease, a median of 0.23 ft/yr decrease, 25th percentile of 0.32 ft/yr decrease, and the 75th percentile of 0.02 ft/yr increase (Table 6). Note that the range of computed annual average groundwater level declines is similar to those reported by UWCD (2013a) (Table 1). Mann-Kendall analyses included within this report are based on all available water level records for each well within the base period, whereas the UWCD (2013a) analysis was based on the highest observed water level elevation within each year.

Average groundwater elevation changes (i.e., linear slope of groundwater elevation hydrographs) were also computed for given representative precipitation years 2000, 2010, and 2012 (Table 6). On average, median (year 2000) and 75th percentile (year 2010) years exhibited increasing trends of 3.5 and 6.1 ft/yr, respectively, and the 25th percentile (year 2012) exhibited a decreasing trend of 4.2 ft/yr.

Available Basin storativity values have been compiled by RCS (Appendix D) and range from 1.2×10^{-4} to 9.0×10^{-3}, which are representative of confined or semiconfined aquifers (Fetter, 2001). These data may be skewed by the duration of the available aquifer tests (typically limited to 24 hours); longer pumping tests may have resulted in calculated storativity values that reflect unconfined conditions in some locations (e.g., Kasenow, 2001). As described in Section 3.6.1, the undifferentiated alluvium, within which some Basin wells are perforated, is considered to be unconfined or semiconfined at least in some locations and therefore is expected to exhibit a greater storativity value of 0.01 to 0.2 (Fetter, 2001; Weight and Sonderegger, 2001). Analytical modeling of streambed percolation from the Santa Clara River in the location of the USGS depth-discrete monitoring well (03N21W15G-series [Figure 4]) obtained a best-fit to available data assuming a storativity value of 0.01 to 0.02 (Reichard et al., 1999). Law-Crandall (1993) estimated a Basin-average storativity of 0.11. Absence of Basin-specific storativity values representative of the unconfined or semiconfined undifferentiated alluvium is recognized as a data gap.

Using Equation 4-3, change in groundwater storage was estimated for the full range of possible groundwater level decline (Δh) and storativity (S) values listed above. Over the base hydrologic period, possible Basin-wide groundwater level decline was considered to range from 0.18 to 0.32 ft/yr, based on the area-weighted average, median and 25th percentile values (Table 6). Possible basin-wide average storativity values were considered to range from 0.01 to 0.2, conservatively assuming the presence of unconfined or semiconfined aquifer conditions. Storativity values smaller than 0.01 result in essentially zero change in groundwater storage.

A sensitivity analysis was conducted to consider two bounding cases, a small storage decline case and a large storage decline case (Table 7). Resulting estimated groundwater storage change over the hydrologic base period ranges from a loss of 42 ac-ft/yr (small storage decline case, $S = 0.01$, $\Delta h = 0.18$ ft/yr) to a loss of 1,477 ac-ft/yr (large storage decline case, $S = 0.2$, $\Delta h = 0.32$ ft/yr).

With this range of uncertainty in mind, a value of 53 ac-ft/yr groundwater storage loss was chosen for the purpose of the final groundwater balance (base case scenario), assuming storativity (S) of 0.01 and groundwater level decline (Δh) of 0.23 ft/yr (the area-weighted median value for base period [Table 6]). The smaller value of storativity (0.01) was chosen, as it is most consistent with (although still greater than) available Basin storativity data (Appendix D).

4.6 Groundwater Extraction

Annual total groundwater extraction rates were obtained from UWCD (2015) and are presented in Table 8 for 1998 through 2012. Well owners in the Basin report extraction totals to UWCD on a six-month basis (January–June and July–December) and calendar-year totals are reported by UWCD (2015). Water-year total extraction (October–September) was estimated from calendar-year totals as presented in Table 8. Adjustment from calendar-year to water-year extraction required estimating the proportion of annual extraction occurring from October through December of each year. This estimate was based on the relative proportion of reference evapotranspiration (ET_o) that occurs in the Basin from October through December of each year using daily ET_o data obtained from CIMIS Station #198 (Figure 5).

This approach assumes that extraction rates are related directly to ET_o and is based on the relationship among reference evapotranspiration, irrigation requirements, and groundwater extraction rates. This assumption is reasonable for agricultural water supply; however, it may not be valid for municipal water supply that includes non-irrigation uses. During the hydrologic base period, 74 percent of extraction reported to UWCD was reported as agricultural water supply, whereas 26 percent was reported as municipal water supply. Further, municipal water usage does include domestic, municipal, and commercial irrigation that is expected to vary with ET_o similar to agricultural irrigation. Because of the lack of water-year or quarterly groundwater extraction data in the Basin and the fact that the majority of groundwater extraction is for agricultural supply, the ET_o-based method for estimating water-year extraction was used.

Using the approach described above, annual average water-year extraction was estimated to be 25,505 ac-ft/yr, with a range of 23,166 ac-ft/yr (2003) to 27,681 ac-ft/yr (2007). Extraction totaled 26,959 ac-ft/yr for the median-condition precipitation year (2000), 26,253 ac-ft/yr for the 25th percentile year (2012), and 24,165 ac-ft/yr for the 75th percentile year (2010).

Annual groundwater extraction exhibits a weak negative correlation with annual precipitation (Table 8). Water years with less than 18 inches of precipitation in the Basin (i.e., at Santa Paula gages 245A/245B) exhibit annual extraction greater than 26,000 ac-ft/yr, whereas those with greater than 18 inches of precipitation exhibit extraction less than 26,000 ac-ft/yr. However, groundwater extraction in the median precipitation year (2000) was higher as compared to the 25th percentile year (2012). Additionally, the greatest-precipitation year (2005) exhibited greater extraction than several years with lower precipitation rates (2001, 2003, 2006, 2010, 2011). Precipitation in the Basin occurs primarily during winter months, and irrigation and extraction are greatest in summer months when temperature and evapotranspiration requirements are highest. Groundwater extraction annual variability is likely driven by summer evapotranspiration requirements, cropping patterns, groundwater management measures, irrigation efficiency changes, and other crop-growth-related factors in addition to winter precipitation rates.

4.7 Natural Groundwater Outflow

Natural outflow components from the Basin includes groundwater outflow to the Mound and Oxnard Forebay basins, groundwater discharge to the Santa Clara River, discharge to creeks following storm events (i.e., from discharge of bank storage within alluvial sediments underlying creeks), and riparian evapotranspiration. For the purpose of the hydrologic balance and safe yield determination, it is assumed that the principal natural groundwater outflow component is groundwater underflow to the Mound Basin and Oxnard Forebay Basin. Estimation of natural groundwater outflow was constrained by consideration of the remaining calculated water balance components as discussed below in Section 4.7.2.

4.7.1 Groundwater Underflow from Santa Paula Basin to Mound Basin and Oxnard Forebay Basin

Groundwater is considered to flow from the Santa Paula Basin to the Mound Basin and Oxnard Forebay Basin. For example, as stated by UWCD (2012):

> Water level records suggest groundwater likely flows from the Oxnard Plain Basin, Forebay Basin, and Santa Paula Basin into the Mound Basin. Although there are some appreciable offsets on the faults bounding the Mound Basin, the low-permeability Santa Barbara formation does not extend to sufficiently shallow depths to impede groundwater flow. In most cases, there is a significant thickness of the San Pedro Formation (aquifer materials) existing above the faults, or on both sides of the faults. The nature of the faults themselves as an impedance to flow is not known. However, groundwater flow and Basin recharge across these zones is most probable.
>
> However, recorded groundwater elevations in shallower wells in the eastern Mound Basin are often 80 to more than 100 feet lower than those in western Santa Paula. This differential in head produces a large hydraulic gradient across the Basin boundary, and likely results in groundwater flow from the Santa Paula to the Mound Basin. The magnitude of this flow, however, remains unquantified.

UWCD (2012) also suggests further geophysical investigations and aquifer tests in the vicinity of the fault zones that define the boundary of the Mound/Santa Paula basins to provide the basis for resolving flow dynamics. The UWCD report includes a generalized map (UWCD, 2012, Figure 3-3) that depicts groundwater flow from Santa Paula Basin to the Mound Basin (larger arrow) and from the Santa Paula Basin to the Oxnard Forebay Basin (smaller arrow).

UWCD (2014b) documents available interpretations regarding connection of the Santa Paula Basin to the Mound Basin and Oxnard Forebay Basin. The California State Water Resources Board (1953) reported:

> Ground water flow in the Mound Basin moves under pressure, generally in a south-westerly direction, from Santa Paula Basin and from areas of outcrop of the San Pedro Formation which receives percolation of direct precipitation and stream flow in minor watercourses... the primary recharge of the [Mound] Basin is by subsurface inflow through the San Pedro formation from the Santa Paula Basin, and that the contribution from the outcrop of the San Pedro formation to the north of the Basin is of secondary magnitude.

UWCD (2014b) also documents more recent interpretations of connections within these basins, including citations of maps and comments by Hopkins Groundwater Consultants indicating that groundwater flows from the Santa Paula Basin to the adjoining Oxnard Forebay, Oxnard Plain, and Mound basins. VCWPD (2013) is also excerpted:

> Following a review of information regarding the Mound Basin boundaries contained in United Water Conservation District's open File Report 2012-01 and DWR Bulletin 118, it appears that the existing mapped boundaries may not in fact be complete barriers to groundwater flow. We have decided to continue potentiometric surface lines across the southern mapped Mound Basin boundary for the upper and lower system, and across the Santa Paula/Mound Basin Boundary for the upper system in this report. Doing so still demonstrates the boundary condition at the Santa Paula Basin and Mound Basin boundary, while providing information about water levels in the Oxnard Plain and Mound Basin on the same map.

At the southwestern or downgradient side of Santa Paula Basin, the Oak Ridge fault forms a partial barrier to groundwater flow within the San Pedro Formation (but perhaps not the alluvium of the Santa Clara River), whereas the Mound Basin and the Oxnard Forebay Basin adjoin the west/southwest and southwest sides of the Santa Paula Basin, respectively. As has been acknowledged in the past by a few prior investigators, the boundary between the Santa Paula and Mound basins is complex but is generally considered to be formed by the Country Club fault. Structural complexities in this region (namely, the Country Club fault and the Oak Ridge fault zone) appear to at least minimize hydraulic communication between the Santa Paula and Mound Basins.

To further assess these structural issues, RCS reviewed available geologic data to try to determine where the projected fault trace might occur at ground surface and what portion of the stratigraphic section may be displaced, disrupted, or folded. The latter interpretation is particularly difficult and subject to uncertainty because of several factors, including lack of E-logs in sufficient locations, lack of E-logs near and on both sides of the fault structures, and lack of E-logs that include resistivity signatures in the shallower sediments (the lack of E-log signatures in shallower sediments is a problem particularly for oil well E-logs).

Using Darcy's Law and methods as described above for groundwater inflow (Section 4.2), RCS estimated groundwater outflow along the southern Basin boundary. Although groundwater outflow within the San Pedro Formation was preliminarily evaluated, based on RCS hydrogeologic interpretation, it was assumed that there is no flow through the San Pedro Formation at the outflow boundary. As illustrated on the groundwater elevation contour maps (Appendix F), available groundwater elevation data suggest that some water may move across the outflow boundary within the San Pedro Formation. This is suggested by the southerly spreading of water level elevation contours across the interpreted ground surface location of the fault. However, the contour maps are based on sparse data and rely on some wells that may be perforated across the San Pedro/undifferentiated alluvium geologic boundary. Further, if the assumption is made that groundwater does indeed move through the fault zone within the San Pedro Formation, determining what the reduced lateral hydraulic conductivity value through the fault area might be is considered subjective (assuming the fault acts as a partial barrier to flow) due to lack of requisite data. Additionally, if water is moving through that outflow boundary within the San Pedro Formation, the movement may not occur through the total thickness of the San Pedro Formation, but rather possibly only through the upper portion of this formation. Data to determine the thickness through which groundwater does move across the boundary (and through a portion of the San Pedro Formation) are unavailable. Therefore, RCS assumed groundwater outflow through the undifferentiated alluvium only. Even if water does move through the fault boundary within the San Pedro Formation, the volume is likely small in comparison to the volume that moves through the more highly permeable alluvial sediments.

Lateral hydraulic conductivity for the undifferentiated alluvium and active channel deposits were determined by RCS data compilation from work by others, including FugroWest (2007), as listed in Table D-4. Hydraulic conductivity of the active channel deposits was assumed to be 300 ft/d (FugroWest, 2007). For the undifferentiated alluvium, hydraulic conductivity was assumed to be 94 ft/d, taken from the geometric mean of (1) the geometric mean of specific capacity-derived values for the West End Santa Paula Basin/Saticoy Area wells interpreted to produce water from only the undifferentiated alluvium (Table D-1) and (2) the geometric mean of hydraulic conductivity for nine wells reported by FugroWest (2007). Hydraulic gradients in the outflow area were obtained from the RCS groundwater elevation contour maps (Appendix F).

Contoured groundwater elevation data for all the maps created (Appendix F) display the impact of the groundwater barriers in the western and particularly the southern portions of the Basin (illustrated by a steepening of the water level elevation contours). This barrier appears to exist in the general vicinity of the fault shown on the geologic map, as also shown on Cross

Section A-A'. Subsurface geologic and/or E-log evidence of the fault extending east of Cross Section A-A' were not observed by RCS. However, the groundwater elevation contour data in the area east of Cross Section A-A' suggest that the barrier extends to the south/southeast toward the Santa Clara River and South Mountain. This barrier appears to be approximately in the area at which the settlement boundary crosses the Santa Clara River. Hence, the geologic data and the groundwater elevation contour data were used to define the southern outflow boundary of the Basin, as illustrated on Cross Section X-X' and the corresponding location map (Appendix B). Cross-sectional areas were determined for each polygonal segment in Cross Section X-X', excluding those segments considered to represent the San Pedro Formation (shown as orange color).

Table D-6 compiles lateral hydraulic conductivity, gradient, and cross-sectional area information for each polygonal segment of Cross Section X-X', and presents the final calculated groundwater outflow for water years 2000, 2010, and 2012. Average annual groundwater outflow for the three selected years is estimated to be 7,349 ac-ft/yr. However, given data gaps and uncertainty as discussed above, this value is considered a general estimate of outflow at the Basin boundary. Future investigations of the Oxnard Forebay and Mound Basins may help to inform the estimated outflow from Santa Paula into these basins.

4.7.2 Estimated Natural Groundwater Outflow

In consideration of uncertainty related to calculating lateral groundwater outflow and discharge to the Santa Clara River, natural groundwater outflow (the combination of lateral outflow, discharge to surface water, and riparian evapotranspiration) was estimated from the remaining groundwater balance components by rearrangement of Equation 4-1:

$$O_{nat} = [P_p + P_i + GW_i + WWTP + Se] – E – \Delta GW_s \qquad \text{[Eq. 4-4]}$$

In this way, average annual natural groundwater outflow was estimated to be 11,808 ac-ft/yr for the entire base period (Table 9). This value is similar in magnitude to the average annual groundwater outflow independently estimated by RCS of approximately 7,349 ac-ft/yr (Table D-6), although larger by approximately 4,460 ac-ft/yr allowing for additional natural outflow components (i.e., discharge to Santa Clara River, riparian evapotranspiration). The estimated average annual natural groundwater outflow of 11,808 ac-ft/yr is therefore considered to be a reasonable estimate for the purpose of the groundwater balance.

4.8 Final Groundwater Balance

The final groundwater balance is presented in Table 9 for the entire base hydrologic period (1999 through 2012) and for the representative years 2000, 2010 and 2012. Average annual groundwater inflow is estimated to be 37,260 ac-ft/yr and to range from 26,783 ac-ft/yr for 2012 (25th percentile) to 48,861 ac-ft/yr for 2010 (75th percentile). Groundwater inflow from the Fillmore Basin represents the majority of groundwater inflow (25,244 ac-ft/yr on average, 68 percent). Note that average groundwater inflow as underflow from the Fillmore Basin is calculated as the average of calculated underflow for April of 2000, 2010 and 2012, the 3 years for which inflow calculations were conducted (Sections 3.8, 4.2). Remaining groundwater inflow component averages were taken as the average of all 14 years within the hydrologic base period. Error associated with using a 3-year rather than a 14-year average for the underflow calculation was evaluated by analysis of precipitation records. The 14-year (1999–2012) average precipitation for Gage 225 (Wheeler Canyon) is 21.6 inches, whereas the 3-year average (2000, 2010, 2012) is 18.9 inches, or 13 percent smaller. Assuming a relationship between precipitation and groundwater flow from Fillmore to Santa Paula, the underflow calculation may be underestimated by a similar margin.

Remaining inflow components, in order of magnitude, include deep percolation of precipitation (6,549 ac-ft/yr, 18 percent), deep percolation of irrigation (3,879 ac-ft/yr, 10 percent), Santa Paula Creek percolation (1,105 ac-ft/yr, 3 percent), and percolation from wastewater effluent and septic systems (483 ac-ft/yr, 1 percent). Increased total groundwater inflow in wet years as compared to drier years is driven by increases in several of the inflow components. Total inflow is 22,078 ac-ft/yr greater in 2010 (75th percentile) compared to 2012 (25th percentile). This 22,078 ac-ft/yr increase is attributed to increased inflow from the Fillmore basin (39 percent), increased deep percolation of precipitation (25 percent), increased deep percolation of irrigation (32 percent), and increased Santa Paula Creek percolation (4 percent).

Annual groundwater outflow was 37,313 ac-ft/yr on average, and ranged from 27,752 ac-ft/yr (2012, 25th percentile) to 47,453 ac-ft/yr (2010, 75th percentile). The principal outflow component was groundwater extraction (25,505 ac-ft/yr, 68 percent), while the remaining outflow was attributed to natural outflow (i.e., the combination of lateral outflow, discharge to surface water, and riparian evapotranspiration; 11,808 ac-ft/yr, 32 percent). Note that because groundwater outflow is calculated based on the remainder of the remaining groundwater balance components (Equation 4-4), including groundwater inflow, it may be underestimated due to the use of a 3-year rather than a 14-year average for the inflow component.

While changes in groundwater extraction rates are relatively minor from year to year, natural groundwater outflow is estimated to increase substantially in wet years as compared to dry years. This indicates that most of the increase in groundwater inflow during wet periods exits the Basin as natural outflow rather than remaining in storage within the Basin for extended periods. This is also consistent with the relatively minor changes in groundwater storage from dry to wet years as compared to corresponding changes in inflow (Table 9). For example, groundwater inflow is 22,078 ac-ft/yr greater in 2010 (75th percentile) compared to 2012 (25th percentile), but estimated difference in the change in storage between the two years is only 2,377 ac-ft/yr. Comparing the same two years, natural groundwater outflow is estimated to be 21,789 ac-ft/yr greater in 2010 compared to 2012.

Table 7 presents a sensitivity analysis of the average groundwater balance (1999–2012) considering the base case, small storage decline, and large storage decline cases (Section 4.5). Groundwater inflow components are identical for all three cases. Change in storage is similar for the small storage decline case (42 ac-ft/yr loss in storage) as compared to the base case (53 ac-ft/yr loss), and the large storage decline case includes 1,477 ac-ft/yr loss. Groundwater extraction is identical for all three cases. Natural groundwater outflow is greatest for the large storage decline case (13,232 ac-ft/yr) and is similar for the base and small storage decline cases (11,808 and 11,796 ac-ft/yr, respectively). The final groundwater balance is shown graphically for the base case scenario in Figure 14 and for the large storage decline case in Figure 15.

4.9 Limitations

The groundwater balance was performed using standard hydrogeologic approaches (e.g., Fetter, 2001; Freeze and Cherry, 1979) and available Basin data. Uncertainties in the groundwater balance are due to data limitations and necessary assumptions inherent to Basin-scale hydrologic analyses, and are typical of similar studies in arid and semi-arid environments. Significant data gaps and limitations are listed below:

- While safe yield analyses generally include a base period on the order of at least 30 to 50 years, the hydrologic base period for this Study was only fourteen years out of necessity, and was chosen because it was a period that reflects changes in Basin hydrologic conditions following construction of the Freeman Diversion (1991) and U.S. Army Corps of Engineers projects on lower Santa Paula Creek (1998).

- Groundwater inflow estimates are based on analysis of three representative years (Section 4.2). This limitation may lead to an underestimate in underflow calculation of 13 percent (Section 4.8).

- Deep percolation of irrigation and precipitation is based on application of the DPWM, and modeling simplifying assumptions included constant annual irrigation rates and land use during the base period. Additional limitations associated with DPWM are listed in Section 4.3.2.

- Santa Paula Creek recharge is based on limited available gage data collected in 2011 and 2012 (Section 4.3.6).

- It is assumed that wastewater discharge prior to 2010 did not contribute to the groundwater balance (Section 4.5).

- Groundwater discharge to Santa Clara River and/or recharge from the river to groundwater are not separately quantified. A net groundwater discharge to the river is assumed, and groundwater discharge is lumped in as a part of 'natural outflow' together with groundwater underflow (Section 4.7).

- Groundwater change-in-storage is sensitive to Basin storativity, and available Basin data may be skewed by the duration of the available aquifer tests (typically limited to 24 hours); Basin-specific storativity values representative of unconfined or semiconfined undifferentiated alluvium are not available (Section 4.5). A sensitivity analysis was conducted to evaluate the impact of uncertainty related to assumed storativity values (Section 4.5).

- Groundwater outflow from the Santa Paula Basin to the Mound and Oxnard Forebay Basins is currently poorly understood and difficult to quantify (Section 4.7). For this reason, natural outflow estimates were constrained by consideration of the remaining calculated water balance components.

- Further study is necessary to determine the impact of historical production that was shifted circa 2014 from the Santa Paula Basin to the Fillmore Basin, specifically to newer wells located within several hundred feet of the Santa Paula Basin-Fillmore Basin boundary. The impact of these changes in production on water levels in the Santa Paula Basin is not analyzed in this Study.

5. Safe Yield

5.1 Safe Yield Methodology

As outlined in the previous Basin safe yield study (SPBEG, 2003), several methodologies are available for estimation of safe yield, including the following:

- *Hydrologic balance:* With an adequate conceptual understanding of the Basin and sufficient hydrologic/hydrogeologic data, safe yield can be estimated such that the sum of groundwater inputs minus the sum of groundwater outputs (including extraction) will equal zero and there will be no predicted net decline in groundwater storage or levels. Uncertainties in calculating components of the hydrologic balance may become problematic for application of this method, and for this reason it was not used in the previous 2003 effort.

- *Correlation of groundwater levels and extractions (e.g., Modified Hill Method):* A statistical comparison of groundwater levels and extraction rates may be used to estimate allowable safe yield. Poor statistical correlations (i.e., coefficient of determination [R^2] < 0.1) have reportedly prevented this from being a valid approach for previous analyses, including the 2003 study.

- *Assumption that average extraction rate during base period is acceptable.* A simplified version of statistical comparison of extraction rates and groundwater levels, this method assumes that if no net decline is observed over a base period, the annual average extraction rate during that period is acceptably safe. However, this method is not viable if groundwater levels actually decline during the base period, because the method provides no basis for calculating necessary reductions in extractions (or augmenting of supply) based on an understanding of the hydrologic balance. The 2003 study conclusions were based on this method, although the study reported that water level measurements for 14 wells with adequate data indicated an average decline of 4.9 feet over the base period.

- *Groundwater modeling.* A sufficiently calibrated groundwater model provides a powerful tool for understanding groundwater inflow and outflow, and if available, is ideal for estimation of safe yield. However, no model is yet available within the Basin (UWCD is currently developing a regional numerical model that includes the Basin). The currently available USGS regional groundwater model (Hanson, 2003) does not include sufficient calibration to observed groundwater levels in the Santa Paula Basin.

Based on previous experiences with estimation of safe yield in the Basin (Law-Crandall, 1993; SPBEG, 2003) and current data availability, it was determined that the hydrologic balance method is the only appropriate methodology currently available for estimation of Basin safe yield and this approach was therefore used. Correlation of groundwater levels and extraction rates (e.g., Modified Hill Method) has reportedly failed during previous attempts; although the Law-Crandall (1993) safe yield determination is based on the Hill method, correlations between annual water-level change and extraction were poor. Basing safe yield on the annual average extraction rate during the base period assumes that there was no net decline in groundwater elevations within the Basin during the base period, and is therefore not applicable. Finally, no sufficiently calibrated groundwater model is currently available, and creation of such a model is beyond the scope of this safe yield study.

5.2 Safe Yield Definition

Several definitions of *safe yield* of a groundwater basin exist in regulatory guidance and the technical literature (including for similar terms such as *operational yield* and *perennial yield*). For the purposes of this study, the definition provided by Groundwater Resources Association of California guidance on groundwater management planning (Bachman et al., 2005) was adopted:

> The maximum quantity of water that can be withdrawn annually from a groundwater resource under a given set of conditions without causing an undesirable result. The phrase “undesirable result” is understood to refer to a gradual lowering of the groundwater levels resulting eventually in depletion of the supply, subsidence, increased energy costs, desiccated wetland or degraded water supply.

The present study does not explicitly account for environmental water uses (e.g., instream flow in the Santa Clara River for aquatic habitat); for the purpose of the safe yield determination it is assumed that water supplied for environmental uses during the hydrologic base period is acceptable.

Fetter (2001) provides a useful discussion of safe yield, focusing on the fact that safe yield cannot be calculated simply as the sum of all groundwater recharge (inputs) into the system:

> No matter how many papers are published on the concept of safe yield and its inherent complexity, misunderstandings seem to persist. Theis (1940) emphatically stated that the safe yield of a ground-water basin was not the long-term recharge to the ground water. In 1938, in his paper on dynamic equilibrium, Theis clearly demonstrated that under natural conditions, recharge was equal to discharge and that any artificial discharge via wells would result in disequilibrium in the system.
>
> Sophocleous (1997) wrote the following in an editorial in Ground Water: "Despite being repeatedly discredited in the literature, safe yield continues to be used as the basis of state and local water-management policies, leading to continued ground-water depletion, stream dewatering and loss of wetland and riparian ecosystems. Traditionally 'safe yield' has been defined as the attainment and maintenance of a long-term balance between the amount of water withdrawn annually and the annual amount of recharge.... Unfortunately, this concept of safe yield ignores discharge from the system."
>
> Thus, more than a half century after Theis's seminal paper on dynamic equilibrium in aquifer systems, practicing hydrogeologists are still not recognizing that ground-water development potential in aquifers is limited to something less than the long-term annual recharge because of natural system discharge.

For the current determination of Basin safe yield, DBS&A adopted these recommendations of Fetter (2001), and citations therein, and considered natural system discharge (outflows). Within the Santa Paula Basin, groundwater inputs are underflow from the Fillmore Basin (GW_i), recharge by percolation of precipitation including Santa Paula Creek percolation (P_p) deep percolation of irrigation (P_i), recharge from the SPWRF (WWTP), and recharge from septic systems (Se). Primary groundwater outflows include extraction (E) and natural groundwater outflow (O_{nat}) (Table 8). Mathematically, the groundwater balance is described by Equation 4-1.

The objective of this safe yield analysis is to estimate the maximum extraction rate that may not result in further long-term declines in groundwater levels and groundwater in storage. Therefore, Equation 4-1 is rearranged by setting ΔGW_s equal to 0 and solving for extractions representative of safe yield ($E_{safe\text{-}yield}$):

$$E_{safe\text{-}yield} = P_p + P_i + GW_i + WWTP + Se - O_{nat} \qquad \text{[Eq. 5-1]}$$

Because O_{nat} is also estimated by rearrangement of Equation 4-1 (see Equation 4-4), $E_{safe\text{-}yield}$ can also be expressed as:

$$E_{safe\text{-}yield} = E + \Delta GW_s \qquad \text{[Eq. 5-2]}$$

where E = Current groundwater extractions

Application of Equation 5-1 to estimate safe yield ignores the possibility that increases in extraction may significantly decrease natural system discharge, or increase recharge (i.e., induced recharge), such that there is no net decline in groundwater storage even with increased extractions and the basin remains in equilibrium. An example of this would be increased extraction causing lowering of the water table near a surface stream, such that the stream changes from a gaining reach (i.e., receiving groundwater discharge) to a losing reach (i.e., recharging groundwater). However, within the Santa Paula Basin, long-term declines in groundwater levels indicate that the basin is not in equilibrium (i.e., the sum of groundwater outflow is greater than sum of groundwater inflow). Therefore, the updated safe yield was determined following estimation of the comprehensive groundwater balance (Table 8) and application of Equation 5-1, as described in Section 5.3. Although numbers are reported to the nearest acre-foot per year, the authors are not asserting that level of accuracy in the findings of this Study.

5.3 Safe Yield Determination

An average safe yield value of 25,452 ac-ft/yr was estimated for the hydrologic base period (1999–2012) from the groundwater balance and application of Equation 5-1 (Table 9). Evaluation of Equation 5-2 indicates that potential sources of uncertainty for safe yield estimation include assumed Basin average annual groundwater elevation decline (Δh), Basin storativity (S), and total Basin extraction (E). Potential sources of error related to the assumed total Basin extraction include unaccounted for extraction that is not correctly reported to UWCD (e.g., wells that are not properly metered or reported, or wells incorrectly assumed to be located in adjacent groundwater Basins), or incorrect inclusion of extraction from wells that are not actually withdrawing groundwater from Basin aquifers. For the purpose of this report, total extraction values were obtained from UWCD (2015).

Assumed groundwater level decline and Basin storativity were identified as the most significant sources of error impacting the safe yield estimate (Equation 5-2). Basin storativity is subject to uncertainty because storativity data are apparently not available for unconfined portions of the Basin (Section 4.5). Average annual groundwater elevation decline varies throughout the Basin, and statistical analyses have been conducted to constrain the estimated range (Section 4.5). A sensitivity analysis was conducted to calculate an acceptably conservative safe yield range given uncertainty related to these parameters (Table 7, Figure 16). The statistically conservative range of groundwater level decline was determined to be 0.18 to 0.32 ft/yr (Table 6), and Basin-wide average storativity is considered to possibly range from 0.01 to 0.2 considering the presence of unconfined aquifer units. As presented on Figure 16, considering the full possible range of each of these parameters, an average safe yield range of 24,028 to 25,463 ac-ft/yr is calculated for the hydrologic base period. The safe yield value of 24,028 ac-ft/yr is based on an assumed groundwater elevation decline of 0.32 ft/yr and a storativity of 0.2 (unconfined); whereas the safe yield value of 25,463 ac-ft/yr is based on an assumed groundwater elevation decline of 0.18 ft/yr and a storativity of 0.01 (confined). Considering an even smaller Basin-wide average storativity value of 0.001 would make essentially no difference in the final calculated range, with the maximum safe yield value still equaling approximately 25,500 ac-ft/yr.

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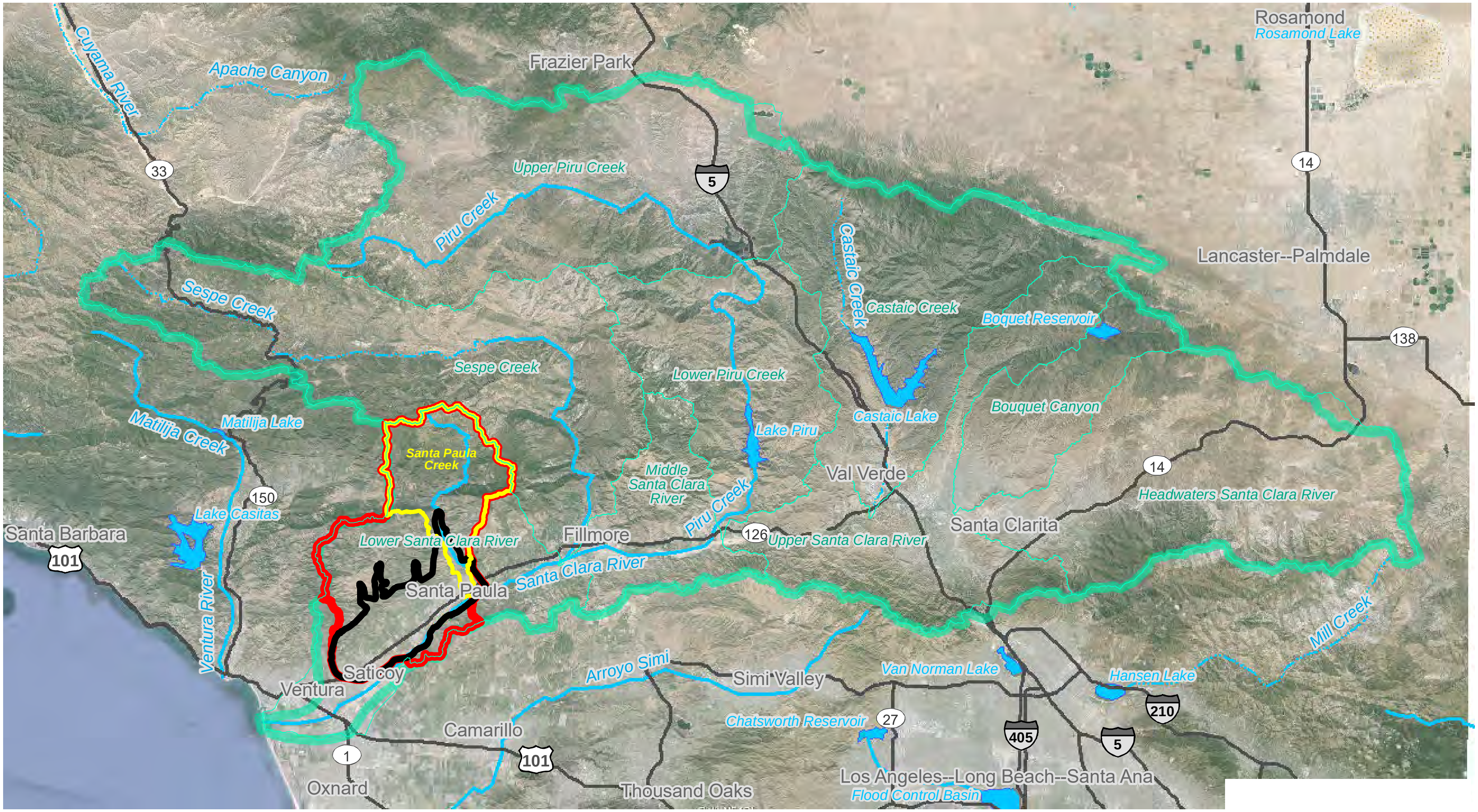
Figures

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\DRAFT_REPORT_FEB_2016\FIG01_BASIN_AND_SUBWATERSHED_LOC.MXD 1/5/2016



N

0 4.5 9 Miles

Explanation

- Santa Paula Creek subwatershed
- Santa Clara River watershed
- Santa Paula Basin settlement boundary
- Subwatershed contributing to Santa Paula Basin
- Other subwatershed

Sources:
1. Aerial imagery dated December 10, 2013 from Google Earth.
2. Watersheds from the National Hydrography Dataset (NHD).

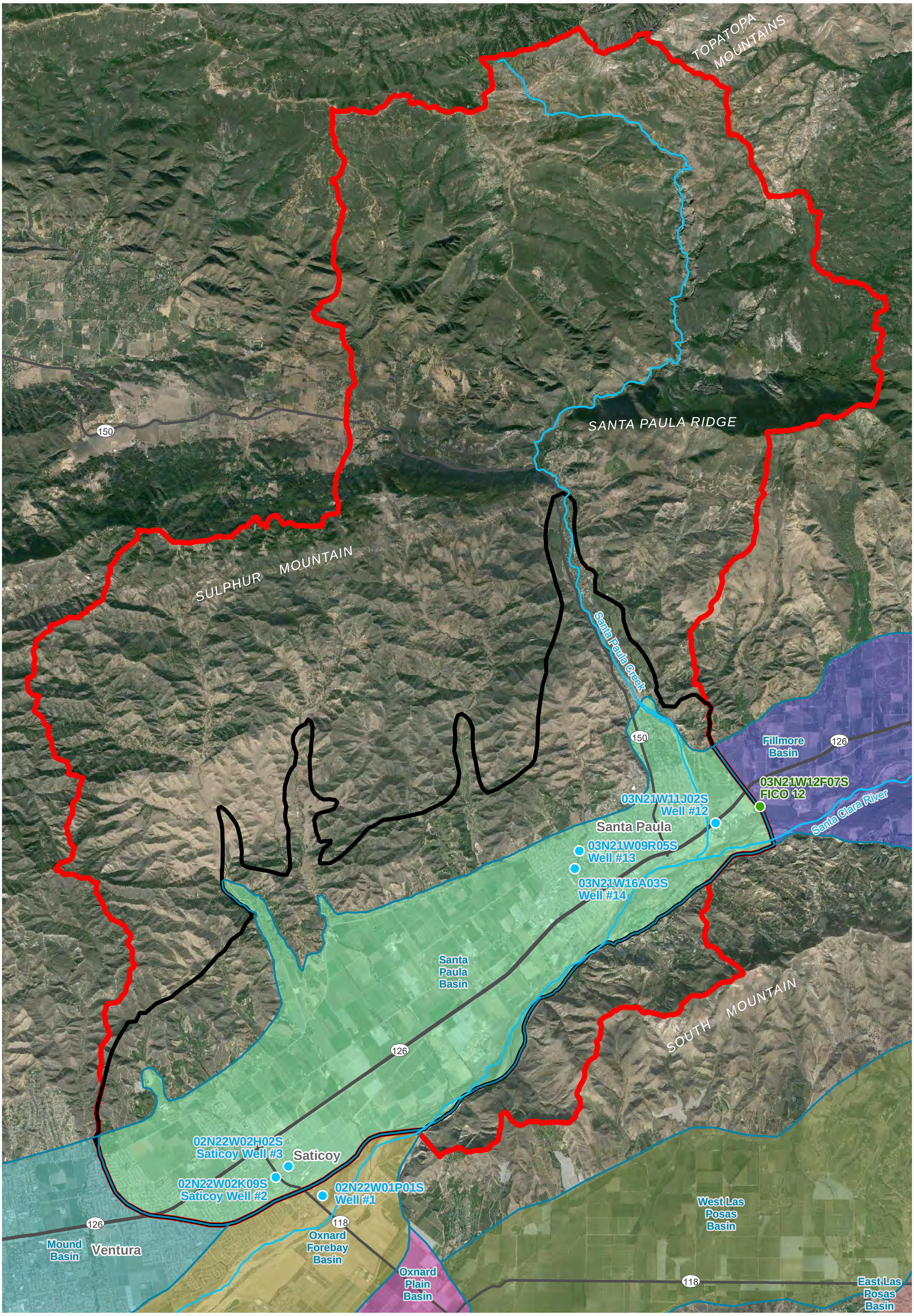
UWCD SAFE YIELD

Santa Paula Basin and Subwatershed Locations

Daniel B. Stephens & Associates, Inc.
1/5/2016
JN WR14.0110

Figure 1

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\DRAFT_REPORT_FEB_2016\FIG02_SANTA_PAULA_BASIN.MXD 1/6/2016



N

0 3,500 7,000 Feet

Explanation

- Municipal production well
- Irrigation well
- Subwatershed contributing to Santa Paula Basin
- Santa Paula Basin settlement boundary
- Extent of alluvium

Sources: 1. Aerial imagery dated December 10, 2013 from Google Earth.
2. Extent of alluvium from UWCD, 2015.
3. Santa Paula Basin settlement boundary from United Water Conservation District vs. City of San Buenaventura, 1996.

UWCD SAFE YIELD

Santa Paula Basin and Contributing Subwatershed

Figure 2

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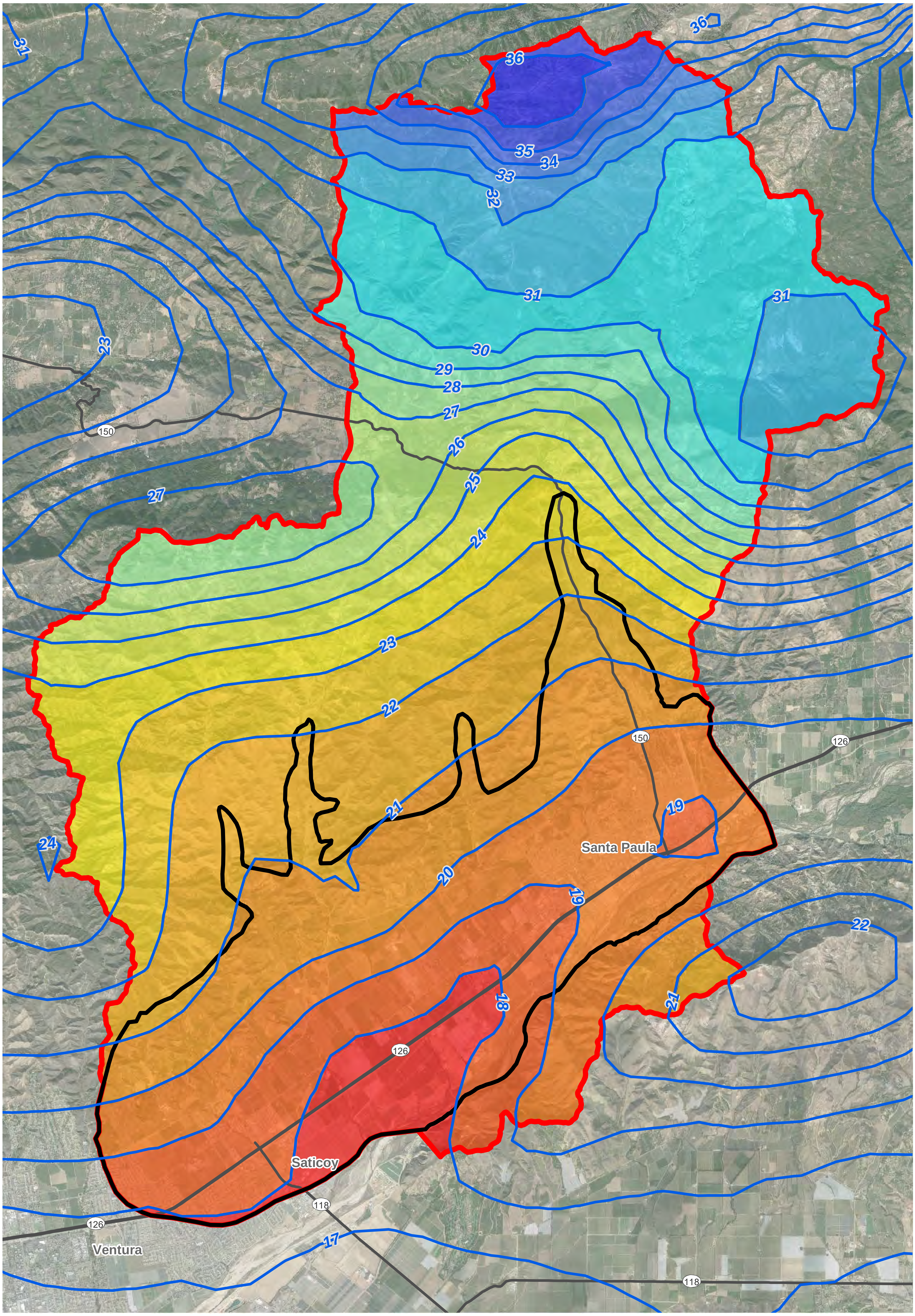
1/6/2016 JN WR14.0110

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\DRAFT_REPORT_FEB_2016\FIG03_AVG_PRECIPITATION.MXD 1/5/2016



Sources: 1. 30-year normal precipitation from PRISM Climate Group, Oregon State University (2013).
2. Aerial imagery dated December 10, 2013 from Google Earth.

Explanation

- Normal annual precipitation (in/yr)
- Subwatershed contributing to Santa Paula Basin
- Santa Paula Basin settlement boundary

UWCD SAFE YIELD

Average Precipitation Isohyetals

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1/5/2016

JN WR14.0110

Figure 3

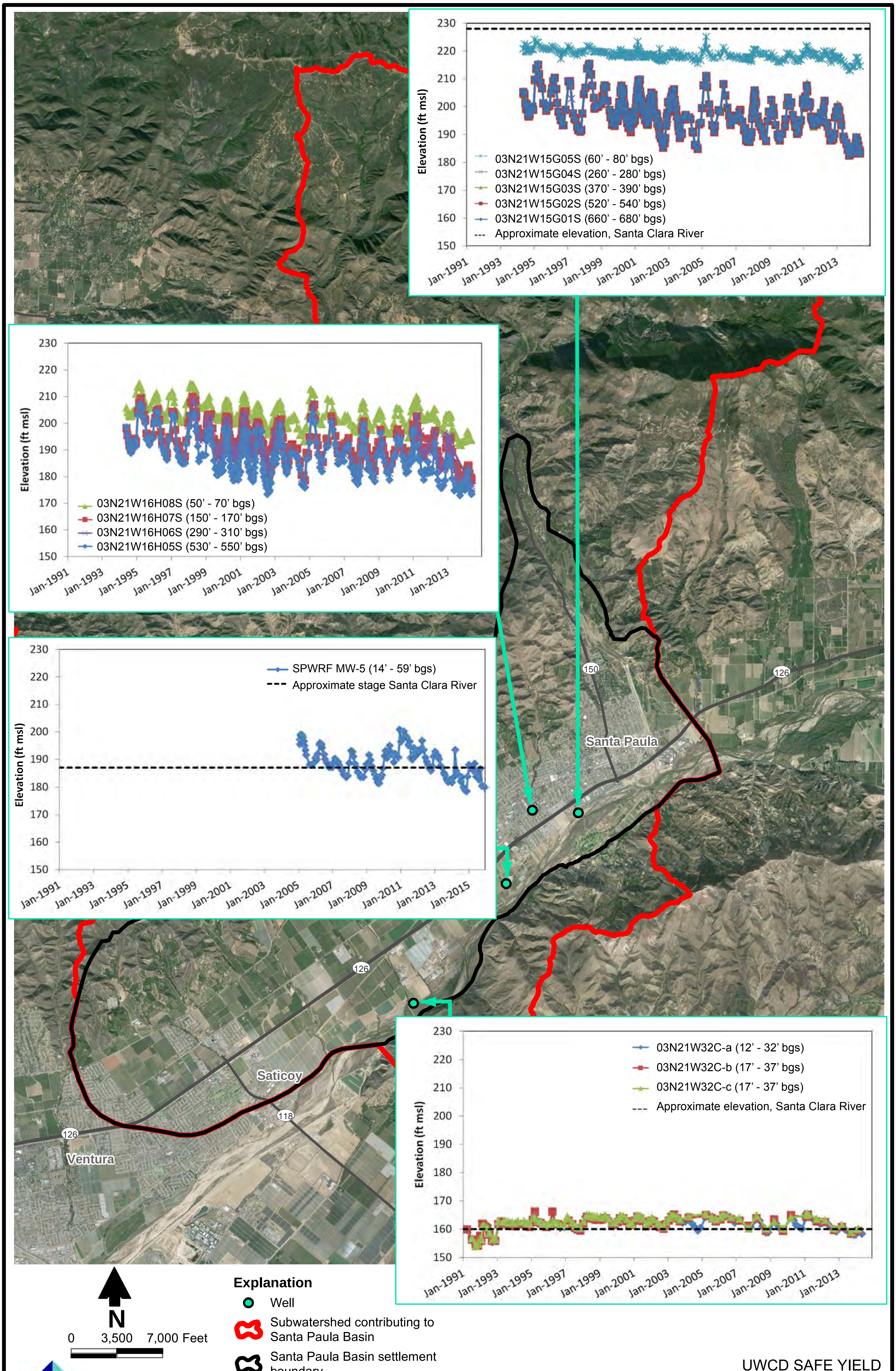


Figure 4

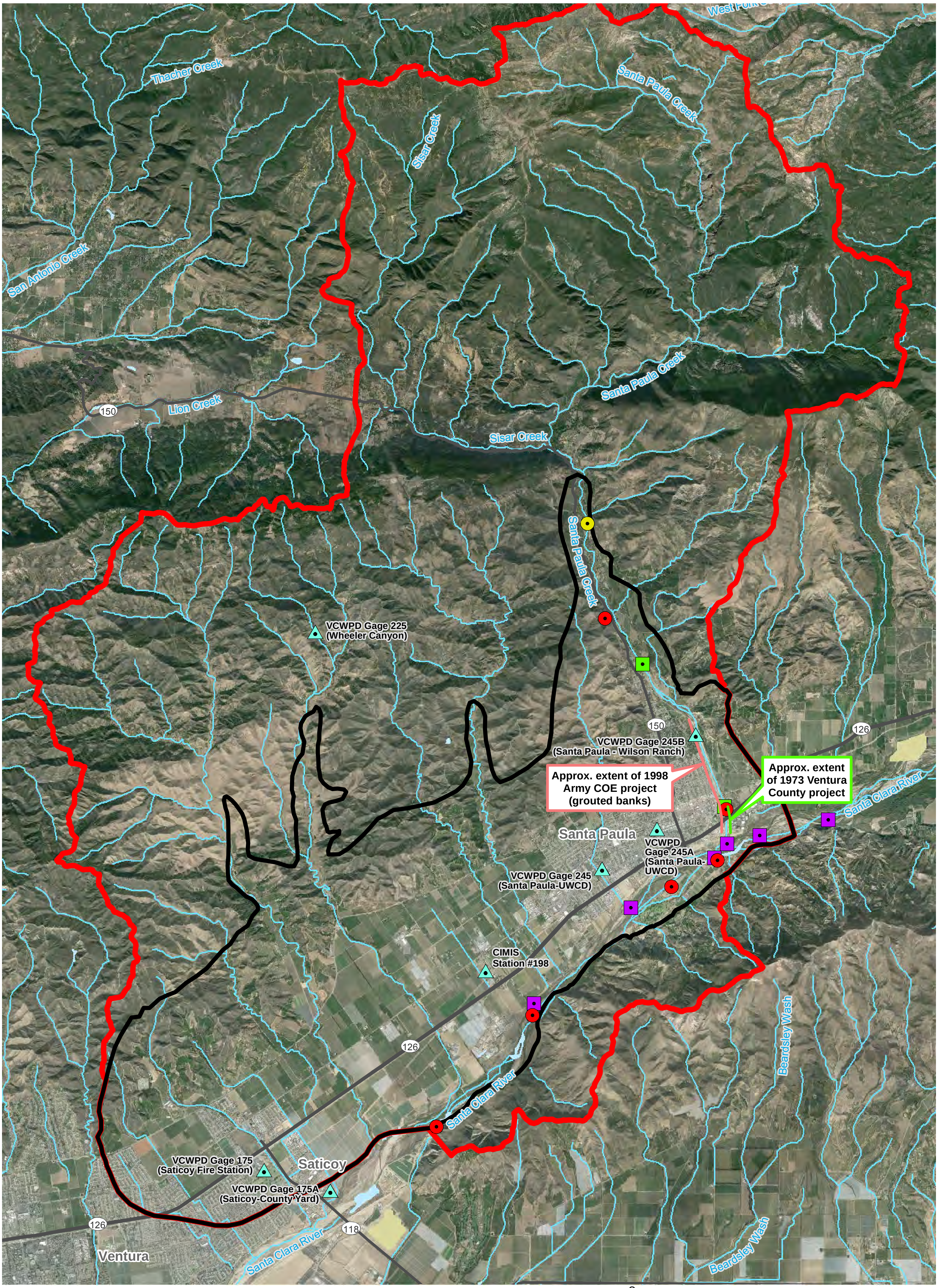
UWCD SAFE YIELD

Hydrographs for Selected Wells

Daniel B. Stephens & Associates, Inc.

2/26/2016

JN WR14.0110



Sources:
1. Aerial imagery dated December 10, 2013 from Google Earth.
2. Streams from ESRI (2010) derived from the USGS National Hydrography Dataset (NHD).

N

0 3,500 7,000 Feet

Explanation

- UWCD gaging locations, April 2011 – February 2012
- UWCD gaging locations, August - September 2011
- USGS (Reichard et al., 1999) gaging location
- USGS Gage 11113500
- Climate station
- Stream
- Subwatershed contributing to Santa Paula Basin
- Santa Paula Basin settlement boundary

Figure 5

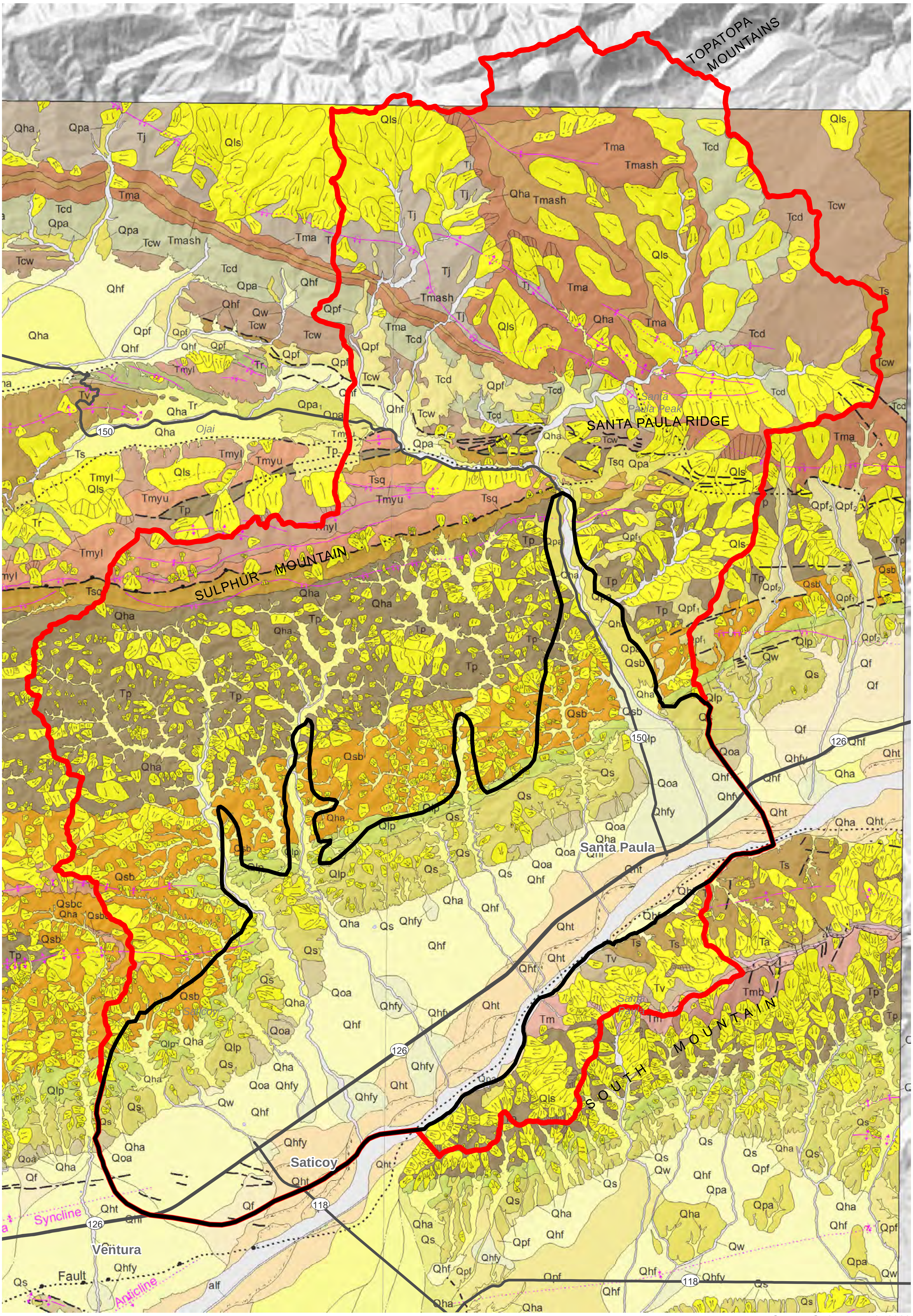
UWCD SAFE YIELD

Surface Water Hydrology and Flow Gaging Locations

Daniel B. Stephens & Associates, Inc.

2/6/2016

JN WR14.0110



Source: Gutierrez et al., 2008

N

0 3,500 7,000 Feet

Explanation

- Subwatershed contributing to Santa Paula Basin
- Santa Paula Basin settlement boundary
- 7.5-minute quadrangle

See Figure 6b for geologic explanation.

UWCD SAFE YIELD
Surficial Geology

Daniel B. Stephens & Associates, Inc.
2/5/2016
JN WR14.0110

Figure 6a

Explanation

Holocene

af	Artificial fill (Holocene)
alf	Artifical levee fill (Holocene)
Qb	Active beach deposits (Holocene)
Qe	Active coastal eolian (sand dune) deposits (Holocene)
Qes	Active coastal estuarine deposits (Holocene)
Qw	Active wash deposits within major river channels (Holocene)
Qw_1	Historically active wash deposits adjacent to active channel (Holocene)
Qhw_3	Wash deposits Unit 3 (Holocene), associated with units Qht_3 and Qha_3
Qhw_2	Wash deposits Unit 2 (Holocene), associated with unit Qha_2
Qhw_1	Wash deposits Unit 1 (Holocene), associated with units Qht_1 and Qha_1
Qhfy	Alluvial fan deposits (latest holocene)
Qhf	Alluvial fan deposits (Holocene)
Qhff	Alluvial fan deposits, fine facies (Holocene)
Ql	Lacustrine deposits (Holocene)
Qls	Landslide deposits (Holocene to Pleistocene)
Qha	Alluvial deposits and colluvial deposits, associated with Qw (Holocene)
Qha_3	Unit 3, associated with unit Qhw_3
Qha_2	Unit 2, associated with unit Qhw_2
Qha_1	Unit 1, associated with unit Qhw_1
Qht	Stream terrace deposits, associated with unit Qw (latest Holocene)
Qht_3	Unit 3, associated with unit Qhw_3
Qht_1	Unit 1, associated with unit Qhw_1
Qhps	Paralic deposits of the Sea Cliff marine terrace (Holocene)

Pleistocene

Qf	Alluvial fan deposits (late Pleistocene)
Qppp	Paralic deposits of Punta Gorda marine terrrace (Pleistocene)
Qpmw	Undivided mass-wasting deposits (Pleistocene)
Qpa	Alluvial deposits, undivided (late Pleistocene)
Qpa_2	Unit 2
Qpa_1	Unit 1
Qpf	Alluvial fan deposits (late to middle Pleistocene)
Qpf_2	Unit 2
Qpf_1	Unit 1
Qoa	Alluvial deposits (early to middle Pleistocene)
Qca	Casitas Formation (Pleistocene)
Qs	Saugus Formation (Pleistocene)
Qlp	Las Posas Formation (Pleistocene)
Qsb / Qsbc	Santa Barbara Formation (Pleistocene) Qsbc - conglomerate

Pliocene

Tp (Tps / Tpsc)	Pico Formation (Pliocene) Tp - undivided Tps -sandstone Tpsc - sandstone and conglomerate
Tsq	Sisquoc Formation (Pliocene-Miocene)

Miocene

Ta	Andesite sill (Miocene)
Tcvai	Conejo Volcanics, andesitic (middle Miocene)
Tcvdi	Conejo Volcanics, dacitic (middle Miocene)
Tcvb	Conejo Volcanics, basaltic (middle Miocene)
Tcvbs	Conejo Volcanics, interbedded with sandstone and siltstone (middle Miocene)
Tcvbb	Conejo Volcanics, basaltic flow breccias (middle Miocene)
Tcvab	Conejo Volcanics, andesitic flow breccias (middle Miocene)
Tcvdb	Conejo Volcanics, dacitic flow breccias (middle Miocene)
Tcvadb	Conejo Volcanics, mix of andesitic and dacitic flow breccias (middle Miocene)
Tdb	Undivided diabase and mafic hypabyssal intrusive rocks (Miocene)
Tmy (Tmyu / Tmyl)	Monterey Formation (middle and late Miocene) Tmy - undivided Tmyu - upper Tmyl - lower
Tm / Tmb	Modelo Formation (Miocene) Tmb - burnt rock
Tr	Rincon Shale (Miocene)
Tt / Tts	Topanga Formation (middle to early Miocene) Tts - dominantly sandstone
Tv / Tvs	Vaqueros Sandstone (early Miocene) Tvs - dominantly sandstone

Oligocene

Ts	Sespe Formation (Oligocene)

Eocene

Tcw / Tcwsh	Coldwater Sandstone (late Eocene) Tcwsh - dominantly shale
Tcd	Cozy Dell Shale (late Eocene)
Tma / Tmash	Matilija Sandstone (middle to late Eocene) Tmash - micaceous shale
Tj / Tjs	Juncal Formation (early to middle Eocene) Tjs - dominantly arkosic sandstone

Cretaceous

Ku	Unnamed conglomerate (late Cretaceous)

Contact between map units - Solid where accurately located, dashed where approximately located; dotted where concealed, queried where uncertain.

27

Fault - Solid where accurately located, dashed where approximately located; short dash where inferred; dotted where concealed, queried where uncertain. Ball and bar on downthrown block. Arrow and number indicate direction and angle of dip of fault plane.

Contact between similar map units; approximately located.

Inferred shoreline angle of marine terraces.

Erosional scarps in terraced alluvial units; hatchures point towards topograhically lower surfaces

Anticline - Solid where accurately located, dashed where approximately located, dotted where concealed, queried where uncertain, arrow indicates direction of plunge.

Overturned Anticline - Solid where accurately located, dotted where concealed, queried where uncertain.

Syncline - Solid where accurately located, dotted where concealed, queried where uncertain arrow indicates direction of plunge.

Overturned Syncline - Solid where accurately located, dotted where concealed, queried where uncertain.

Landslide - arrow indicates principal direction of movement; hachured where headscarp is mappable. The existence of some landslides may be questionable; .

Source: Gutierrez et al., 2008

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\DRAFT_REPORT_FEB_2016\FIG06_GEOLOGY_LEGEND.MXD 2/2/2016

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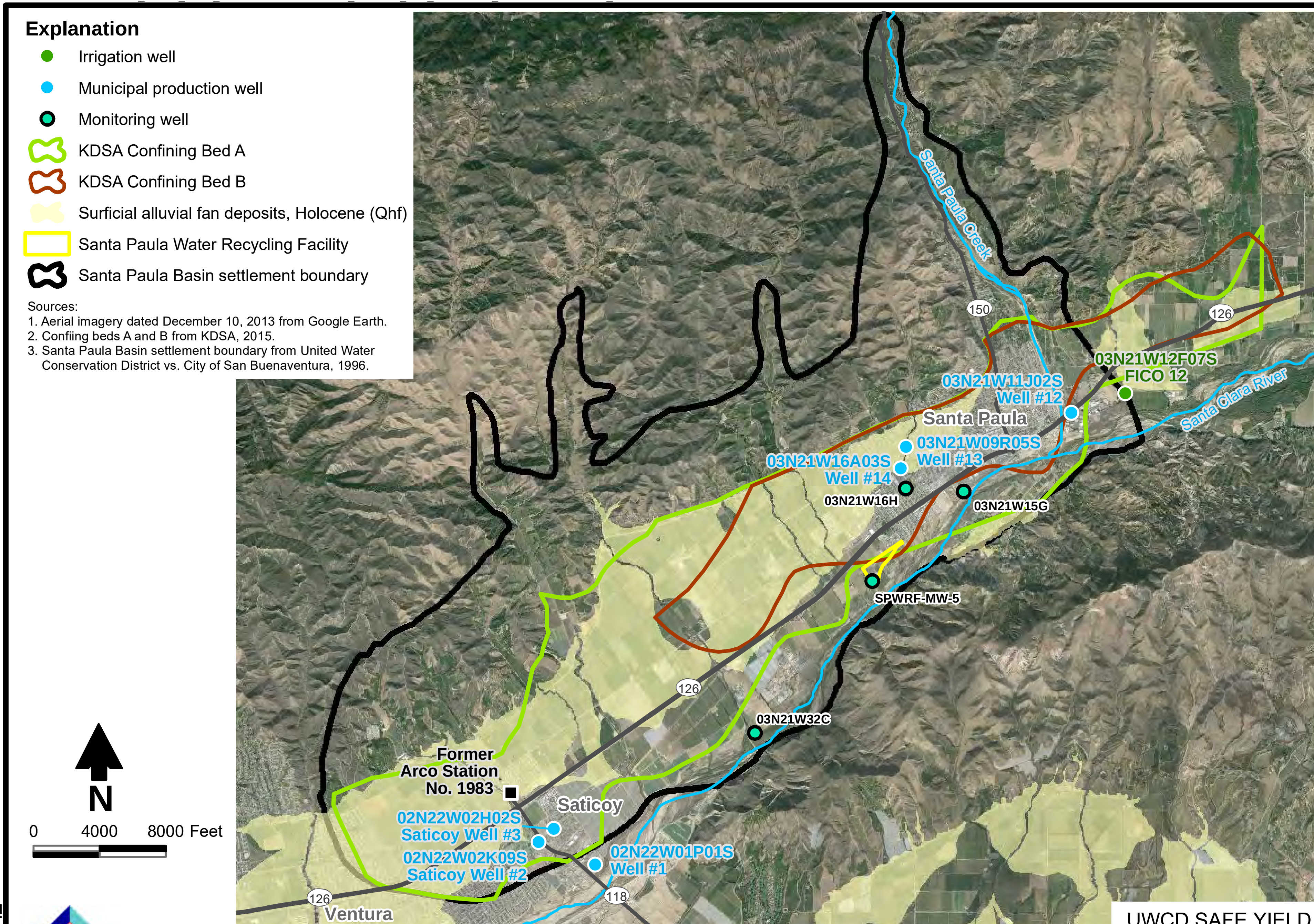
2/2/2016 JN WR14.0110

UWCD SAFE YIELD
Surficial Geology

Figure 6b

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\DRAFT_REPORT_FEB_2016\FIG07_LOW-PERMEABILITY_SEDIMENTS.MXD 2/3/2016



Sources:
1. Aerial imagery dated December 10, 2013 from Google Earth.
2. Confiing beds A and B from KDSA, 2015.
3. Santa Paula Basin settlement boundary from United Water Conservation District vs. City of San Buenaventura, 1996.

UWCD SAFE YIELD

Extent of Low-Permeability Sediments in Alluvial Aquifer

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2/3/2016 JN WR14.0110

Figure 7

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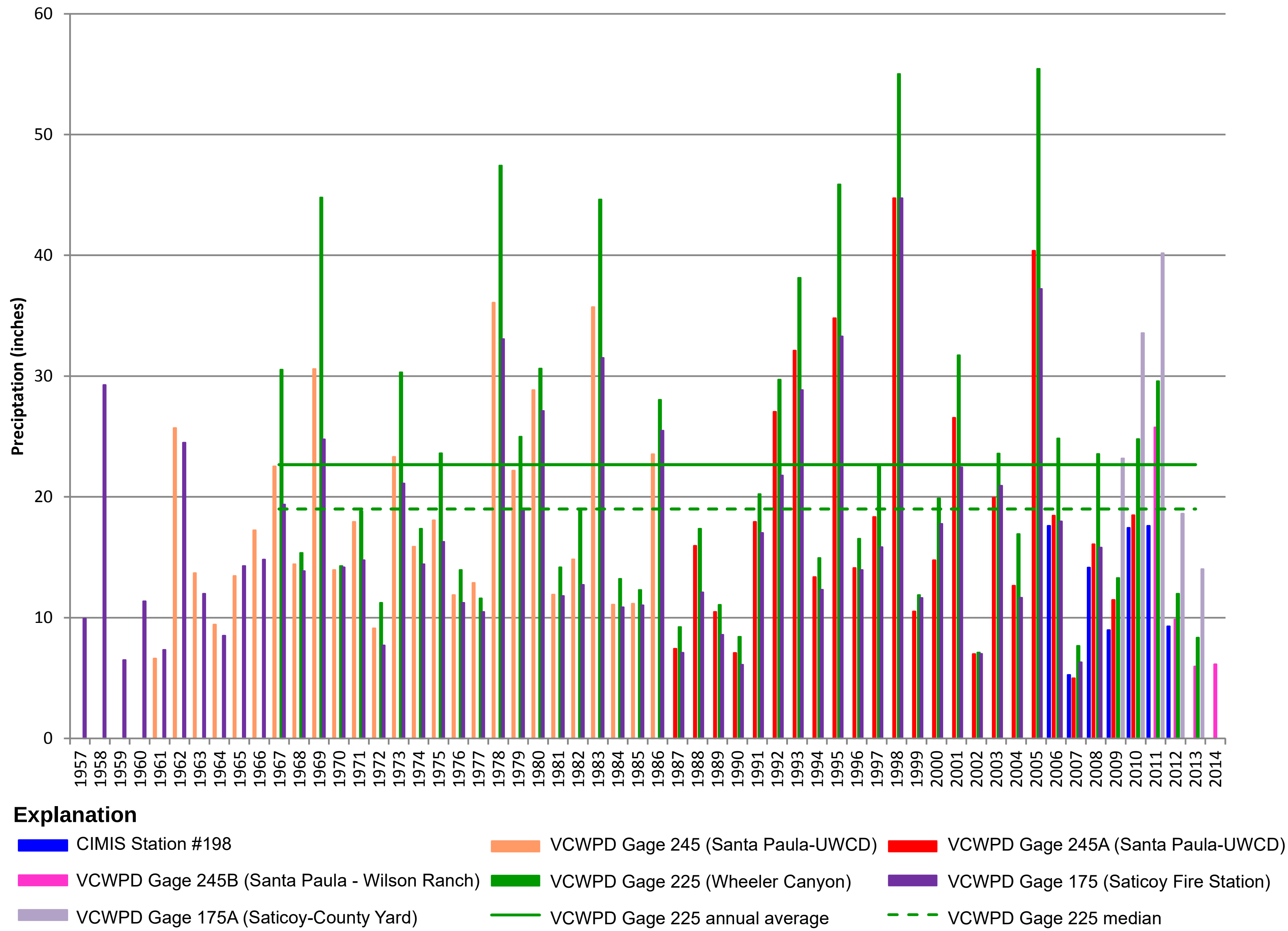

UWCD SAFE YIELD

Annual Precipitation Volume from Available Gage Locations

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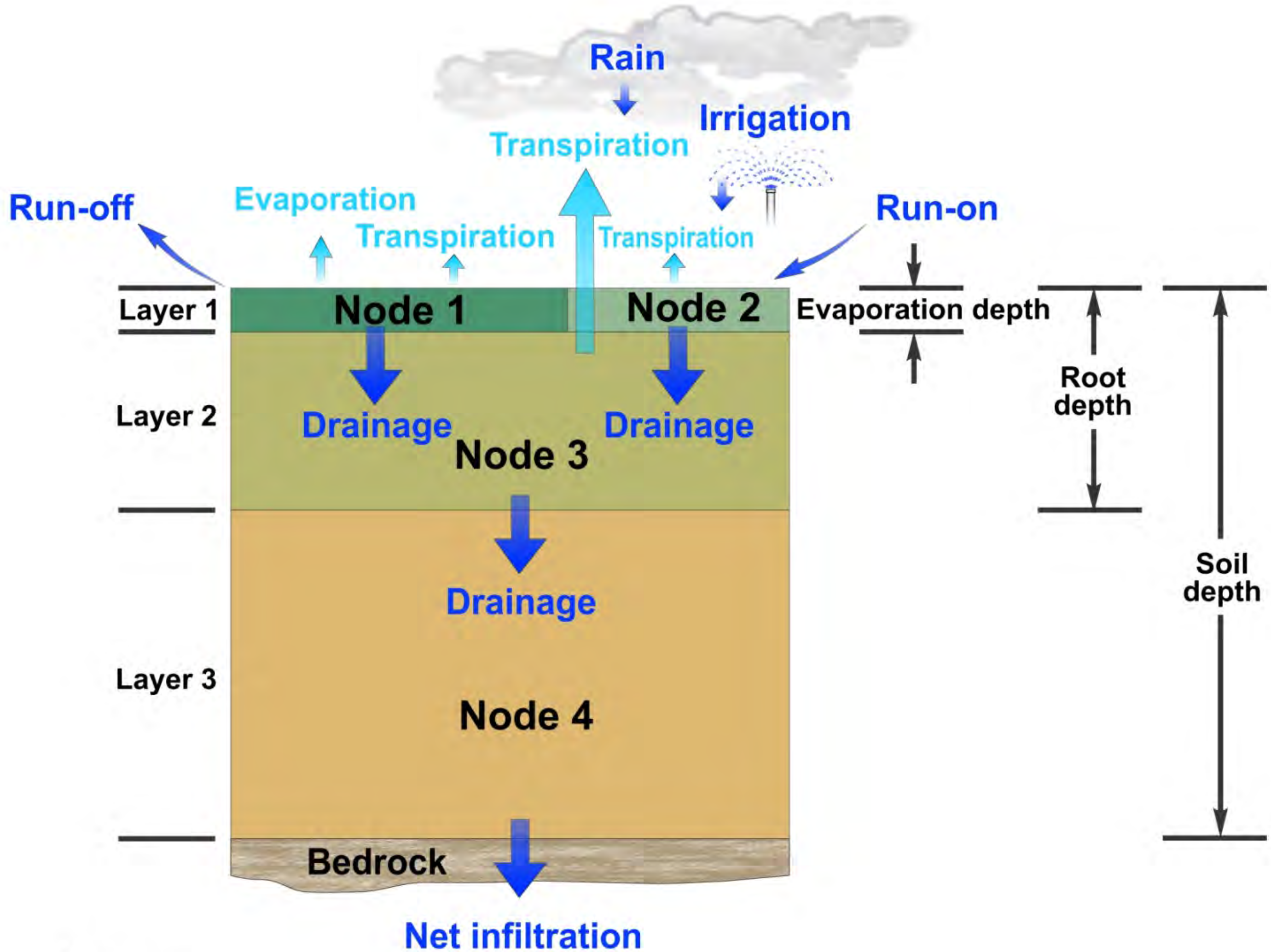
2/2/2016 JN WR14.0110

Figure 8



Notes:

Node 1 = fraction exposed and wetted (f_{ew})
Node 2 = fraction covered by vegetation canopy (f_c)

UWCD SAFE YIELD
Distributed Parameter Watershed Model Schematic

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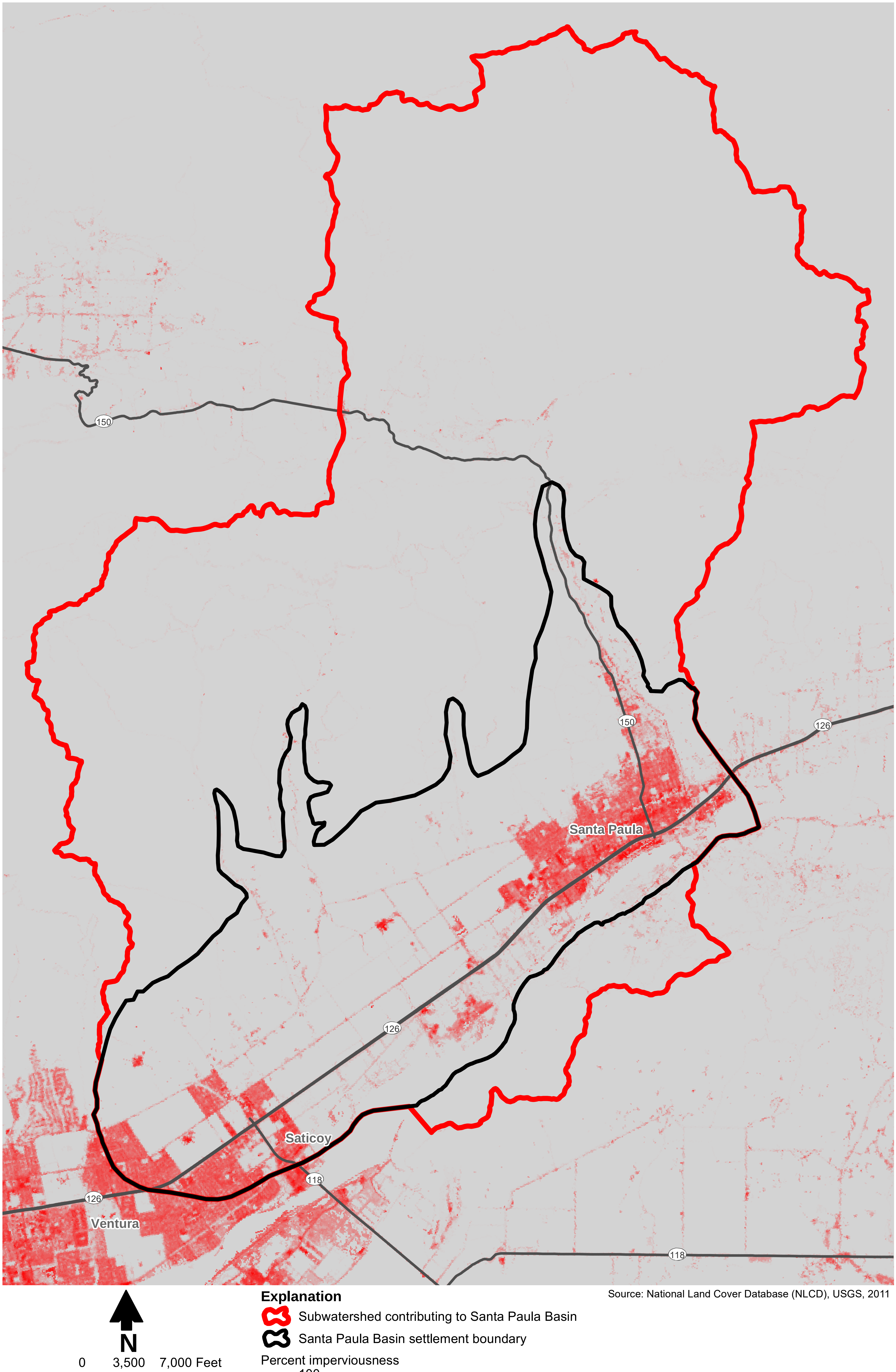
2-2-16
JN WR14.0110



UWCD SAFE YIELD

Percent Impervious Surfaces, 2006

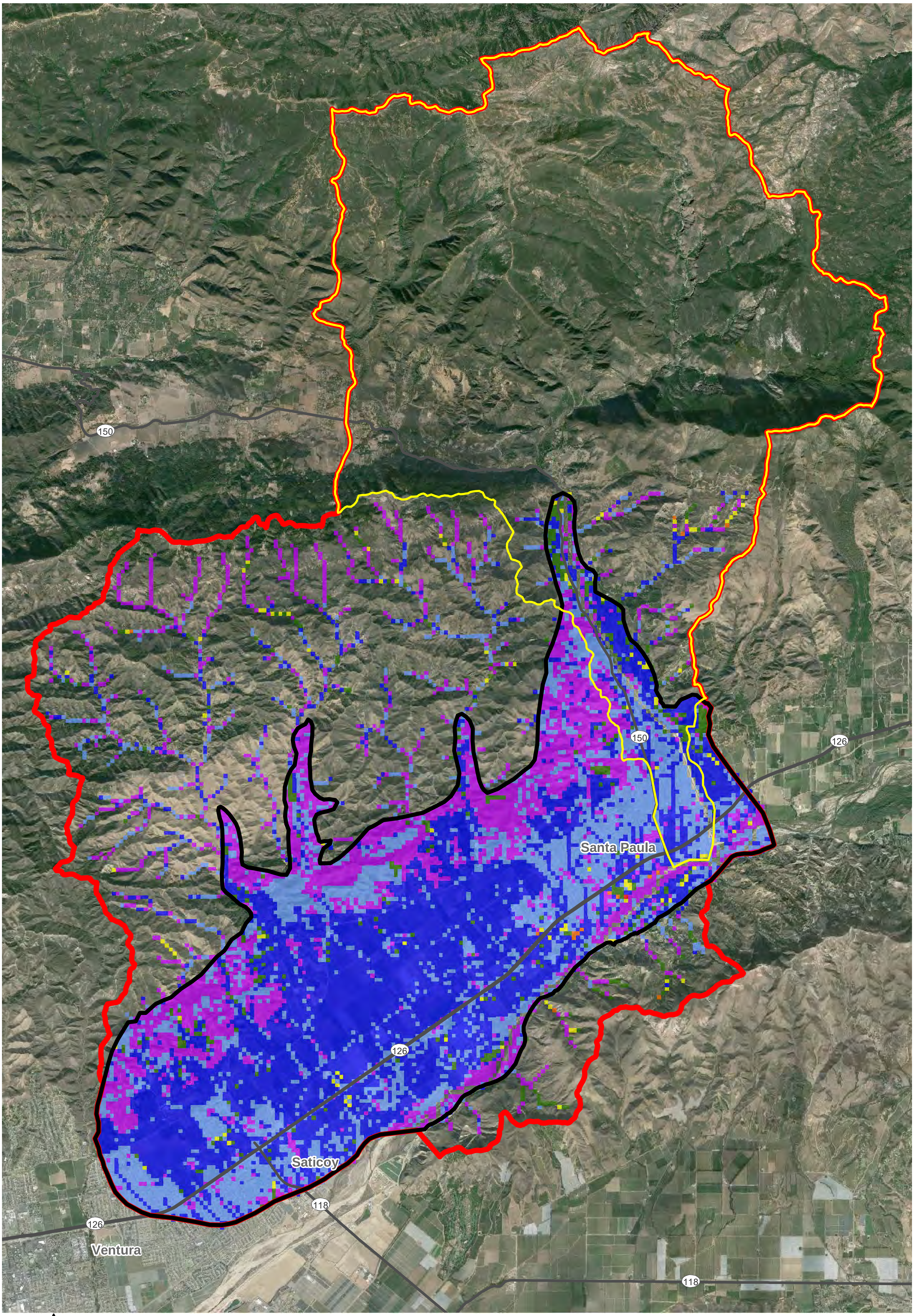
Figure 10

Daniel B. Stephens & Associates, Inc.

2/2/2016

JN WR14.0110

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\DRAFT_REPORT_FEB_2016\FIG11_DPWM_MODEL_RESULTS.MXD 2/2/2016



Aerial imagery dated December 10, 2013 from Google Earth.

N

0 3,500 7,000 Feet

Explanation

Subwatershed contributing to Santa Paula Basin

Santa Paula Basin settlement boundary

Santa Paula Creek subwatershed

Recharge (in/yr)

- 0.001 - 2
- 2.001 - 5
- 5.001 - 10
- 10.001 - 20
- 20.001 - 50
- 50.001 - 100
- > 100

UWCD SAFE YIELD

DPWM Model Results
Average Percolation from Precipitation and Irrigation, 1999-2012

Figure 11

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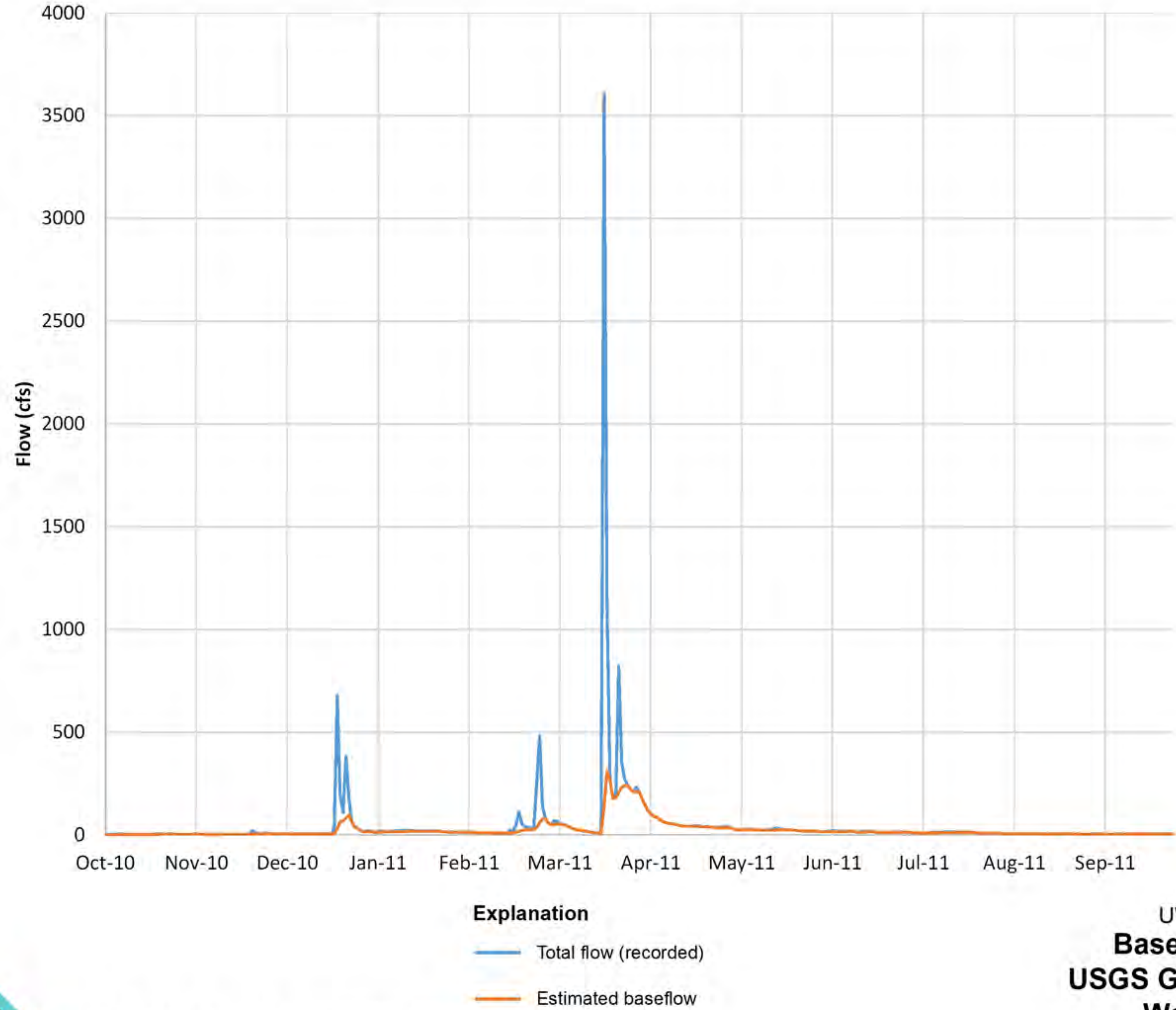
2/2/2016
JN WR14.0110



UWCD SAFE YIELD

Baseflow Analysis
USGS Gage 11113500
Water Year 2011

Figure 12

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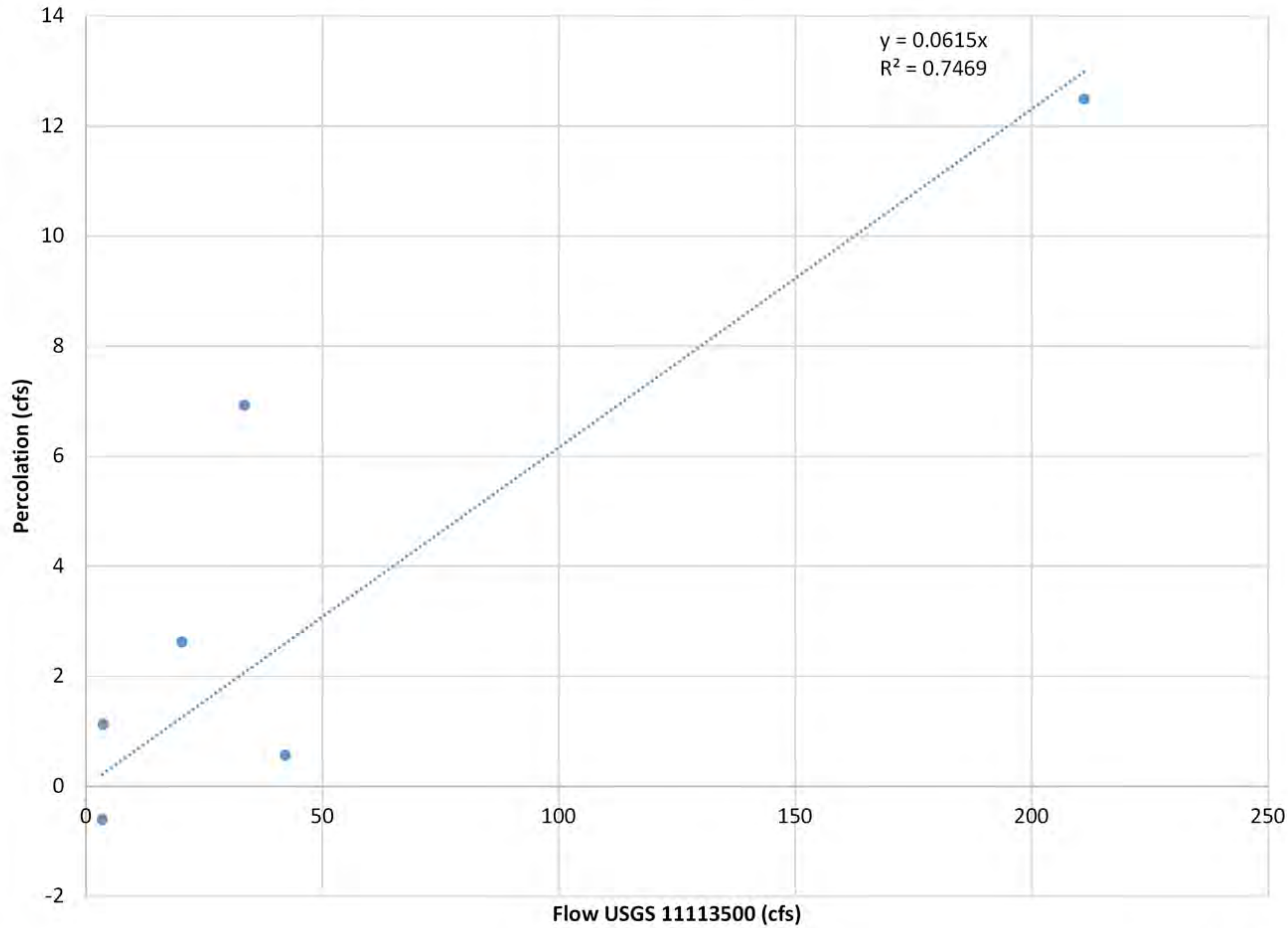
2/2/2016 JN WR14.0110

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\DRAFT_REPORT_FEB_2016\FIG13_LINEAR_REGRESSION.MXD 2/2/2016



UWCD SAFE YIELD

Linear Regresssion

Estimated Percolation and Flow at USGS Gage 11113500

Figure 13

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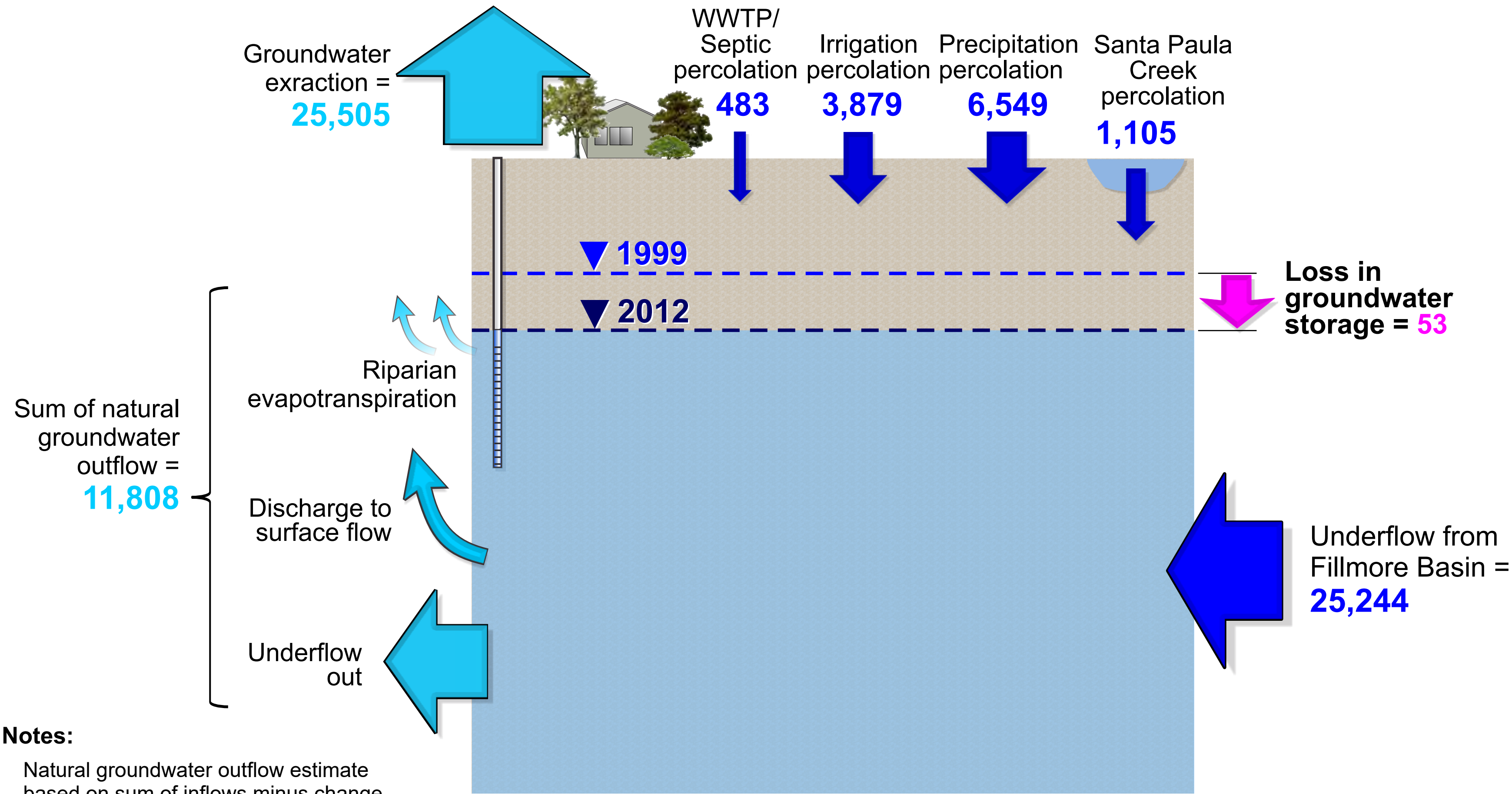
2/2/2016 JN WR14.0110

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\VR_DRAWINGS\FIG14_CONCEPTUAL_GW_BALANCE_MODEL_BASE_CASE.CDR 2-3-16



Notes:

Natural groundwater outflow estimate based on sum of inflows minus change in groundwater storage.

Assumes average groundwater elevation change = -0.23 ft/yr

Storativity = 0.01

Estimated average groundwater inflows/outflows 1999 - 2012 (ac-ft/yr)

UWCD SAFE YIELD

Conceptual Groundwater Balance Model
Base Case

Figure 14

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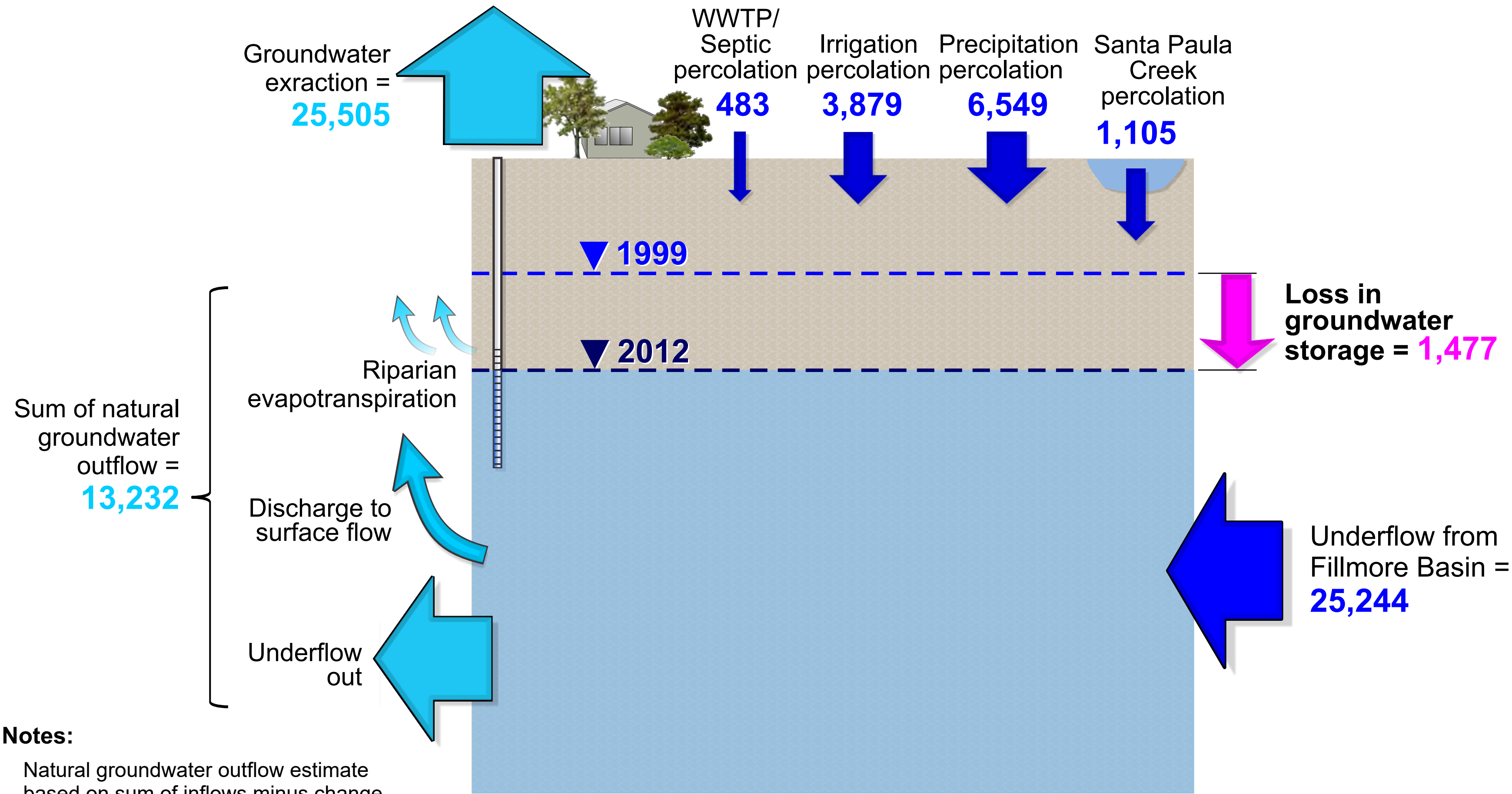
3-7-16
JN WR14.0110



Notes:

Natural groundwater outflow estimate based on sum of inflows minus change in groundwater storage.

Assumes average groundwater elevation change = -0.32 ft/yr

Storativity = 0.20

Estimated average groundwater inflows/outflows 1999 - 2012 (ac-ft/yr)

UWCD SAFE YIELD

Conceptual Groundwater Balance Model
Large Storage Decline Case

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3-7-16
JN WR14.0110

Figure 15

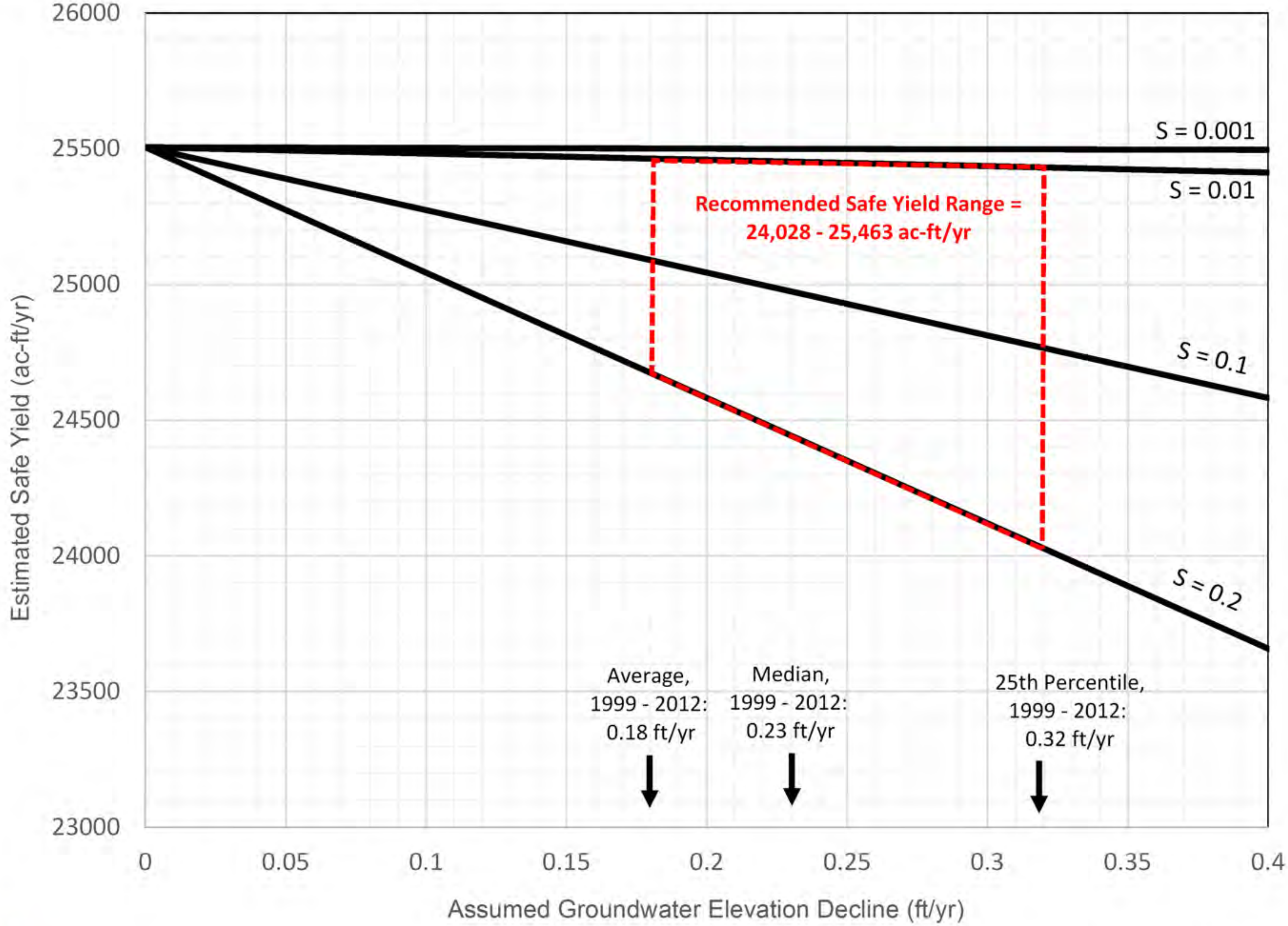

Figure 16

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3/7/2016 JN WR14.0110

UWCD SAFE YIELD
Safe Yield Sensitivity Analysis

Tables

Table 1. UWCD, 2013 Trend Analysis Results

First Year	Last Year	Average Decline for Period (feet)	Average Annual Decline (ft/yr)
1944	1998	10	0.19
1944	2005	13.3	0.22
1983	1995	1.6	0.13
1983	2005	6.7	0.30
1999	2009	5.5	0.55
1980	2011	4.7	0.15
1983	2011	9.2	0.33
1986	2011	4.1	0.16
1997	2011	2.4	0.17
1999	2011	2.2	0.18

Table 2. Baseflow Analysis and Estimated Santa Paula Creek Percolation USGS Gage 11113500

Water Year	Total Observed Flow at Gage (ac-ft/yr)	Estimated Baseflow at Gage (ac-ft/yr)	Estimated Percolation Downstream of Gage (ac-ft/yr)
1999	5,576	4,883	513
2000	8,611	5,936	756
2001	24,465	14,435	1,551
2002	2,517	2,135	232
2003	8,562	5,706	763
2004	5,058	3,099	377
2005	107,327	58,090	3,894
2006	22,711	14,155	1,587
2007	3,313	2,914	305
2008	27,952	14,578	1,433
2009	4,395	3,348	404
2010	16,344	9,438	1,356
2011	32,892	17,819	1,892
2012	4,466	2,966	406
Average	19,585	11,393	1,105

ac-ft/yr = Acre-feet per year

Table 3. DPWM Results, Deep Percolation of Precipitation and Irrigation

Water Year(s)	Deep Percolation (ac-ft/yr)				
	Precipitation			Irrigation	Total Precipitation and Irrigation
	Basin Floor [a]	Ephemeral Washes [b]	Precipitation Total		
2000 (Median)	3,880	1,093	4,973	3,623	8,596
2010 (75th Percentile)	4,944	1,242	6,186	8,125	14,311
2012 (25th Percentile)	385	229	613	1,159	1,772
Average 1999-2012	5,430	1,119	6,549	3,879	10,428

[a] Excludes Santa Paula Creek and Santa Clara River
[b] Outside of settlement boundary, excluding Santa Paula Creek subwatershed

DPWM = Distributed Parameter Watershed Model
ac-ft/yr = Acre-feet per year

Table 4a. Wastewater Facility Recharge

Facility	Years Discharging	Annual Volume (ac-ft/yr)
City of Santa Paula Water Recycling Facility	2010 – present	2,130
Limoneria Company	2002 – present [a]	76
Briggs Elementary	Unknown	2.5
Olivelands Elementary	Unknown	2.8

[a] Dates estimated

ac-ft/yr = Acre-feet per year

Table 4b. Septic System Recharge

Number of Septic Systems in Basin [a]	Recharge Rate (ac-ft/yr)	
	Per System [b]	Total
464	0.16	74

[a] Ventura County septic systems permits database

[b] Hantzche and Finnemore, 1992

ac-ft/yr = Acre-feet per year

Table 5. Groundwater Elevation Trend Analysis Results, All Wells
Page 1 of 3

Well	Geographic Area	Depth Zone	First Year	Last Year	Mann-Kendall 1999-2012	Slope (ft/yr)			
						1999–2012	2012	2000	2010
03N21W11J01S	Santa Paula Creek	Older Alluvium	1998	2010	NA	NA	NA	–4.53	–23.56
03N21W12E04S	Santa Paula Creek	Older Alluvium	1998	2012	Increasing	0.24	0.51	–1.53	1.33
03N21W12E08S	Santa Paula Creek	Older Alluvium	1998	2012	Increasing	0.35	–2.13	7.23	3.56
03N21W12F03S	Santa Paula Creek	Older Alluvium	1998	2012	No trend	0.00	0.37	7.20	2.36
03N21W02R02S	Santa Paula Creek	Older/San Pedro	1998	2012	No trend	0.00	3.69	25.24	6.94
03N21W11E03S	Santa Paula Creek	Older/San Pedro	1999	2012	NA	NA	–0.51	–0.95	0.97
03N21W11F03S	Santa Paula Creek	Older/San Pedro	1999	2012	NA	NA	–0.80	3.47	11.94
03N21W11J02S	Santa Paula Creek	Older/San Pedro	1998	2012	Decreasing	–0.23	–8.11	NA	–4.71
03N21W11B01S	Santa Paula Creek	Unknown	1998	2012	No trend	0.00	–6.90	–0.79	–14.76
03N21W11H03S	Santa Paula Creek	Unknown	1998	2012	No trend	0.00	–5.77	–7.23	–5.52
03N21W12B01S	Santa Paula Creek	Unknown	1998	2012	Decreasing	–0.03	0.55	0.60	1.79
03N21W15C04S	East basin	Older Alluvium	1998	2012	Decreasing	–0.83	–2.88	17.02	5.73
03N21W15G04S	East basin	Older Alluvium	1998	2012	Decreasing	–0.34	–6.39	–1.15	–3.41
03N21W16H07S	East basin	Older Alluvium	1998	2012	Decreasing	–0.37	–7.93	–1.42	–2.76
03N21W16K01S	East basin	Older Alluvium	1998	2012	Decreasing	–0.47	–3.69	16.36	11.54
03N21W16K02S	East basin	Older/San Pedro	1998	2012	Decreasing	–0.34	–1.90	27.61	11.76
03N21W09K02S	East basin	Older/San Pedro	1998	2012	Decreasing	–0.37	–11.98	40.91	–5.44
03N21W15C02S	East basin	Older/San Pedro	1999	2012	NA	NA	–2.75	9.28	4.78
03N21W16H06S	East basin	Older/San Pedro	1998	2012	Decreasing	–0.35	–7.82	–1.63	–3.22
03N21W15G05S	East basin	Recent Alluvium	1998	2012	Decreasing	–0.04	–0.67	–0.65	–1.08
03N21W16H08S	East basin	Recent Alluvium	1998	2012	Decreasing	–0.22	–3.53	–0.23	2.77
03N21W09R04S	East basin	San Pedro	1998	2012	Increasing	0.98	1.97	11.54	3.13
03N21W09R05S	East basin	San Pedro	1998	2012	Decreasing	–0.38	–7.09	–5.84	–2.52
03N21W15C06S	East basin	San Pedro	1998	2012	Decreasing	–0.39	–7.27	–10.26	–19.91

ft/yr = Feet per year
NA = Water elevation data unavailable for given time period

Table 5. Groundwater Elevation Trend Analysis Results, All Wells

Well	Geographic Area	Depth Zone	First Year	Last Year	Mann-Kendall 1999-2012	Slope (ft/yr)			
						1999–2012	2012	2000	2010
03N21W15G01S	East basin	San Pedro	1998	2012	Decreasing	–0.33	–6.83	–1.21	–3.07
03N21W15G02S	East basin	San Pedro	1998	2012	Decreasing	–0.18	–5.55	–1.29	–3.10
03N21W15G03S	East basin	San Pedro	1998	2012	Decreasing	–0.31	–6.14	–1.25	–3.33
03N21W16A02S	East basin	San Pedro	1998	2012	Decreasing	–0.52	–8.07	3.26	1.48
03N21W16H05S	East basin	San Pedro	1998	2012	No trend	0.00	–7.20	–3.73	–5.11
03N21W16K03S	East basin	San Pedro	1998	2012	Decreasing	–0.90	–1.27	–1.35	2.36
03N21W15C03S	East basin	Unknown	1998	2004	NA	NA	NA	–74.88	NA
03N21W17Q01S	Middle basin	Older Alluvium	1998	2012	Decreasing	–0.53	–5.37	–8.07	2.32
03N21W19M01S	Middle basin	Older Alluvium	1999	2012	No trend	NA	NA	–29.44	NA
03N21W19R01S	Middle basin	Older Alluvium	1998	2012	Decreasing	–0.53	–13.26	–5.52	22.79
03N21W30E01S	Middle basin	Older Alluvium	1998	2012	Decreasing	–0.34	–8.88	12.71	–7.78
03N21W31F03S	Middle basin	Older Alluvium	1998	2001	NA	NA	NA	4.24	NA
03N21W30F01S	Middle basin	Older/San Pedro	1998	2012	Decreasing	–0.38	11.47	–9.46	6.76
03N21W30H04S	Middle basin	Older/San Pedro	1998	2005	NA	NA	NA	NA	NA
03N21W31F04S	Middle basin	Recent Alluvium	1998	2012	Decreasing	–0.11	0.11	–0.16	NA
03N21W31F05S	Middle basin	Recent Alluvium	1998	2012	Decreasing	–0.45	–6.03	–3.69	4.31
03N21W31G03S	Middle basin	Recent Alluvium	1998	2012	Decreasing	–0.26	–1.10	–1.14	4.82
03N21W32C–a	Middle basin	Recent Alluvium	1998	2012	No trend	0.00	–1.96	1.91	1.00
03N21W32C–b	Middle basin	Recent Alluvium	1998	2012	No trend	0.00	–0.52	2.41	12.53
03N21W32C–c	Middle basin	Recent Alluvium	1998	2012	No trend	0.00	–0.81	2.10	8.44
03N21W19G01S	Middle basin	San Pedro	1998	2005	NA	NA	NA	6.14	NA
03N21W19G04S	Middle basin	San Pedro	1998	2012	Decreasing	–0.34	–18.37	9.72	14.83
03N21W19H06S	Middle basin	San Pedro	1998	1999	NA	NA	NA	NA	NA
03N21W20J03S	Middle basin	San Pedro	1999	2012	NA	NA	–13.30	28.60	NA

ft/yr = Feet per year
NA = Water elevation data unavailable for given time period

Table 5. Groundwater Elevation Trend Analysis Results, All Wells

Well	Geographic Area	Depth Zone	First Year	Last Year	Mann-Kendall 1999-2012	Slope (ft/yr) 1999–2012	Slope (ft/yr) 2012	Slope (ft/yr) 2000	Slope (ft/yr) 2010
03N21W21B01S	Middle basin	Unknown	1998	2005	NA	NA	NA	–5.08	NA
03N21W31B01S	Middle basin	Unknown	1998	2004	NA	NA	NA	–7.23	NA
02N22W02C01S	Saticoy Area	Older Alluvium	1998	2012	Decreasing	–0.28	–6.43	2.76	6.72
03N21W31L01S	Saticoy Area	Older Alluvium	1998	2012	Decreasing	–0.26	–2.65	–2.86	4.31
03N22W36K05S	Saticoy Area	Older Alluvium	1998	2012	Decreasing	–0.50	–9.35	0.74	3.59
02N22W02K07S	Saticoy Area	Older/San Pedro	1998	2012	No trend	0.00	–4.35	5.95	16.36
03N22W34R01S	Saticoy Area	Older/San Pedro	1998	2012	Decreasing	–0.28	2.69	15.82	8.80
03N22W35Q02S	Saticoy Area	Older/San Pedro	1999	2012	NA	NA	NA	10.45	NA
03N22W36H01S	Saticoy Area	Older/San Pedro	1999	2012	NA	NA	NA	1.30	NA
02N22W02K09S	Saticoy Area	San Pedro	1998	2012	No trend	0.00	–6.90	4.53	17.75
03N22W23Q01S	Saticoy Area	San Pedro	1999	2012	NA	NA	NA	8.47	NA
02N22W03K02S	West end	Older Alluvium	1998	2012	No trend	0.00	–2.09	7.78	14.03
02N22W03M02S	West end	San Pedro	1998	2012	Increasing	0.27	–3.43	–0.58	9.93
02N22W02N04S	West end	Unknown	1999	2012	NA	NA	NA	5.77	NA
02N22W03F02S	West end	Unknown	1999	2011	NA	NA	NA	83.64	NA
02N22W03Q01S	West end	Unknown	1999	2012	NA	NA	NA	0.08	NA

ft/yr = Feet per year
NA = Water elevation data unavailable for given time period

ft/yr = Feet per year
NA = Water elevation data unavailable for given time period

Table 6. Summary Groundwater Elevation Trend Analysis Results

Geographic Area	Area (acres)	Number of Wells with Trend, 1999–2012 (Mann-Kendall Trend Analysis)				Slope (ft/yr) 1999 - 2012				Average Slope (ft/yr) Selected Years		
		Total	Increasing	Decreasing	No Trend	Average	Median	25th %	75th %	2000	2010	2012
Santa Paula Creek	2,152	8	2	2	4	0.04	0.00	–0.02	0.18	2.87	–1.79	–1.91
East Basin	1,847	18	1	16	1	–0.30	–0.34	–0.41	–0.21	1.05	–0.49	–5.10
Middle Basin	6,575	11	0	8	3	–0.27	–0.34	–0.45	0.00	–0.12	7.00	–4.83
Saticoy Area	3,904	6	0	4	2	–0.22	–0.27	–0.34	0.00	5.24	9.59	–4.50
West end	1,486	2	1	0	1	0.13	0.13	0.00	0.27	19.34	11.98	–2.76
All areas	15,962	45	4	30	11	–0.20	–0.26	–0.38	0.00	3.14	2.55	–4.22
					Area weighted	–0.18	–0.23	–0.32	0.02	3.54	6.05	–4.20

ft/yr = Feet per year
% = Percentile

Table 7. Groundwater Balance and Safe Yield Sensitivity Analysis, Average 1999-2012

Source	Base Case	Small Storage Decline Case	Large Storage Decline Case
Groundwater inputs (ac-ft/yr)			
Groundwater Inflow from Fillmore Basin	25,244	25,244	25,244
Deep percolation of precipitation	6,549	6,549	6,549
Deep percolation of irrigation	3,879	3,879	3,879
Santa Paula Creek percolation	1,105	1,105	1,105
WWTP and septic system percolation	483	483	483
Total inputs	37,260	37,260	37,260
Groundwater storage			
Assumed groundwater elevation change (ft/yr)	–0.23	–0.18	–0.32
Storativity (–)	0.01	0.01	0.20
Groundwater storage change (ac-ft/yr)	–53	–42	–1,477
Groundwater outflows (ac-ft/yr)			
Groundwater extraction	25,505	25,505	25,505
Natural groundwater outflow	11,808	11,796	13,232
Total outflows	37,313	37,301	38,737
Safe yield = Total inputs – Natural outflow	25,452	25,463	24,028

Table 8. Groundwater Extraction, 1998–2012

Year	Water Year Precipitation (inches)		ET_o (inches)		Fraction ET_o (Oct – Dec)[c] (%)	Extraction (ac-ft/yr)		
	Gage 225 Wheeler Canyon	Gage 245A/245B Santa Paula[a]	Calendar Year Total[b]	Oct – Dec[b]		Calendar Year Total[d]	Estimated Oct – Dec[e]	Estimated Water Year[f]
1998	55.0	44.7	—	—	18	21,622	3,849	—
1999	11.9	10.5	—	—	18	27,700	4,931	26,618
2000	19.9	14.8	—	—	18	26,798	4,770	26,959
2001	31.7	26.5	—	—	18	22,530	4,010	23,290
2002	7.1	7.0	—	—	18	27,259	4,852	26,417
2003	23.6	19.9	—	—	18	22,280	3,966	23,166
2004	16.9	12.6	—	—	18	27,306	4,860	26,411
2005	55.4	40.4	—	—	18	24,700	4,397	25,164
2006	24.8	18.4	49.0	9.8	20	24,830	4,946	24,281
2007	7.7	5.0	50.3	9.6	19	28,077	5,342	27,681
2008	23.6	16.1	54.7	10.1	18	26,686	4,902	27,126
2009	13.3	11.5	52.9	9.4	18	25,820	4,569	26,153
2010	24.8	18.5	51.0	7.8	15	23,115	3,520	24,165
2011	29.6	25.8	51.8	9.3	18	24,202	4,334	23,388
2012	12.0	9.9	52.9	8.0	15	25,824	3,905	26,253
Average, 1999 – 2012						25,509	4,522	25,505

[a] VCWPD Gage 245A (1998 – 2010), Gage 245B (2011 – 2012)
[b] CIMIS Station #198
[c] Assumed for 1998 – 2005 based on average of years with available data (2005 – 2015)
[d] UWCD, 2015
[e] Calendar year total extraction x Fraction ET_o (Oct – Dec)
[f] Calendar year total + (Oct to Dec of previous calendar year) – (Oct to Dec of current calendar year)

ET_o = Reference evapotranspiration
ac-ft/yr = Acre-feet per year

Table 9. Groundwater Balance and Safe Yield

Source	Annual Average (1999–2012)	Representative Precipitation Year (Percentile)		
		2012 (25th)	2000 (50th)	2010 (75th)
Groundwater inflows (ac-ft/yr)				
Groundwater inflow from Fillmore Basin	25,244 [a]	22,320	22,502	30,909
Deep percolation of precipitation	6,549	613	4,973	6,186
Deep percolation of irrigation	3,879	1,159	3,623	8,125
Santa Paula Creek percolation	1,105	406	756	1,356
WWTP and septic system percolation	483	2,285	155	2,285
Total inflows	37,260	26,783	32,009	48,861
Groundwater storage				
Assumed groundwater elevation change (ft/yr)	–0.23	–4.2	3.5	6.1
Groundwater storage change (S = 0.01) (ac-ft/yr)	–53	–969	817	1,408
Groundwater outflows (ac-ft/yr)				
Groundwater extraction	25,505	26,253	26,959	24,165
Natural groundwater outflow	11,808	1,499	4,233	24,288
Total outflows	37,313	27,752	31,192	47,453
Safe yield = Total inputs – Natural outflow	25,452			

[a] Average of three years (2000, 2010, 2012)

Appendix A

KDSA (2015)
Confining Bed Evaluation
Cross Sections and Maps

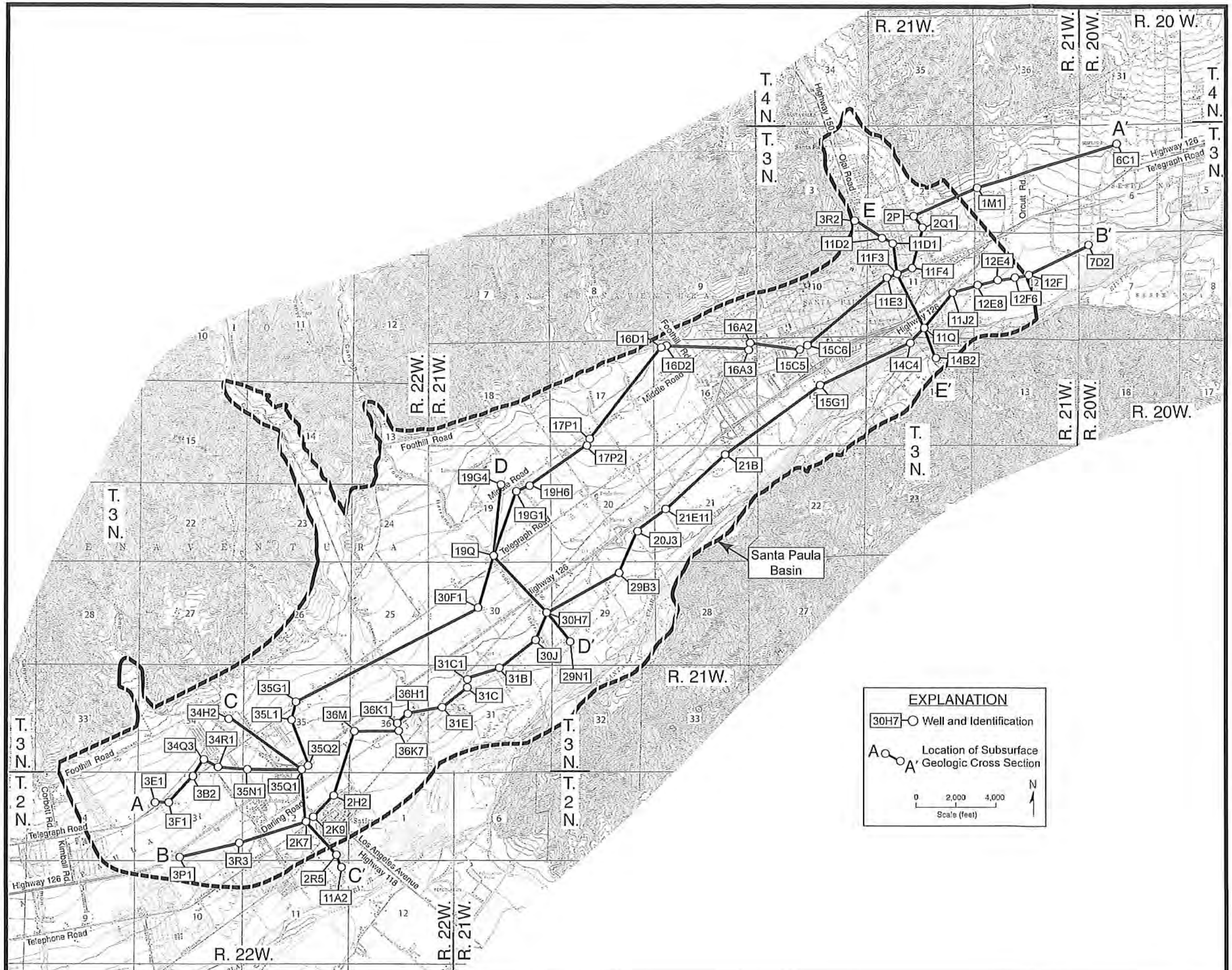


FIGURE 1 - LOCATION OF SUBSURFACE GEOLOGIC CROSS SECTIONS

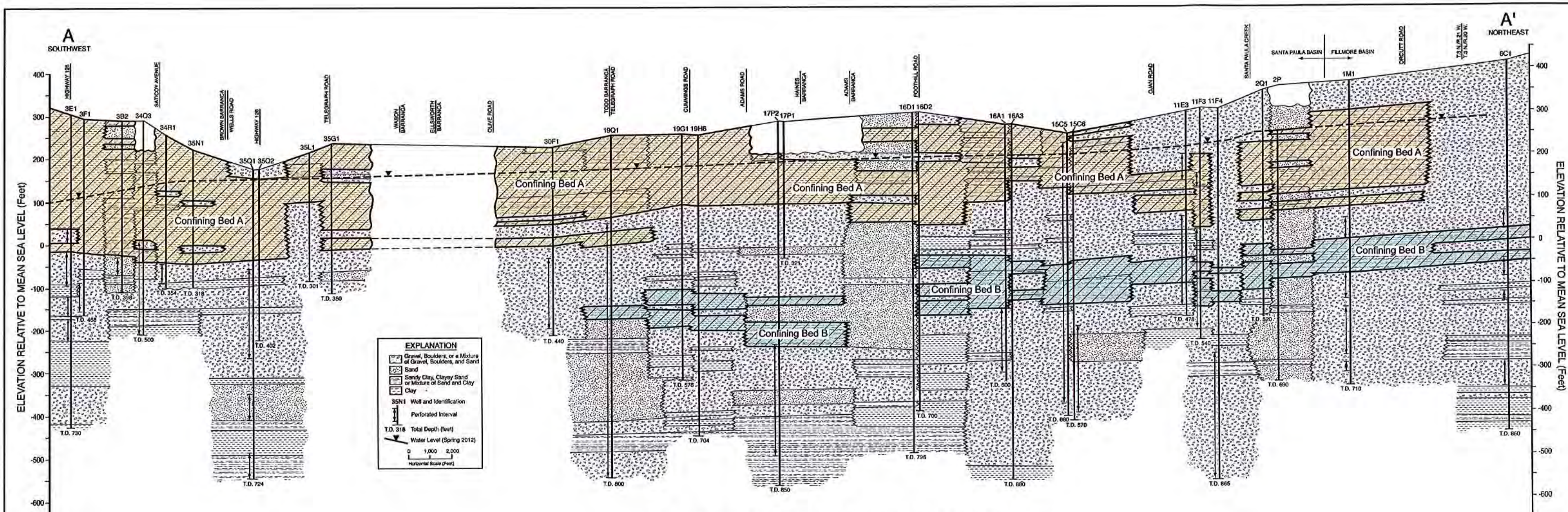


FIGURE 2 - SUBSURFACE GEOLOGIC CROSS SECTION A - A'

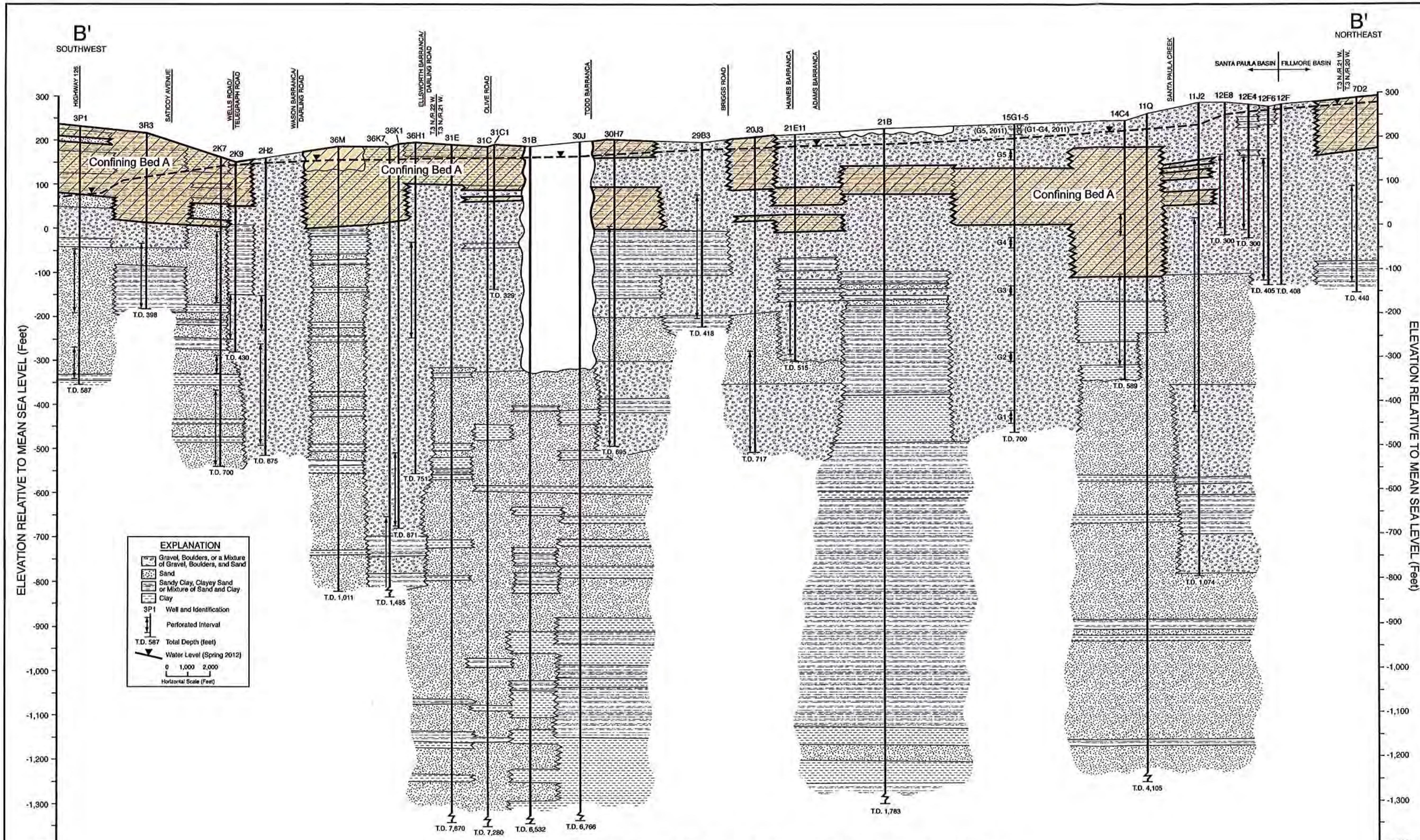


FIGURE 3 - SUBSURFACE GEOLOGIC CROSS SECTION B - B'

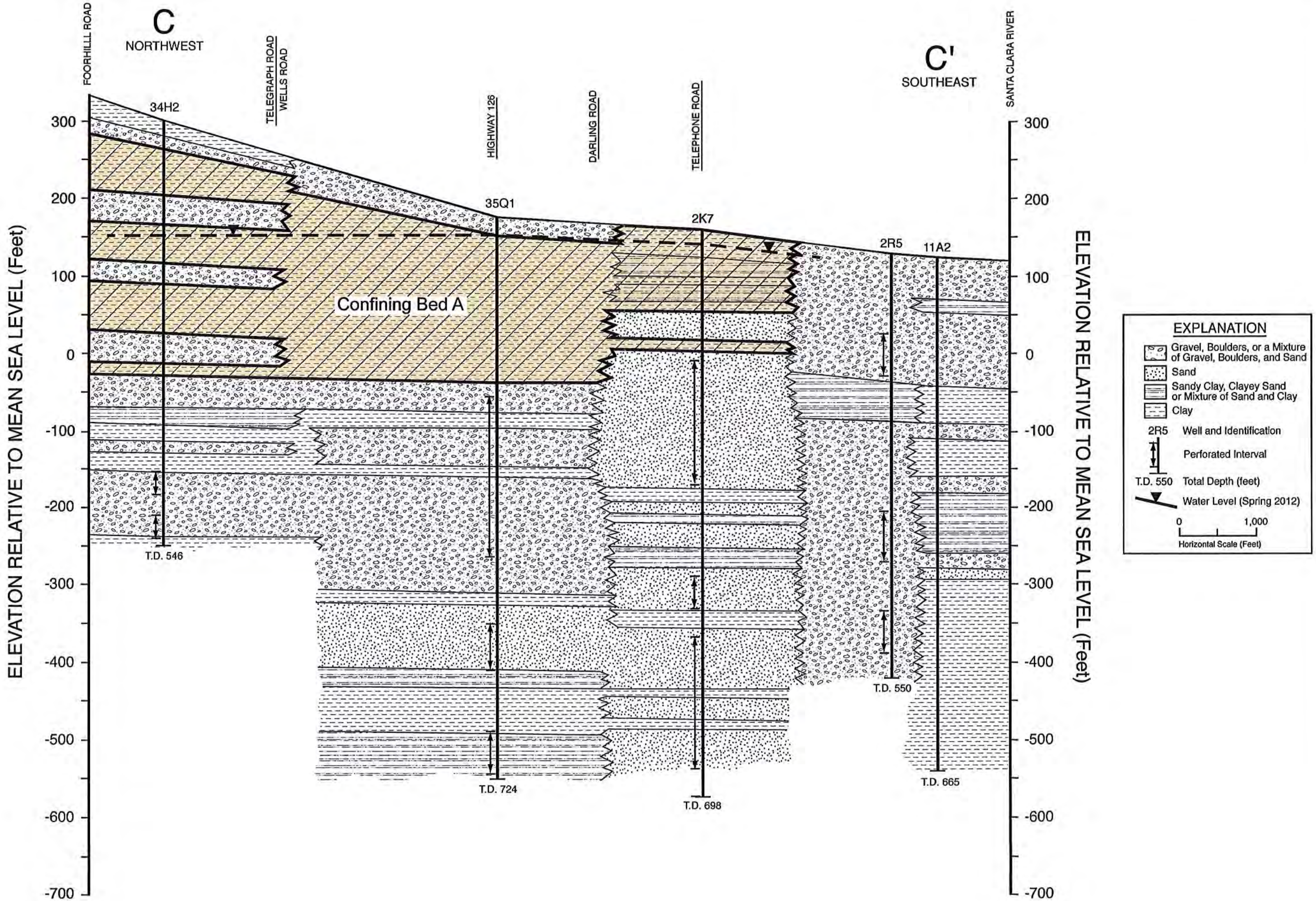


FIGURE 4 - SUBSURFACE GEOLOGIC CROSS SECTION C - C'

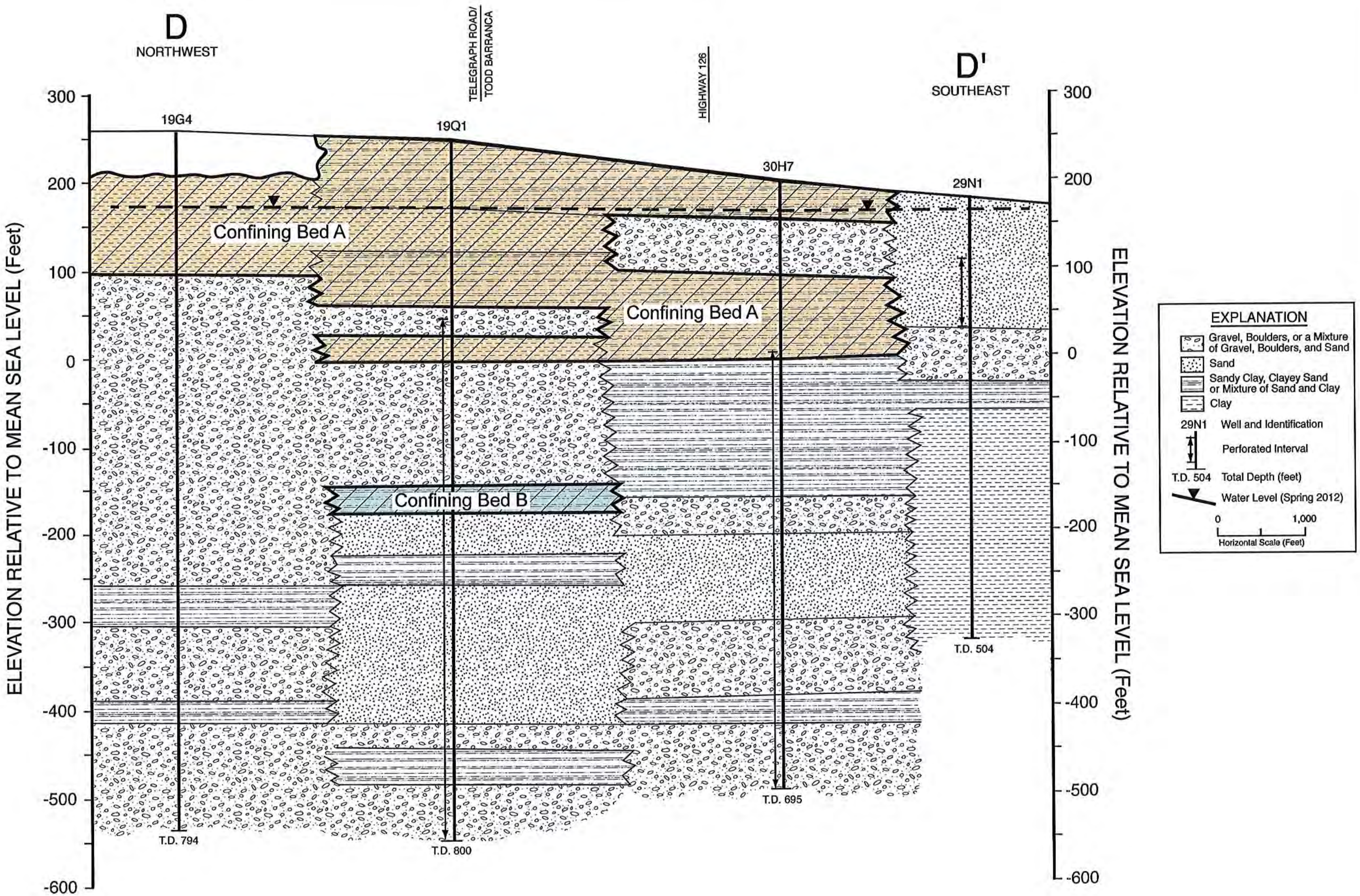


FIGURE 5 - SUBSURFACE GEOLOGIC CROSS SECTION D - D'

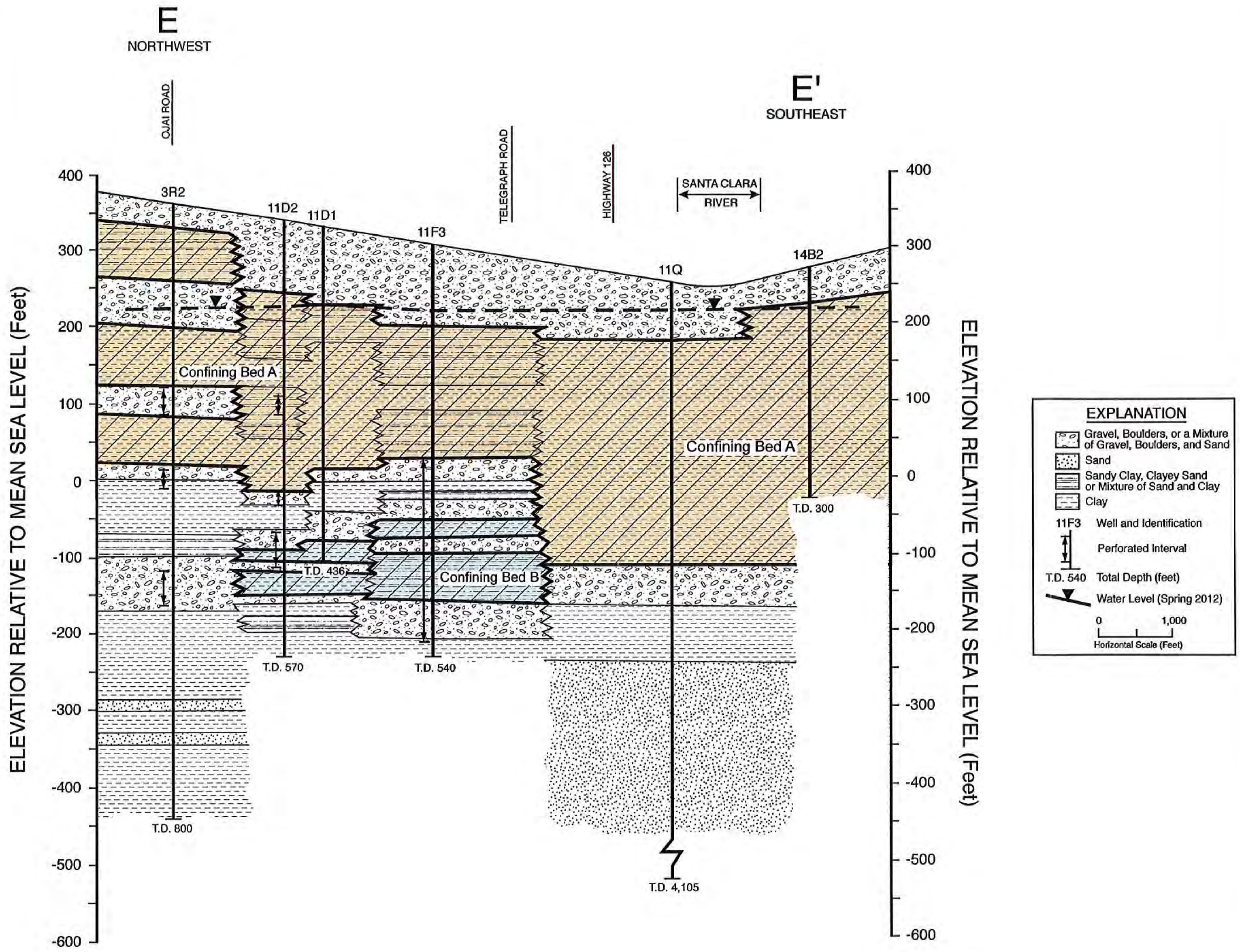


FIGURE 6 - SUBSURFACE GEOLOGIC CROSS SECTION E - E'

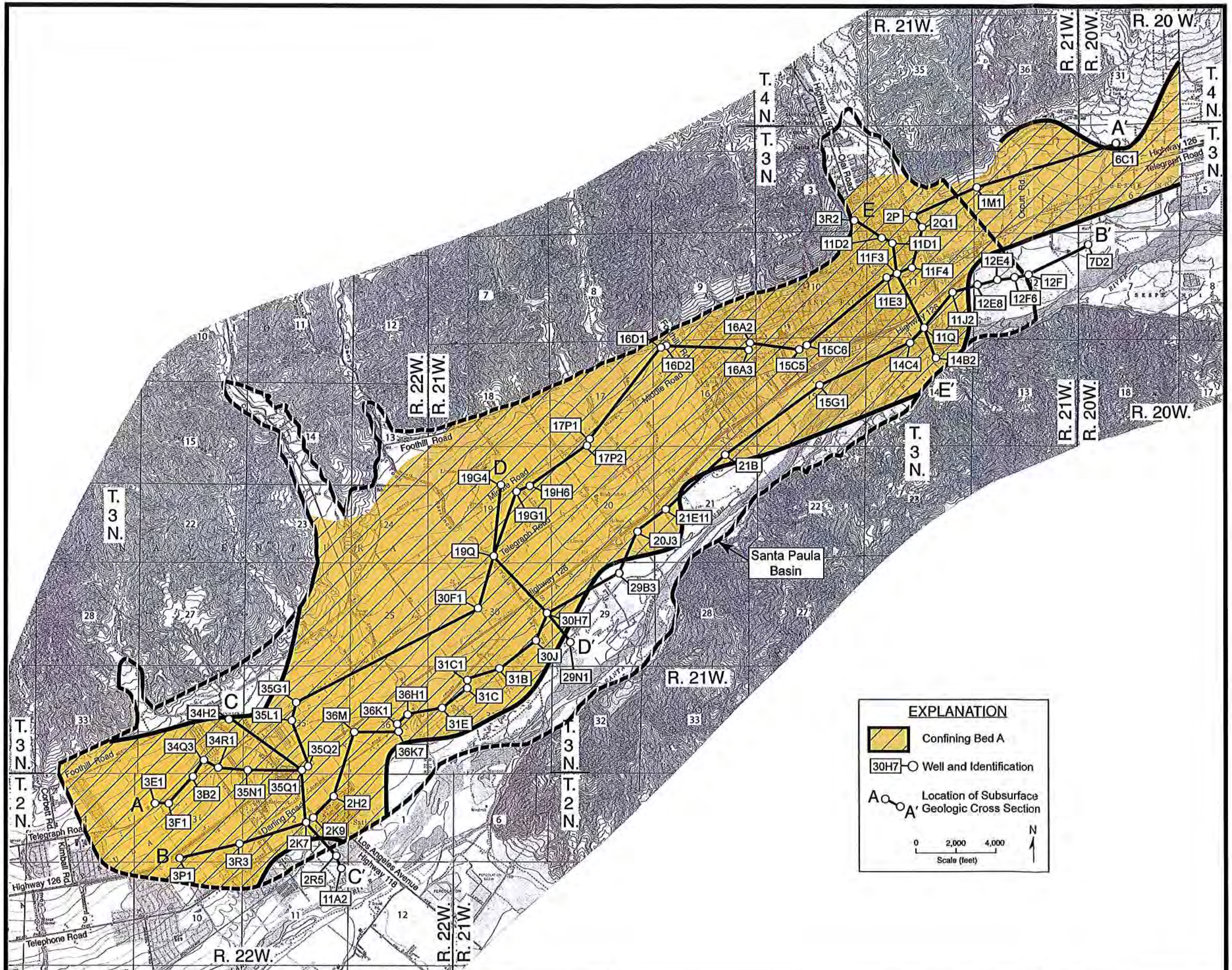


FIGURE 7 - LOCATION OF CONFINING BED A AND SUBSURFACE GEOLOGIC CROSS SECTIONS

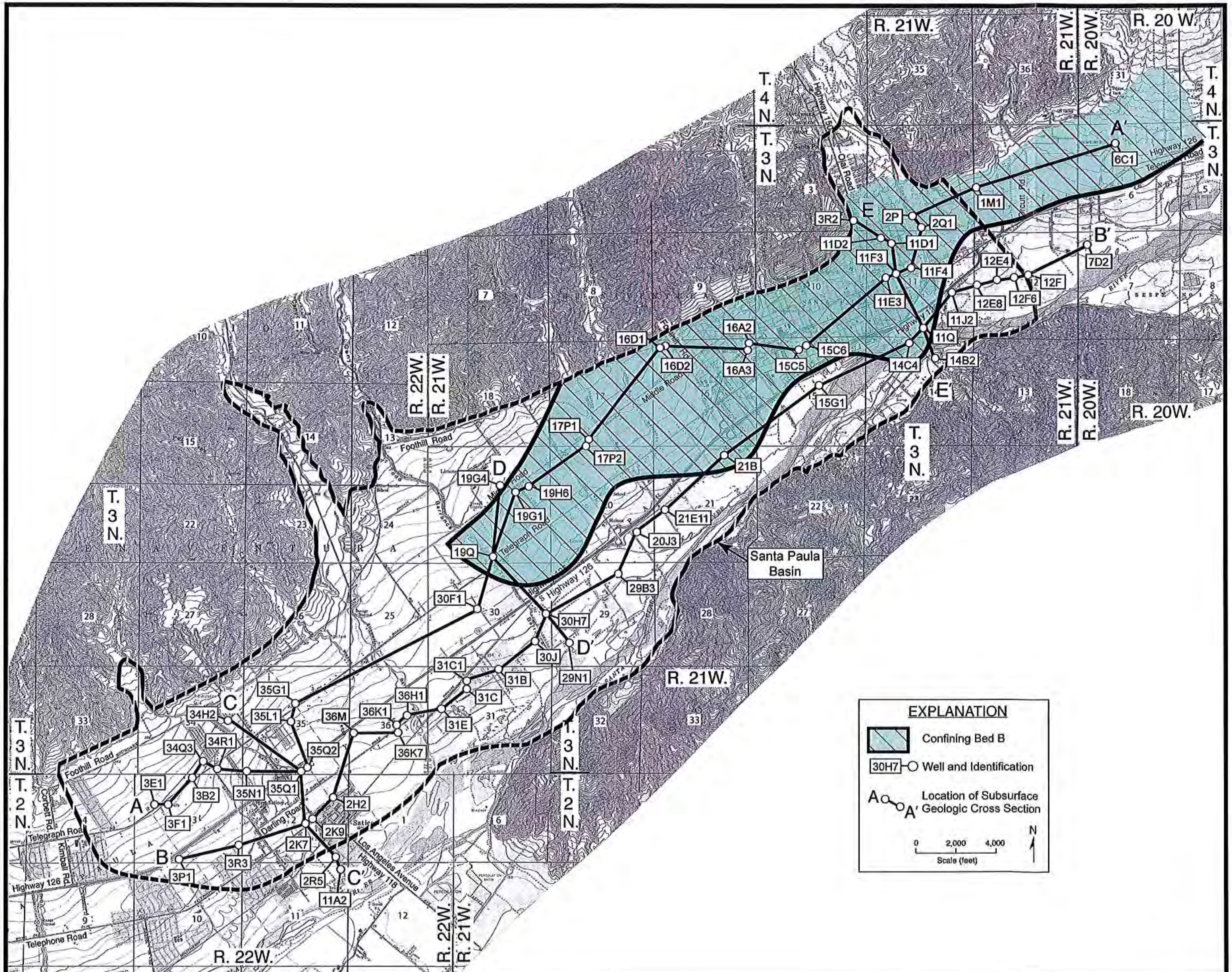
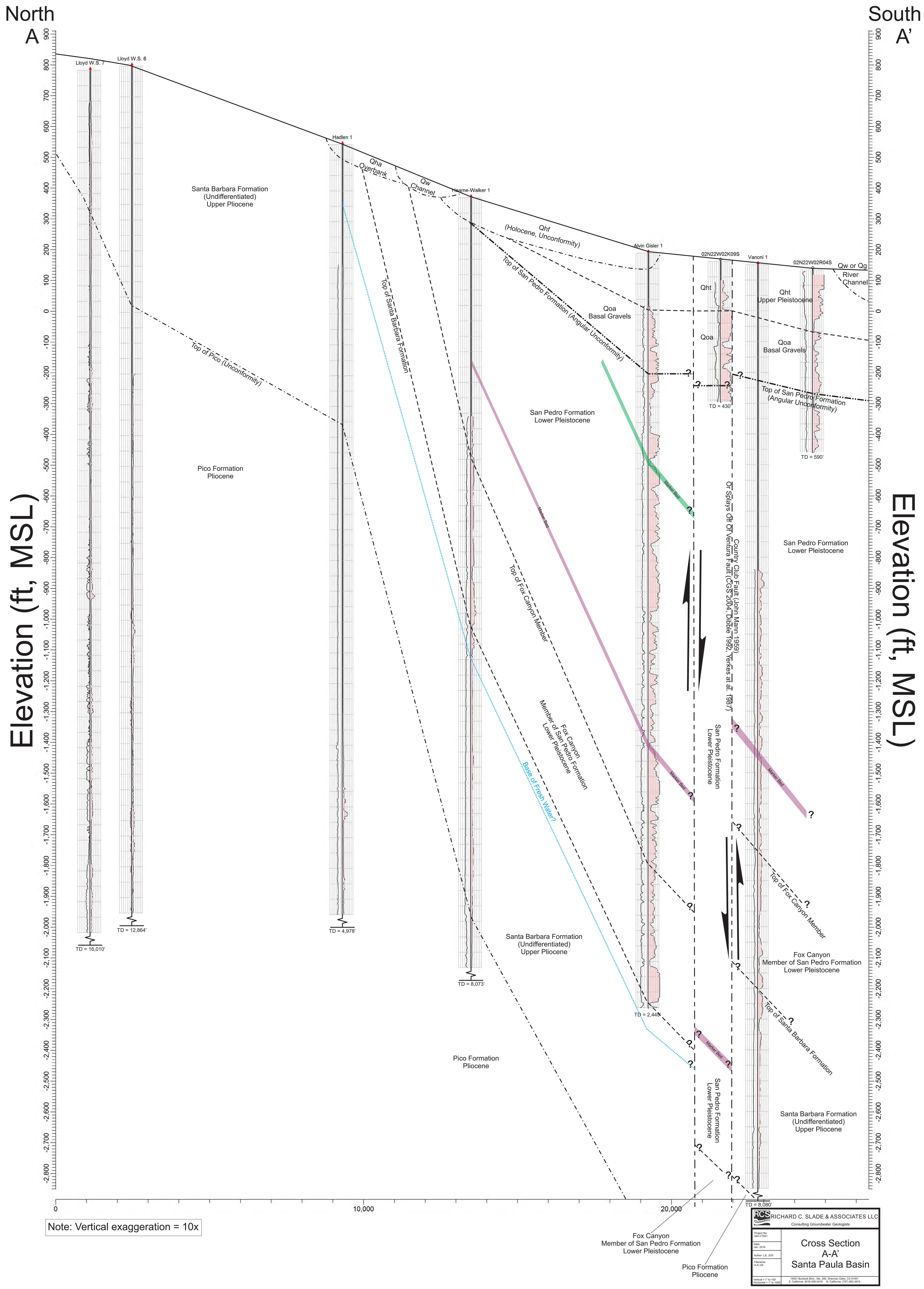


FIGURE 8 - LOCATION OF CONFINING BED B AND SUBSURFACE GEOLOGIC CROSS SECTIONS

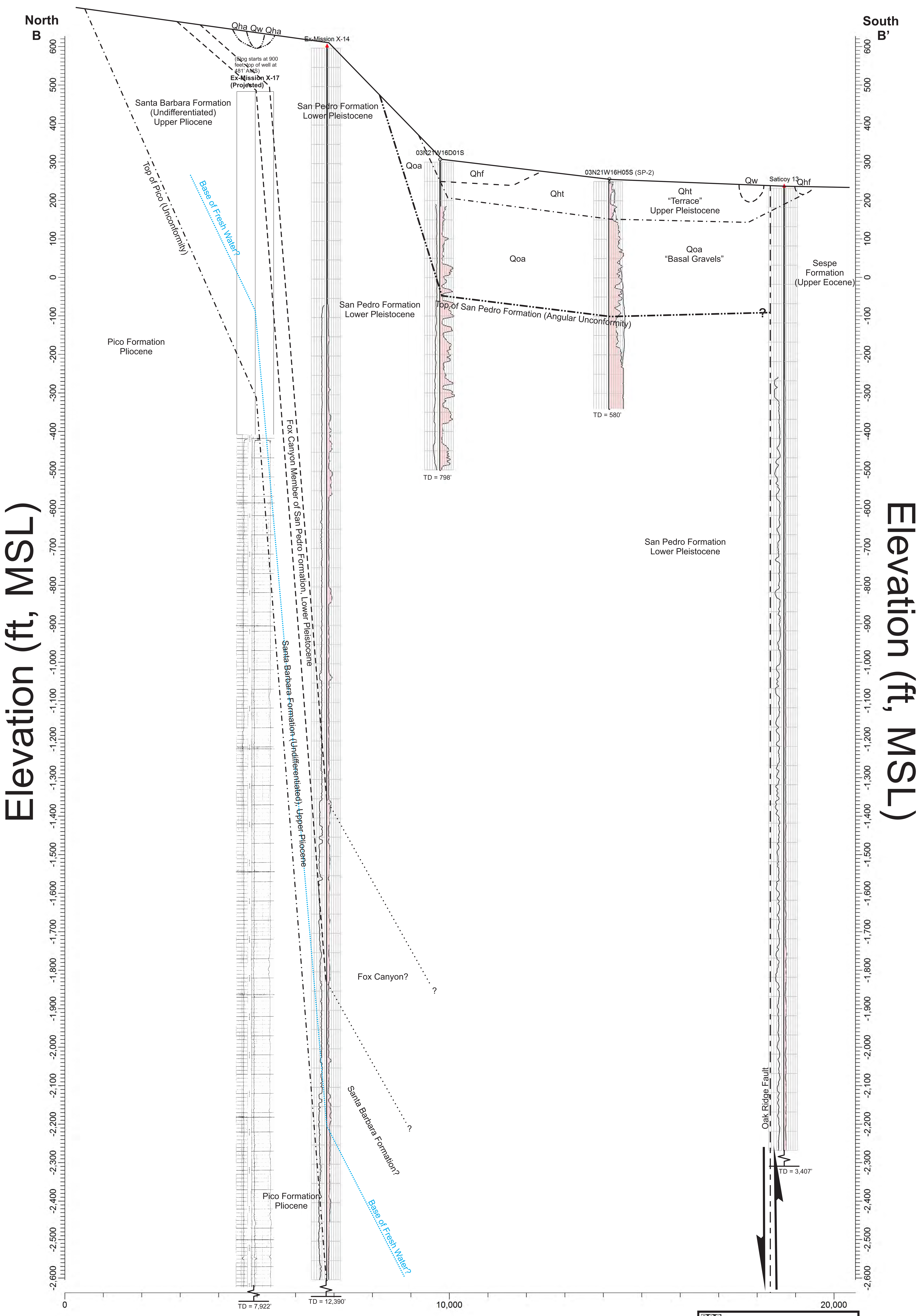
Appendix B

RCS Geologic Cross Sections

Legend
Groundwater Basin Boundary
Oil Well
Water Well with Elog Data
Water Well with Driller's Log Data
RCS In House Elog Data
Cross Section Line
A A'
Scematic Section Line
X X'
A
A'
B
B'
X
X'
Y
Y'
City of Santa Paula #13
03N21W09R05S
City of Santa Paula #14
03N22W16A02S
City of Santa Paula #12
03N21W11J02S
FICO 12
03N21W12F07S
9 Wells FugroWest 2007
03N21W20A01S
03N21W21E07S
03N21W20F04S
03N21W21B03S
Approximate Location of DH-4, DH-5, and 03N21W21G03S
03N21W20J04S
03N21W28F01S
Saticoy 3
02N22W02H02S
Saticoy 2
02N22W02K09S
EX MISSION
SAN BUENAVENTURA
GRANT
SANTA PAULA
SANTA CLARA
SOUTH MOUNTAIN
LAS POSAS
SANTA CLARA DEL NORTE
N
W
E
S
2500
0
2500
Feet
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: LAB/JDS
Filename:
Location Map
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343



North
A
South
A'
Elevation (ft, MSL)
Elevation (ft, MSL)
Lloyd W.S. 7
Lloyd W.S. 6
Hadlen 1
Hearne-Walker 1
Alvin Gisler 1
02N22W02K09S
Vanoni 1
02N22W02R04S
Qw or Qg
River
Channel
Qha
Overbank
Qw
Channel
Qhf
(Holocene, Unconformity)
Santa Barbara Formation
(Undifferentiated)
Upper Pliocene
Top of Pico (Unconformity)
Top of Santa Barbara Formation
Top of San Pedro Formation (Angular Unconformity)
Qoa
Basal Gravels
Qht
Qoa
Qht
Upper Pleistocene
Qoa
Basal Gravels
Top of San Pedro Formation
(Angular Unconformity)
TD = 430'
TD = 590'
San Pedro Formation
Lower Pleistocene
Pico Formation
Pliocene
Marker Bed
Country Club Fault (John Mann 1959)
Or splays Off Of Ventura Fault (CGS 2004, Dibblee 1992, Yerkes at al. 1987)
San Pedro Formation
Lower Pleistocene
Top of Fox Canyon Member
Fox Canyon
Member of San Pedro Formation
Lower Pleistocene
Base of Fresh Water?
San Pedro Formation
Lower Pleistocene
Top of Fox Canyon Member
Fox Canyon
Member of San Pedro Formation
Lower Pleistocene
Top of Santa Barbara Formation
Santa Barbara Formation
(Undifferentiated)
Upper Pliocene
Santa Barbara Formation
(Undifferentiated)
Upper Pliocene
Pico Formation
Pliocene
San Pedro Formation
Lower Pleistocene
TD = 16,010'
TD = 12,864'
TD = 4,978'
TD = 8,073'
TD = 2,448'
TD = 8,080'
0
10,000
20,000
Note: Vertical exaggeration = 10x
Fox Canyon
Member of San Pedro Formation
Lower Pleistocene
Pico Formation
Pliocene
RICHARD C. SLADE & ASSOCIATES LLC
Consulting Groundwater Geologists
Cross Section
A-A'
Santa Paula Basin



Note: Vertical exaggeration = 10x

RICHARD C. SLADE & ASSOCIATES LLC
Consulting Groundwater Geologists

Project No: 544-VTA01

Date: Jan. 2016

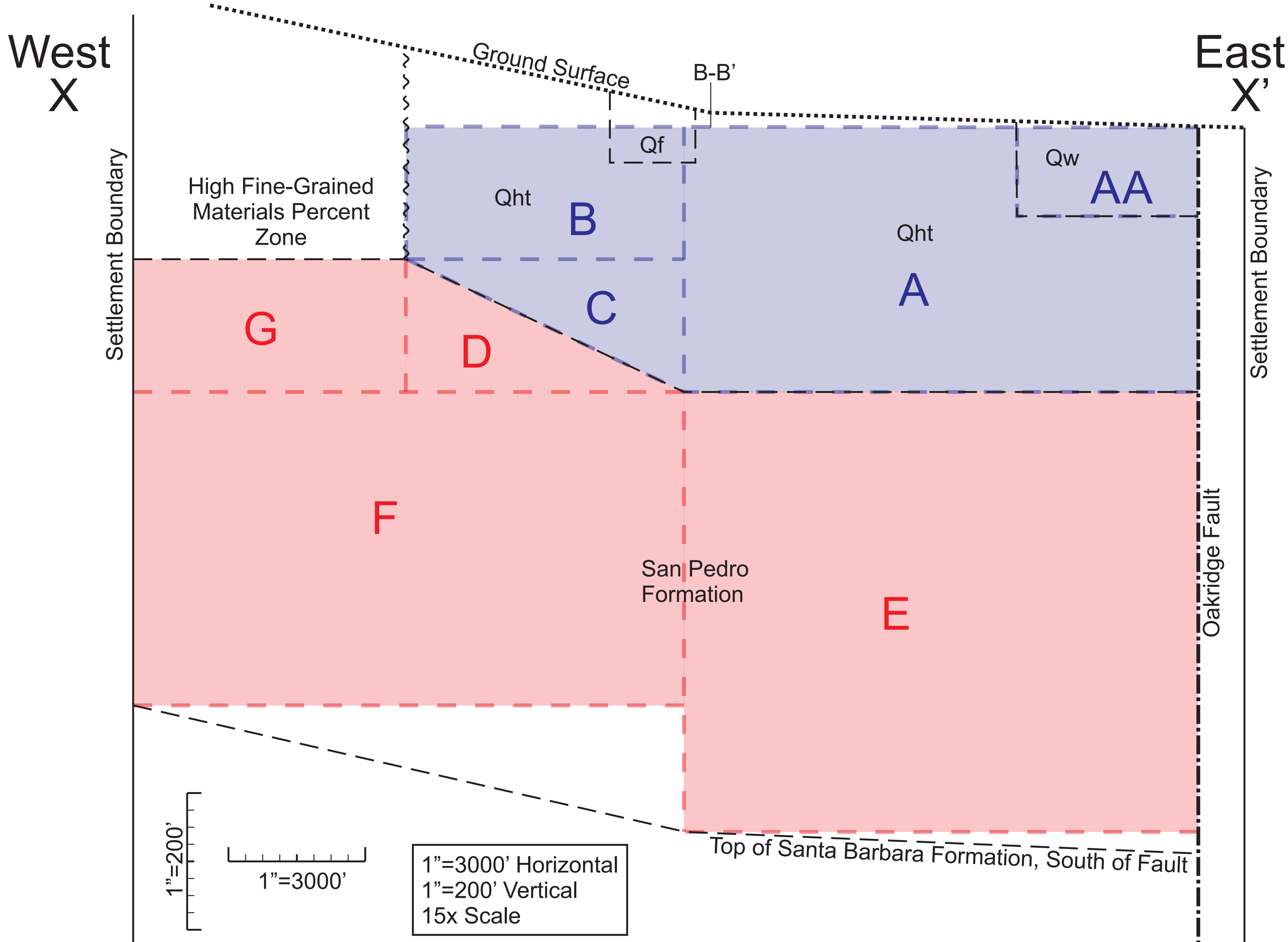
Author: LS, JDS

Filename: B-B'.cdr

Vertical = 1" to 100'
Horizontal = 1" to 1000'

Cross Section B-B' Santa Paula Basin

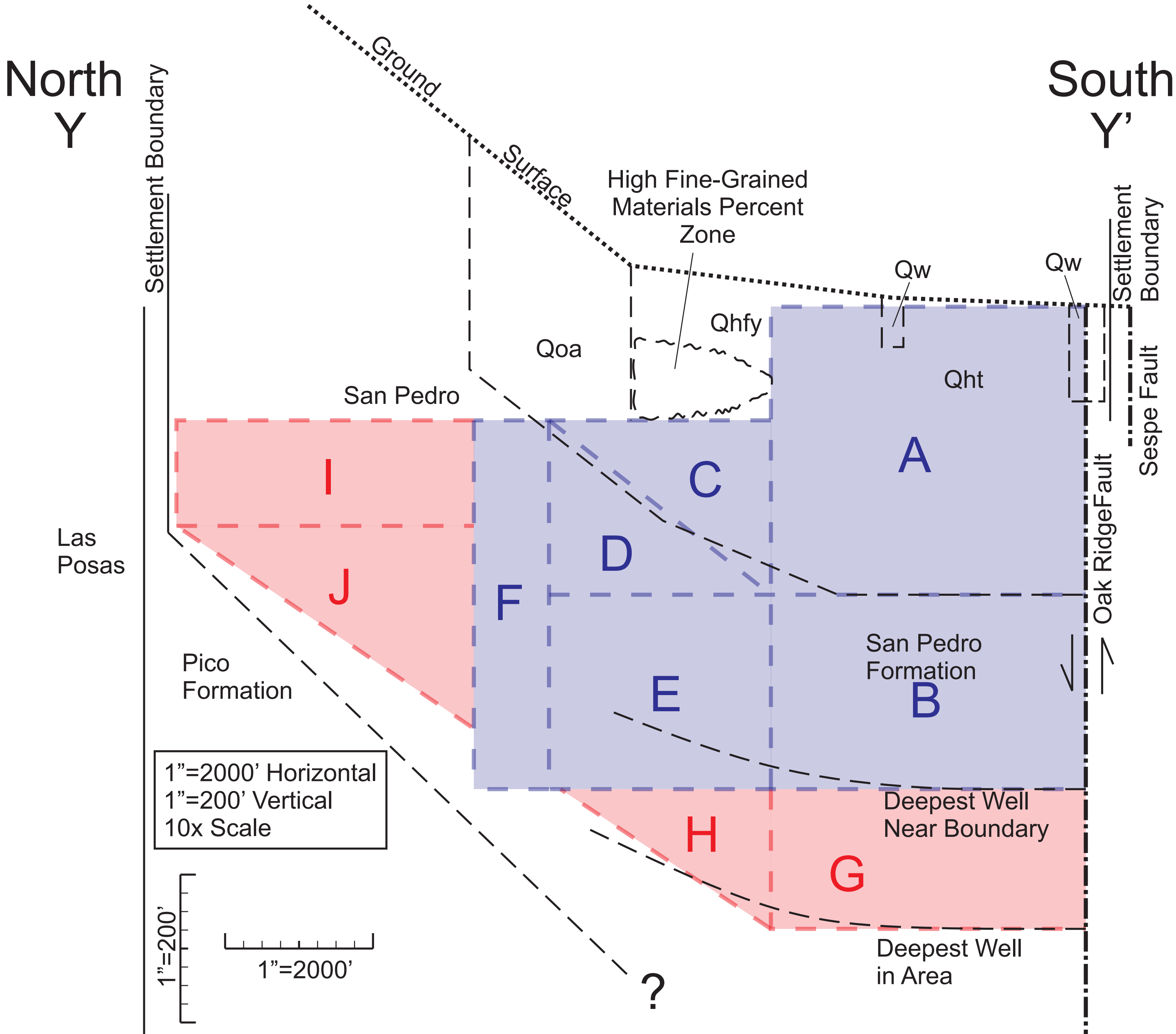
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
S. California: (818) 506-0418 N. California: (707) 963-3914



RCS
RICHARD C. SLADE & ASSOCIATES LLC
CONSULTING GROUNDWATER GEOLOGISTS
14051 Burbank Blvd., Suite 300
Sherman Oaks, CA 91401
Southern California Phone (818) 506-0418
Northern California Phone (707) 963-3914

OUTFLOW AREA CALCULATION
SCHEMATIC CROSS SECTION X-X'

Job No. 544-VTA01 **January 2016**



RCS
RICHARD C. SLADE & ASSOCIATES LLC
CONSULTING GROUNDWATER GEOLOGISTS
14051 Burbank Blvd., Suite 300
Sherman Oaks, CA 91401
Southern California Phone (818) 506-0418
Northern California Phone (707) 963-3914

INFLOW AREA CALCULATION
SCHEMATIC CROSS SECTION Y-Y'

Job No. 544-VTA01 **January 2016**

Appendix C

RCS Estimated Percent Clay from Driller's Logs

Legend
Location of water well with available driller's log from which percent fine grained materials data were calculated for depth zone indicated
Santa Paula Settlement Basin Boundary
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: Percent Clay 0 to 25 .wor
Percent Fine Grained Materials
0 to 25-Foot Depth
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343
2000 0 2000 4000 6000
Feet
Santa Paula
Saticoy
Limoneira
SESPE NO 2
SANTA CLARA
SOUTH MOUNTAIN

RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists

Project No: 544-VTA01

Date: Jan 2016

Author: JDS

Filename: Percent Clay 25 to 50 .wor

Percent Fine Grained Materials 25 to 50-Foot Depth

14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

Legend
Location of water well with available driller's log from which percent fine grained materials data were calculated for depth zone indicated
Santa Paula Settlement Basin Boundary
SANTA PAULA
SANTA CLARA RIVER
SOUTH MOUNTAIN
Santa Paula
Saticoy
Limoneira
Feet
2000
0
2000
4000
6000
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: Percent Clay 50 to 75 .wor
Percent Fine Grained Materials
50 to 75-Foot Depth
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

Richard C. Slade & Associates LLC
Consulting Groundwater Geologists

Project No: 544-VTA01

Date: Jan 2016

Author: JDS

Filename: Percent Clay 75 to 100 .wor

Percent Fine Grained Materials 75 to 100-Foot Depth

14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

Legend
Location of water well with available driller's log from which percent fine grained materials data were calculated for depth zone indicated
Santa Paula Settlement Basin Boundary
Santa Paula
Saticoy
Limoneira
SANTA CLARA RIVER
SOUTH MOUNTAIN
2000 0 2000 4000 6000
Feet
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: Percent Clay 100 to 125 .wor
Percent Fine Grained Materials
100 to 125-Foot Depth
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

RCS Richard C. Slade & Associates LLC
Consulting Groundwater Geologists

Project No: 544-VTA01	**Percent Fine Grained Materials 125 to 150-Foot Depth**
Date: Jan 2016	
Author: JDS	
Filename: Percent Clay 125 to 150 .wor	

14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

Richard C. Slade & Associates LLC
Consulting Groundwater Geologists

Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: Percent Clay 150 to 175 .wor

Percent Fine Grained Materials 150 to 175-Foot Depth

14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343


Legend
Location of water well with available driller's log from which percent fine grained materials data were calculated for depth zone indicated
Santa Paula Settlement Basin Boundary
SANTA PAULA
Santa Paula
Saticoy
West Saticoy
Limoneira
SANTA CLARA RIVER
SOUTH MOUNTAIN
EX MISSION
SAN BUENAVENTURA
SESPE NO 2
SESPE NO 1
GRANT
2000 0 2000 4000 6000
Feet
N
S
E
W
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: Percent Clay 175 to 200 .wor
Percent Fine Grained Materials
175 to 200-Foot Depth
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

Legend
Location of water well with available driller's log from which percent fine grained materials data were calculated
Santa Paula Settlement Basin Boundary
Holocene Alluvial fan deposits (Qhf) "low permeability sediment" Boundary Adapted from CGS 2008
Santa Paula
SANTA PAULA
Saticoy
S A N   B U E N A V E N T U R A
E X   M I S S I O N
S O U T H   M O U N T A I N
SANTA CLARA RIVER
SESPE NO 2
Feet
2000 0 2000 4000 6000
N S E W
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: Low Perm Sediments .wor
Low Permeability Sediment Zone
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

Appendix D

RCS Compiled
Aquifer Data and
Inflow/Outflow Calculations

Table D-1
Hydraulic Conductivity Values Derived from Specific Capacity Values

Well	Producing Aquifer[1]	Geographic Area	Hydraulic Conductivity[2]
03N20W06D03S	Undifferentiated Alluvium/San Pedro	Santa Paula Creek/East end	41
03N21W02P01S	San Pedro	Santa Paula Creek/East end	647
03N21W01P03S	Undifferentiated Alluvium	Santa Paula Creek/East end	4086
03N20W06N02S	Undifferentiated Alluvium	Santa Paula Creek/East end	1989
03N21W11E03S	Undifferentiated Alluvium/San Pedro	Santa Paula Creek/East end	362
03N21W11F03S	Undifferentiated Alluvium/San Pedro	Santa Paula Creek/East end	561
03N21W12E07S	Undifferentiated Alluvium	Santa Paula Creek/East end	450
03N21W09R04S	San Pedro	Santa Paula Creek/East end	692
03N21W15C06S	San Pedro	Santa Paula Creek/East end	597
03N21W16A02S	San Pedro	Santa Paula Creek/East end	1333
03N21W11D02S	Undifferentiated Alluvium/San Pedro	Santa Paula Creek/East end	11
03N21W29C02S	Undifferentiated Alluvium	Middle Basin	875
03N21W29G02S	Undifferentiated Alluvium	Middle Basin	248
03N21W30F01S	Undifferentiated Alluvium/San Pedro	Middle Basin	1377
03N21W30H07S	Undifferentiated Alluvium/San Pedro	Middle Basin	196
03N21W29K01S	Undifferentiated Alluvium	Middle Basin	1900
03N21W29K02S	Undifferentiated Alluvium	Middle Basin	1750
03N22W36H01S	Undifferentiated Alluvium	West end/Saticoy	1264
03N22W36K04S	San Pedro	West end/Saticoy	1131
03N22W36R01S	Undifferentiated Alluvium	West end/Saticoy	1330
03N22W35Q02S	Undifferentiated Alluvium	West end/Saticoy	158
03N21W16G01S	Undifferentiated Alluvium	Santa Paula Creek/East end	1950
03N21W16K03S	San Pedro	Santa Paula Creek/East end	659
03N21W16P01S	Undifferentiated Alluvium	Middle Basin	36
03N21W17P02S	San Pedro	Middle Basin	521
03N21W20A01S	Undifferentiated Alluvium	Middle Basin	298
03N21W21B03S	Undifferentiated Alluvium	Middle Basin	218
03N21W19G04S	San Pedro	Middle Basin	719
03N21W19G02S	San Pedro	Middle Basin	325
03N21W19G03S	Undifferentiated Alluvium/San Pedro	Middle Basin	200
03N21W20J04S	Undifferentiated Alluvium	Middle Basin	1663
02N22W02K06S	Undifferentiated Alluvium	Fault area/south	908
02N22W12A02S	Undifferentiated Alluvium	Fault area/south	1315
02N22W11C03S	Undifferentiated Alluvium/San Pedro	Fault area/south	30
02N22W10C02S	Undifferentiated Alluvium/San Pedro	Fault area/south	887
02N22W10A02S	Undifferentiated Alluvium	Fault area/south	92
02N22W12E02S	Undifferentiated Alluvium	Fault area/south	240
02N22W12E04S	Undifferentiated Alluvium/San Pedro	Fault area/south	296
02N21W07K01S	Undifferentiated Alluvium	Fault area/south	1750
02N21W07K02S	Undifferentiated Alluvium	Fault area/south	60
02N22W12E03S	Undifferentiated Alluvium	Fault area/south	285
02N22W12L04S	Undifferentiated Alluvium	Fault area/south	315

Table D-1
Hydraulic Conductivity Values Derived from Specific Capacity Values

Well	Producing Aquifer[1]	Geographic Area	Hydraulic Conductivity[2]
02N22W08L01S	San Pedro	Fault area/south	216
02N22W09K05S	San Pedro	Fault area/south	84
02N22W12L02S	Undifferentiated Alluvium	Fault area/south	150
02N21W07M03S	Undifferentiated Alluvium/San Pedro	Fault area/south	133
02N22W11R02S	Undifferentiated Alluvium	Fault area/south	321
02N22W11R03S	Undifferentiated Alluvium	Fault area/south	131

Notes:
[1]Based on Perforated Interval and RCS subsurface interpretations
[2]Values derived from specific capacity values reported in UWCD GIS database using methods of Driscoll (1986), see text.

gpd/ft^2 = gallons per day per square foot

Table D-2
Compilation of Available Transmissivity and Storativity Values

Consultant	Report Date	Well	Source of Data/Notes	Reported Transmissivity (gpd/ft)	Reported Storativity (dimensionless)	Perforated Interval Length for Tested Well (ft)	Hydraulic Conductivity (gpd/ft^2)	Location
Staal, Gardner & Dunne (SGD)	February 1988	2N/22W-2K9	Constant rate test of City of Ventura Saticoy Well No. 2 South but near fault	109,600 to 111,700 calculated from drawdown data; 135,100 to 170,600 calculated from recovery data.	9×10^{-3} to 1.2×10^{-4} from onsite monitoring well	100 (300-400)	±1090 to ±1170 ±1350 to 1706 recovery data Geometric Mean = 1296	Outflow
Staal, Gardner & Dunne (SGD)	December 1992	2N/22W-2H2	Evaluation of theoretical distance-drawdown values for then-proposed City of Ventura Saticoy Well No. 3	130,000 (estimated)	10^{-4} (est'd)	N/A	N/A	--
Richard C. Slade & Associates	July 1995	3N/21W-11J2	Evaluation of Several Specific Capacity Tests in Santa Paula Well No. 12	Geometric Mean of 7 values = 269,300	NA	440 (260-700)	±545 to 691 Geometric Mean = 610	Inflow
Richard C. Slade & Associates	June 1996	3N/21W-9R5	Constant rate test following construction of new City of Santa Paula Well No. 13 Santa Paula Well 13 Data	254,000 to 286,000; geometric mean of 2 values =261,000	NA	330 (320-380, 400-670)	770 to 812 Geometric Mean = 791	Inflow
Richard C. Slade & Associates	June 1996	3N/21W-9R5	Constant rate test following construction of new City of Santa Paula Well No. 13 (Fico 10 and Santa Paula Well 11 Observation Data)	285,000 to 491,000; geometric mean of 2 values =374,000	4.1×10^{-4} (for SP Well No. 11) to as low as 4.3×10^{-4} (for Fico Well No. 10)	Fico 10 = 406 (360-756) SP Well No. 11 = 150 (430-580)	701 to 3273 Geometric Mean = 1515	Inflow
Richard C. Slade & Associates	April 1997	3N/21W-6A3	Constant rate test following construction of new City of Santa Paula Well No. 14	267,000 to 300,000 (calculated); Geometric Mean = 284,000	N/A; no nearby observation wells.	430 (370-800)	±621 to ±698 Geometric Mean = 660	Inflow
Fugro West	October 2007	Many	Evaluation of Several Specific Capacity Tests Multiple Wells	not directly estimated	NA	Ranging from 20 to 200	247 to 1668 Geometric mean = 763	Middle Basin
UWCD	February 2013	3N/21W-11J1	Step drawdown test of Fico 12; unplanned pumping of Fico 11	276,600 - represnetative value based on work by UWCD	1.2×10^{-3}	280 (120-400)	988	Inflow
Hopkins Groundwater Consultants	February 2013	2N/22W-2H2	Constant rate test of City of Ventura Saticoy Well No. 3; North of fault	197,000 to 227,500 (calculated); Geometric mean of four datasets = 202,500	1.2×10^{-3}, 9.6×10^{-4} Calculated from Alta Mutual Well No. 9 Geometric Mean = 1×10^{-3}	300 (312-392, 422-502, 512-652)	612 to 758 Geometric Mean = 675	Outflow

N/A = Not available

Table D-3
Hydraulic Conductivity Values Used in Inflow Calculation

Source	Hydraulic Conductivity	
	gpd/ft^2	ft/d
Active Channel Deposits		
FugroWest, 2007 (Plate 16)	2244	300
Undifferentiated Alluvium		
Specific Capacity, Geometric Mean Santa Paula Creek/East end wells[1]	1634	219
FugroWest, 2007 (Geometric Mean 9 wells)	763	102
SPWC 13 Aquifer Test[2]	696	93
FICO 12 Aquifer Test (incl.unplanned FICO 11 pumping)	898	120
Geometric Mean:	940	126
San Pedro		
Specific Capacity, Average Santa Paula Creek/East end wells[1]	748	100
SPWC 13 Aquifer Test[2]	812	109
SPWC 14 Aquifer Test - SPWC Well 4 Data	660	88
SPWC 14 Aquifer Test - FICO 10 and SPWC 11 Data	1516	203
Geometric Mean:	883	118

Notes

[1]See Table C-1

[2]Geometric mean of high and low values, divided between aquifers using spinner log data

gpd/ft^2 = gallons per day per square foot

ft/d = feet per day

Table D-4
Hydraulic Conductivity Values Used in Outflow Calculation

Source	Hydraulic Conductivity	
	gpd/ft2	ft/d
Active Channel Deposits		
FugroWest, 2007 (Plate 16)	2244	300
Undifferentiated Alluvium		
Geometric Mean Specific Capacity, Median West end/Saticoy wells[1]	643	86
FugroWest, 2007 (Geometric Mean 9 wells)	763	102
Geometric Mean:	700	94

Notes
[1]See Table C-1

gpd/ft^2 = gallons per day per square foot
ft/d = feet per day

Table D-5
Darcy's Law Calculation of Groundwater Inflow

Schematic Section Region	Shape	Formation	Length (ft)	Height (ft)	Saturated Area (ft^2)			Gradient			Hydraulic Conductivity		Inflow (ac-ft/y)			
					2012	2010	2000	2012	2010	2000	gpd/ft^2	ft/d	2012	2010	2000	Average
A[1,2]	Rectangle	Alluvium	4,200	395	1,580,350	1,564,550	1,608,000	0.0048	0.005	0.0041	940	126	8,012	8,262	6,963	7,746
AA[2]	Rectangle	Active Channel	500	125	56,500	54,500	60,000	0.0048	0.005	0.0041	2,244	300	682	685	619	662
B	Rectangle	San Pedro	4,200	270	1,134,000	1,134,000	1,134,000	0.0023	0.0039	0.0026	883	118	2,588	4,388	2,925	3,300
C	Triangle	Alluvium	3,000	230	345,000	345,000	345,000	0.0048	0.005	0.0041	940	126	1,749	1,822	1,494	1,688
D	Triangle	San Pedro	3,000	230	345,000	345,000	345,000	0.0023	0.0039	0.0026	883	118	787	1,335	890	1,004
E	Rectangle	San Pedro	3,000	270	810,000	810,000	810,000	0.0023	0.0039	0.0026	883	118	1,848	3,134	2,089	2,357
F	Rectangle	San Pedro	1,000	500	500,000	500,000	500,000	0.0023	0.0039	0.0026	883	118	1,141	1,935	1,290	1,455
G	Rectangle	San Pedro	4,200	180	756,000	756,000	756,000	0.0023	0.0039	0.0026	883	118	1,725	2,925	1,950	2,200
H	Triangle	San Pedro	3,000	180	270,000	270,000	270,000	0.0023	0.0039	0.0026	883	118	616	1,045	696	786
I	Rectangle	San Pedro	4,000	140	560,000	560,000	560,000	0.0023	0.0039	0.0026	883	118	1,278	2,167	1,445	1,630
J	Triangle	San Pedro	4,000	415	830,000	830,000	830,000	0.0023	0.0039	0.0026	883	118	1,894	3,212	2,141	2,416
												Total	22,320	30,909	22,502	25,244

Notes

[1]One-half of Section AA substracted from area of Section A

[2]Saturated area adjusted based on depth-to-water for Sections A and AA from water level contour maps, assuming depth-to-water equals 12 ft for 2012, 16 feet for 2010, and 5 ft for 2000

gpd/ft^2 = gallons per day per square foot

ft/d = feet per day

ac-ft/yr = acre feet per year

ft = feet

Table D-6
Darcy's Law Calculation of Groundwater Outflow

Schematic Section Region	Shape	Formation	Length (ft)	Height (ft)	Saturated Area (ft^2)			Gradient			Hydraulic Conductivity		Outflow (ac-ft/y)			
					2012	2010	2000	2012	2010	2000	gpd/ft^2	ft/d	2012	2010	2000	Average
A[1,2]	Rectangle	Alluvium	7,500	395	2,539,500	2,539,500	2,515,000	0.0019	0.0027	0.0017	700	94	3,795	5,393	3,363	4,184
AA[2]	Rectangle	Active Channel	2,600	125	273,000	273,000	260,000	0.0019	0.0027	0.0017	2,244	300	1,305	1,854	1,112	1,424
B[2]	Rectangle	Alluvium	4,000	190	680,000	680,000	660,000	0.0019	0.0027	0.0017	700	94	1,016	1,444	882	1,114
C	Triangle	Alluvium	4,000	190	380,000	380,000	380,000	0.0019	0.0027	0.0017	700	94	568	807	508	628
												Total	6,684	9,498	5,865	7,349

Notes

[1]Section AA substracted from area of Section A

[2]Saturated area adjusted based on depth-to-water for Sections A, AA, and B based on water-level contour maps assuming depth-to-water equals 20 ft for 2012 and 2010, and 25 ft for 2000

gpd/ft^2 = gallons per day per square foot

ft/d = feet per day

ac-ft/yr = acre feet per year

ft = feet

Table D-7
Groundwater Gradients Comparison

gradient (i)	RCS Gradient (i, ft/ft) Spring Data			Bachman Gradient (i, ft/ft) Average of Spring and Fall Data			Bachman Gradient (i, ft/ft) Spring Data			Bachman Gradient (i, ft/ft) Fall Data		
	2012	2010	2000	2012	2010	2005	2012	2010	2005	2012	2010	2005
Undiff. alluvium	0.0048	0.005	0.0041	0.004345	0.00533	0.004665	0.00428	0.00459	0.00624	0.00441	0.00607	0.00309
San Pedro Fm[1]	0.0023	0.0039	0.0026	0.004345	0.00533	0.004665	0.00428	0.00459	0.00624	0.00441	0.00607	0.00309

Notes
[1]Bachman Memorandum (2015) uses the same values for the San Pedro Formation as the undifferentiated alluvium

Table D-8a
Vertical Gradient Evaluation
SP-1

					Depth-to-water in April			Depth-to-water in October		
	Well Depth	**Top Perf**	**Bottom Perf**	**"Middle"**	**2000**	**2010**	**2012**	**2000**	**2010**	**2012**
03N21W15G04S (Bottom of Qoa)	SP1-280	260	280	270	42.72	43.59	42.77	53.33	53.64	56.3
03N21W15G03S (Top of San Pedro)	SP1-390	370	390	380	42.68	43.64	42.73	53.36	53.67	56.38
				ΔHead:	-0.04	0.05	-0.04	0.03	0.03	0.08
				Δdistance:	110	110	110	110	110	110
				ΔHead/Δdistance: *	-0.0004	0.000455	-0.000364	0.000273	0.000273	0.000727
						average	-0.0001		average	0.000424

* Negative gradient = upward flow

Table D-8b
Vertical Gradient Evaluation
SP-2

					Water Level in April			Water Level in October		
	Perf Depth	**Top Perf**	**Bottom Perf**	**"Middle"**	**2000**	**2010**	**2012**	**2000**	**2010**	**2012**
03N21W16H07S (Bottom of Qoa)	SP2-170	150	170	160	43.58	45.82	44.66	55.13	55.65	57.28
03N21W16H06S (Top of San Pedro)	SP2-310	290	310	300	44.69	46.63	44.84	56.00	57.22	58.85
				ΔHead:	1.11	0.81	0.18	0.87	1.57	1.57
				Δdistance:	140	140	140	140	140	140
				ΔHead/Δdistance:	0.007929	0.005786	0.001286	0.006214	0.011214	0.011214
						average	0.0050		average	0.009548

Appendix E

Well Location Map (UWCD, 2013)

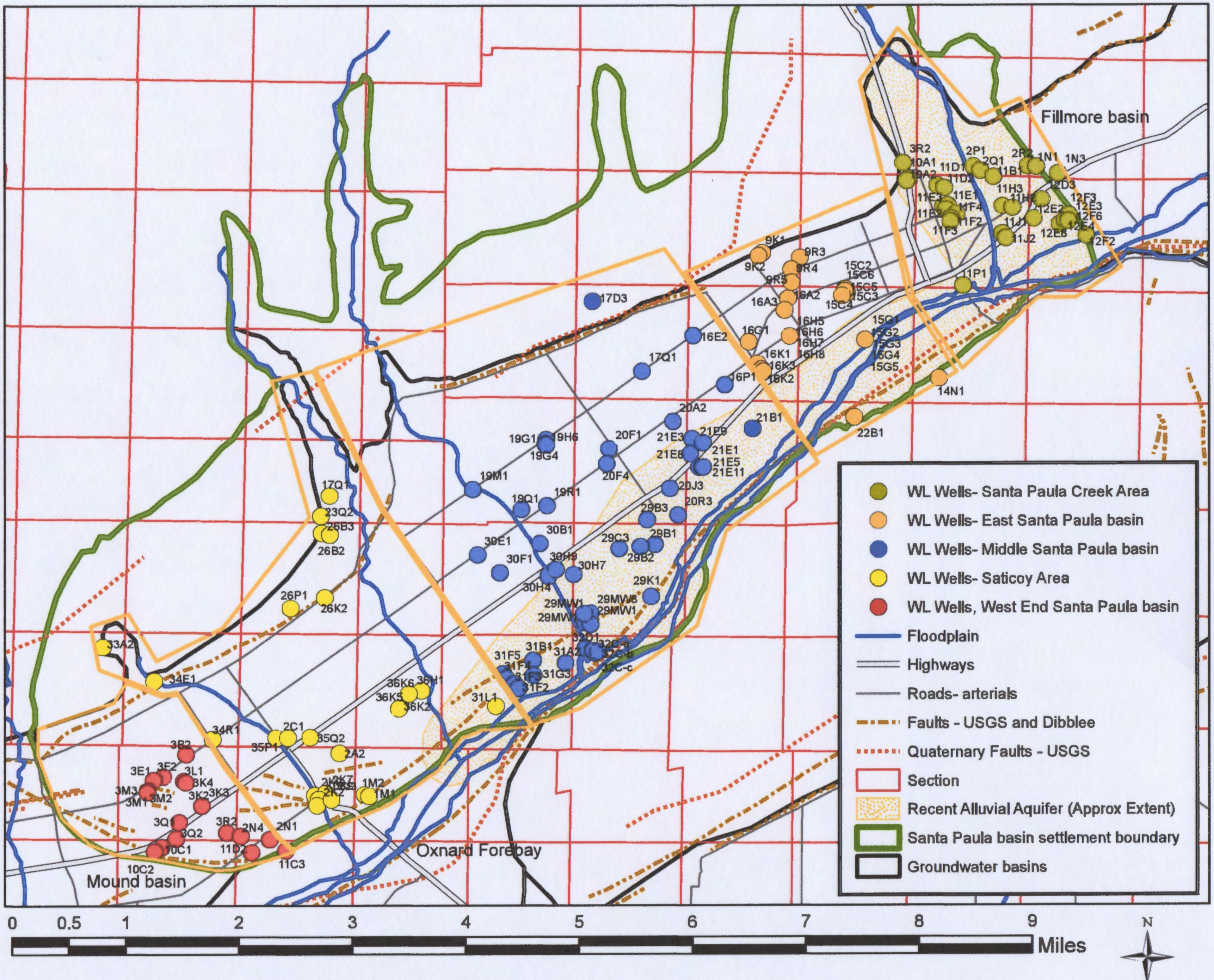
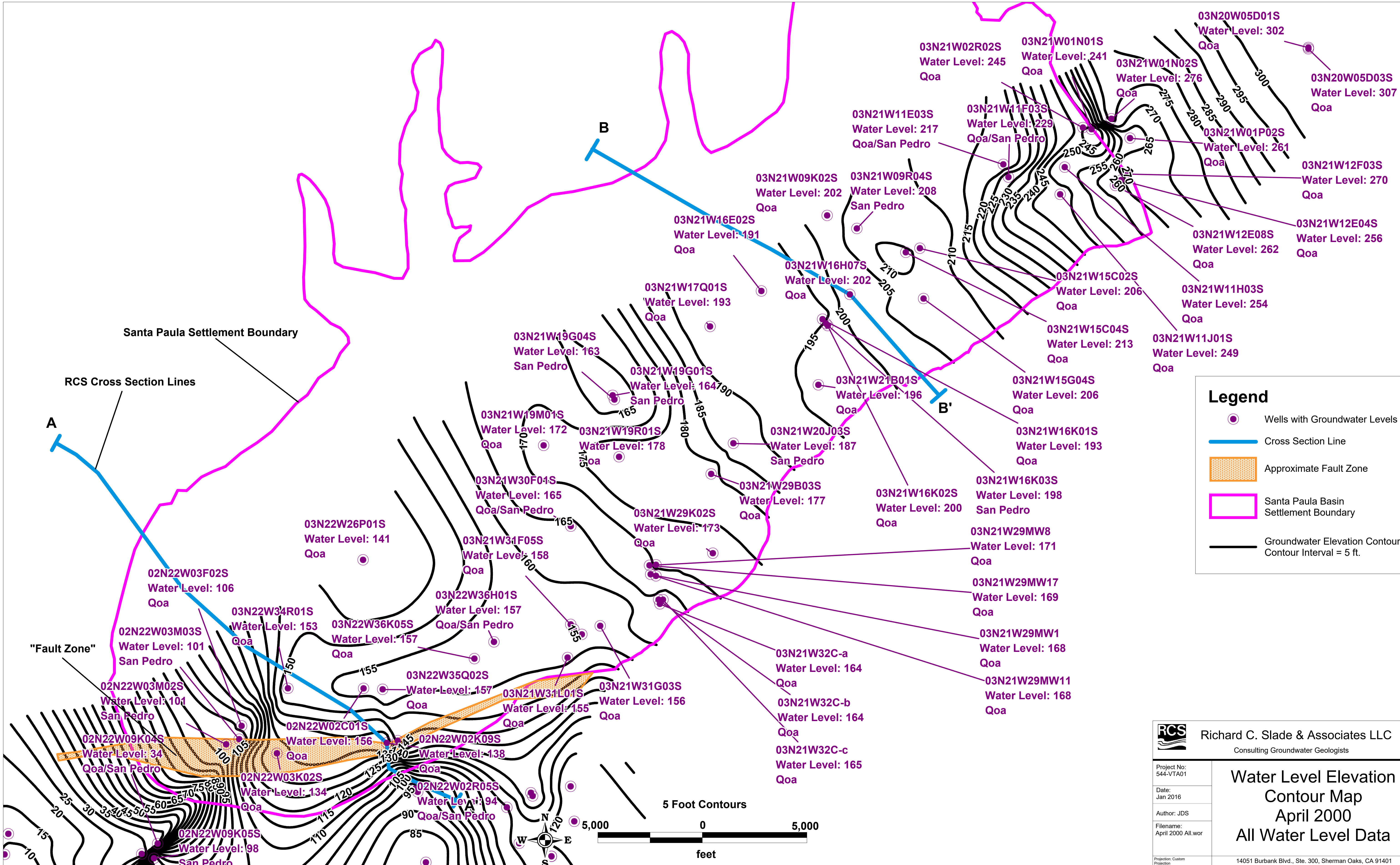


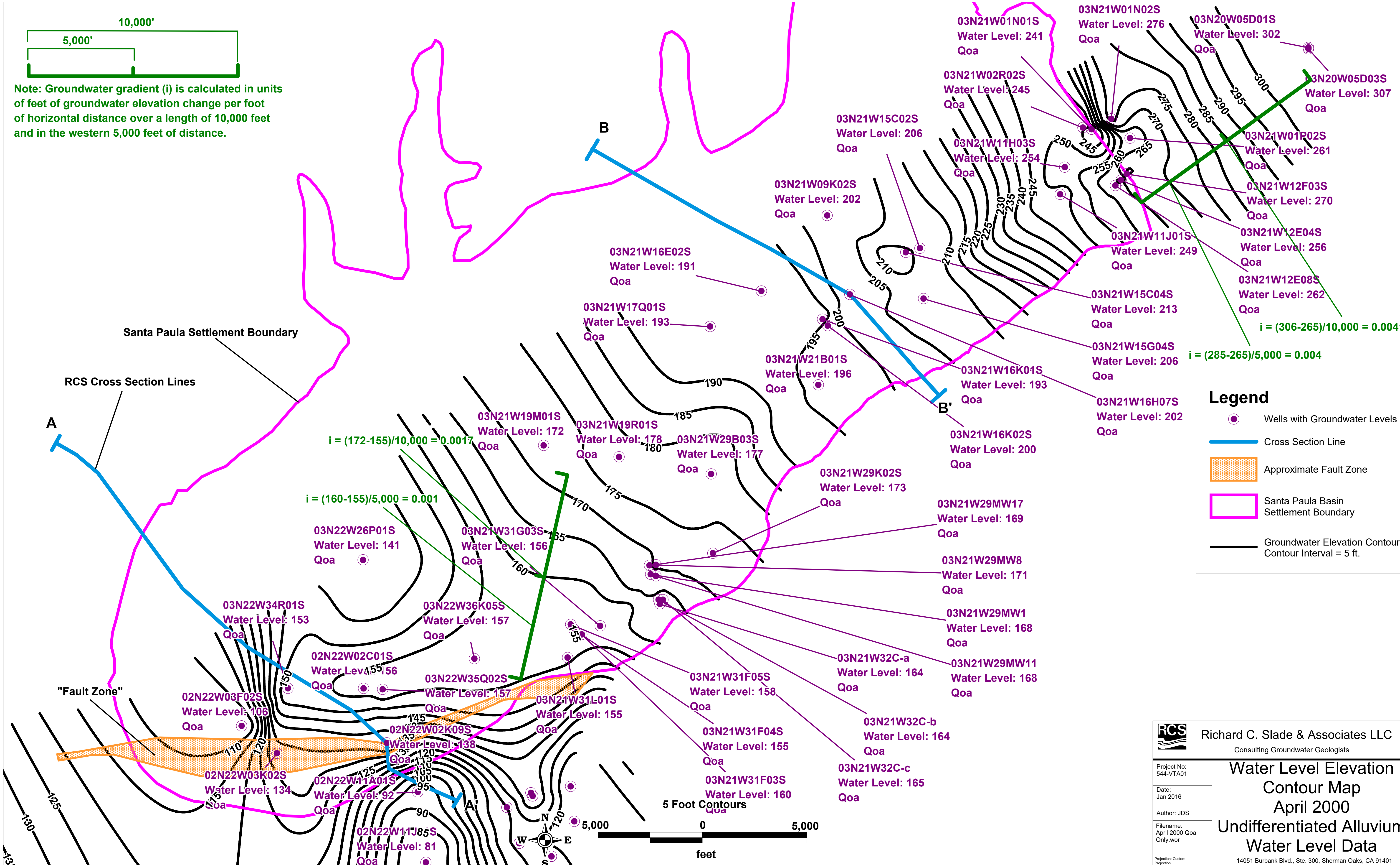
Figure 1. Geographic divisions and wells with water level records, Santa Paula basin

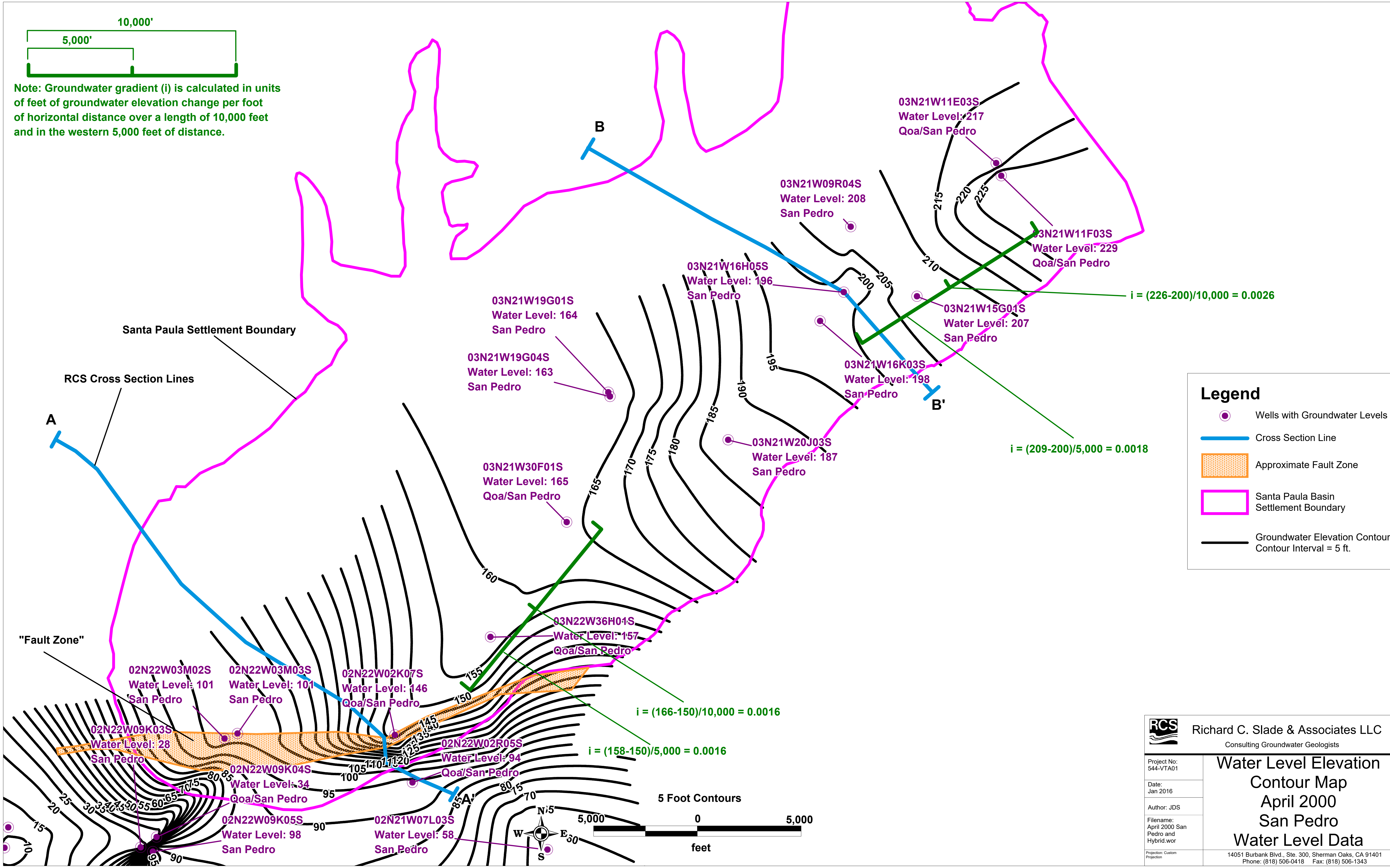
Appendix F

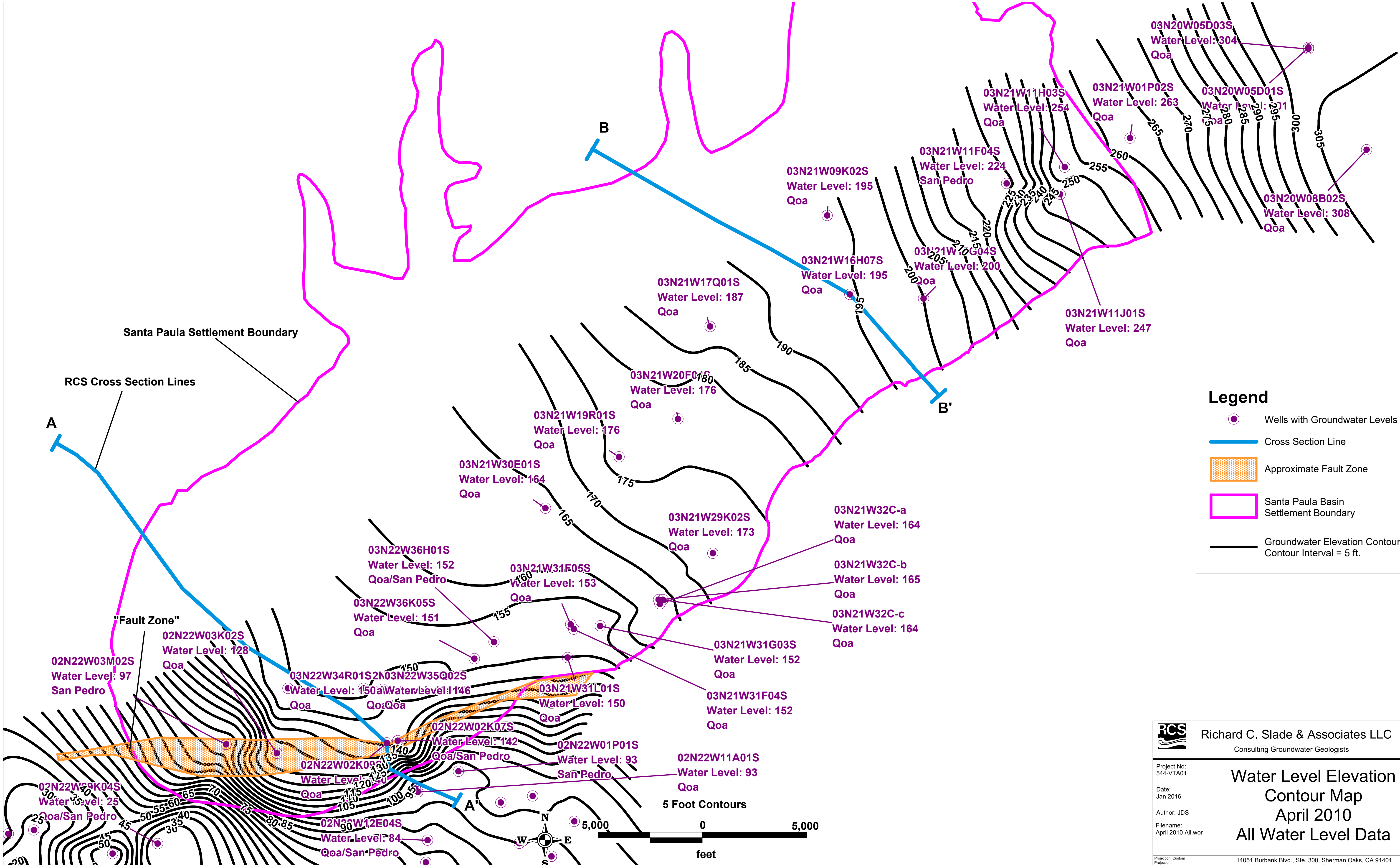
RCS Groundwater Elevation Contour Maps and Stiff-Diagram Map

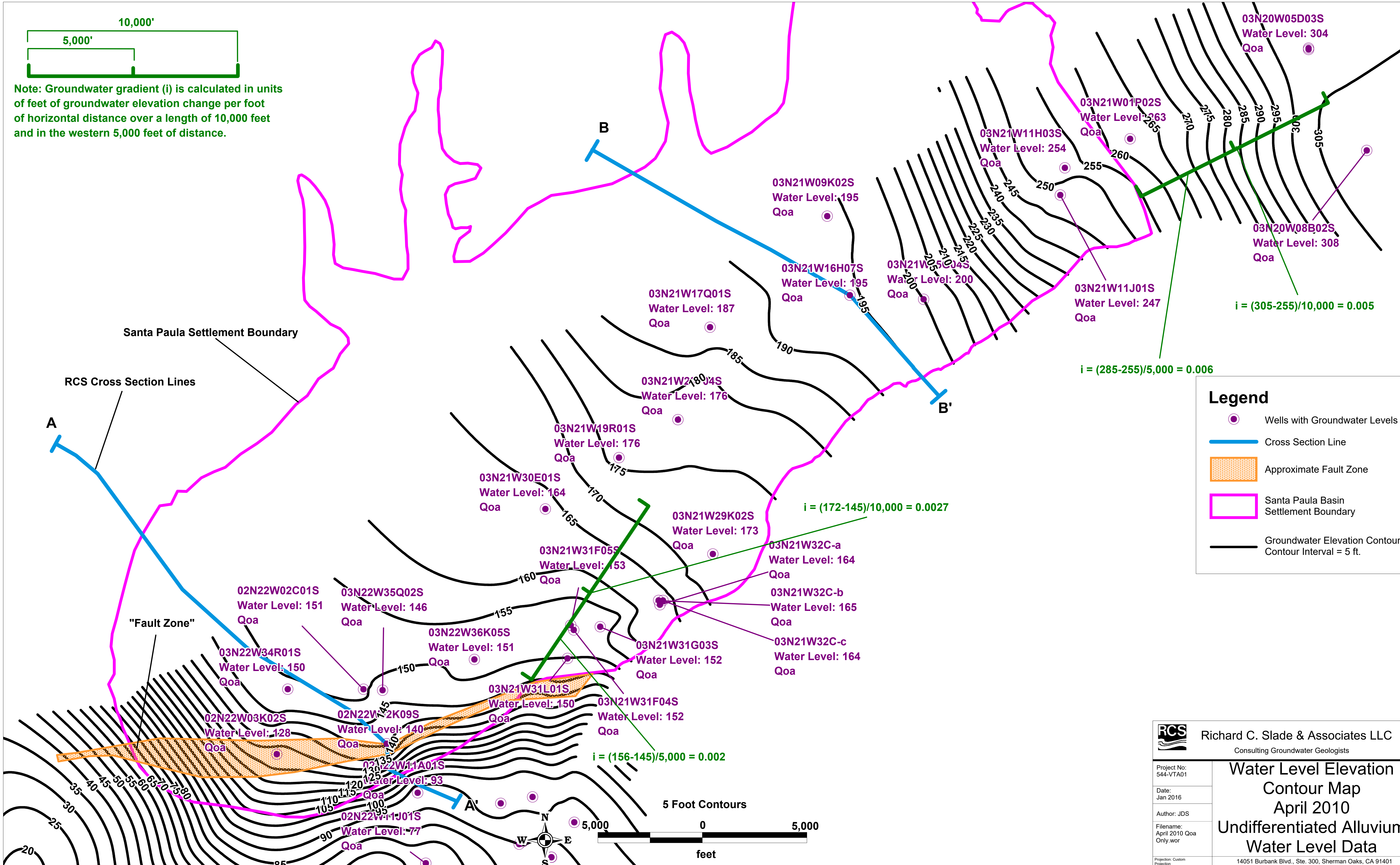


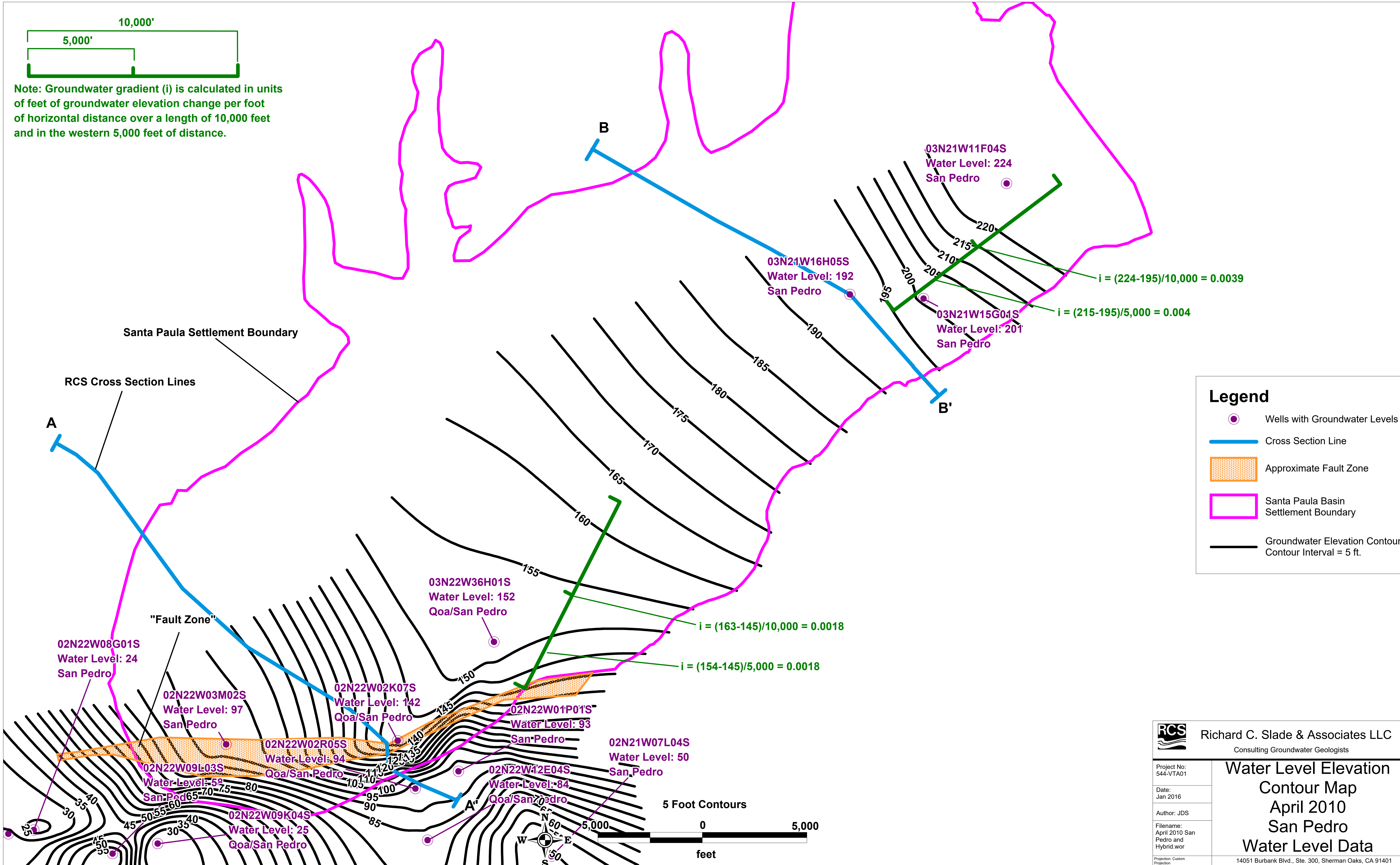
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours
Contour Interval = 5 ft.
Santa Paula Settlement Boundary
RCS Cross Section Lines
"Fault Zone"
A
A'
B
B'
5 Foot Contours
5,000
0
5,000
feet
N
E
S
W
03N20W05D01S Water Level: 302 Qoa
03N20W05D03S Water Level: 307 Qoa
03N21W02R02S Water Level: 245 Qoa
03N21W01N01S Water Level: 241 Qoa
03N21W01N02S Water Level: 276 Qoa
03N21W11F03S Water Level: 229 Qoa/San Pedro
03N21W11E03S Water Level: 217 Qoa/San Pedro
03N21W01P02S Water Level: 261 Qoa
03N21W12F03S Water Level: 270 Qoa
03N21W09K02S Water Level: 202 Qoa
03N21W09R04S Water Level: 208 San Pedro
03N21W12E04S Water Level: 256 Qoa
03N21W12E08S Water Level: 262 Qoa
03N21W16E02S Water Level: 191 Qoa
03N21W16H07S Water Level: 202 Qoa
03N21W15C02S Water Level: 206 Qoa
03N21W11H03S Water Level: 254 Qoa
03N21W17Q01S Water Level: 193 Qoa
03N21W15C04S Water Level: 213 Qoa
03N21W11J01S Water Level: 249 Qoa
03N21W19G04S Water Level: 163 San Pedro
03N21W19G01S Water Level: 164 San Pedro
03N21W21B01S Water Level: 196 Qoa
03N21W15G04S Water Level: 206 Qoa
03N21W19M01S Water Level: 172 Qoa
03N21W19R01S Water Level: 178 Qoa
03N21W20J03S Water Level: 187 San Pedro
03N21W16K01S Water Level: 193 Qoa
03N21W30F01S Water Level: 165 Qoa/San Pedro
03N21W29B03S Water Level: 177 Qoa
03N21W16K02S Water Level: 200 Qoa
03N21W16K03S Water Level: 198 San Pedro
03N22W26P01S Water Level: 141 Qoa
03N21W31F05S Water Level: 158 Qoa
03N21W29K02S Water Level: 173 Qoa
03N21W29MW8 Water Level: 171 Qoa
02N22W03F02S Water Level: 106 Qoa
03N21W29MW17 Water Level: 169 Qoa
03N22W36H01S Water Level: 157 Qoa/San Pedro
03N22W34R01S Water Level: 153 Qoa
03N22W36K05S Water Level: 157 Qoa
02N22W03M03S Water Level: 101 San Pedro
03N21W29MW1 Water Level: 168 Qoa
03N21W32C-a Water Level: 164 Qoa
03N21W29MW11 Water Level: 168 Qoa
02N22W03M02S Water Level: 101 San Pedro
03N22W35Q02S Water Level: 157 Qoa
03N21W31L01S Water Level: 155 Qoa
03N21W31G03S Water Level: 156 Qoa
03N21W32C-b Water Level: 164 Qoa
02N22W02C01S Water Level: 156 Qoa
02N22W09K04S Water Level: 34 Qoa/San Pedro
02N22W02K09S Water Level: 138 Qoa
03N21W32C-c Water Level: 165 Qoa
02N22W03K02S Water Level: 134 Qoa
02N22W02R05S Water Level: 94 Qoa/San Pedro
02N22W09K05S Water Level: 98 San Pedro
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2000 All.wor
Water Level Elevation Contour Map April 2000 All Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

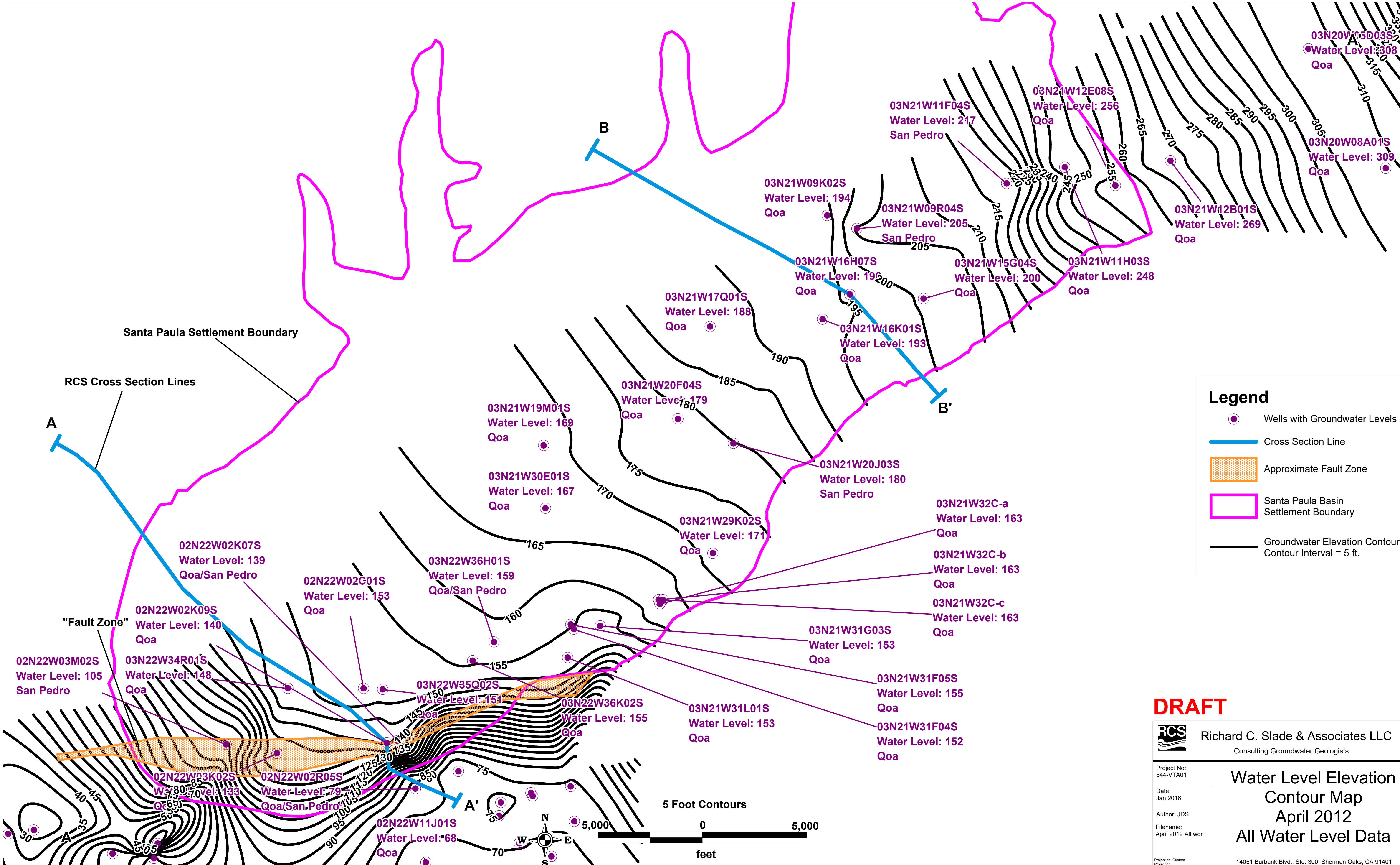

10,000'
5,000'
Note: Groundwater gradient (i) is calculated in units of feet of groundwater elevation change per foot of horizontal distance over a length of 10,000 feet and in the western 5,000 feet of distance.
Santa Paula Settlement Boundary
RCS Cross Section Lines
"Fault Zone"
A
A'
B
B'
i = (172-155)/10,000 = 0.0017
i = (160-155)/5,000 = 0.001
i = (306-265)/10,000 = 0.0041
i = (285-265)/5,000 = 0.004
03N21W01N01S Water Level: 241 Qoa
03N21W01N02S Water Level: 276 Qoa
03N20W05D01S Water Level: 302 Qoa
03N20W05D03S Water Level: 307 Qoa
03N21W02R02S Water Level: 245 Qoa
03N21W15C02S Water Level: 206 Qoa
03N21W11H03S Water Level: 254 Qoa
03N21W01P02S Water Level: 261 Qoa
03N21W12F03S Water Level: 270 Qoa
03N21W09K02S Water Level: 202 Qoa
03N21W12E04S Water Level: 256 Qoa
03N21W11J01S Water Level: 249 Qoa
03N21W12E08S Water Level: 262 Qoa
03N21W16E02S Water Level: 191 Qoa
03N21W15C04S Water Level: 213 Qoa
03N21W17Q01S Water Level: 193 Qoa
03N21W15G04S Water Level: 206 Qoa
03N21W21B01S Water Level: 196 Qoa
03N21W16K01S Water Level: 193 Qoa
03N21W16H07S Water Level: 202 Qoa
03N21W16K02S Water Level: 200 Qoa
03N21W19M01S Water Level: 172 Qoa
03N21W19R01S Water Level: 178 Qoa
03N21W29B03S Water Level: 177 Qoa
03N21W29K02S Water Level: 173 Qoa
03N21W29MW17 Water Level: 169 Qoa
03N22W26P01S Water Level: 141 Qoa
03N21W31G03S Water Level: 156 Qoa
03N21W29MW8 Water Level: 171 Qoa
03N21W29MW1 Water Level: 168 Qoa
03N22W34R01S Water Level: 153 Qoa
03N22W36K05S Water Level: 157 Qoa
03N21W32C-a Water Level: 164 Qoa
03N21W29MW11 Water Level: 168 Qoa
02N22W02C01S Water Level: 156 Qoa
03N22W35Q02S Water Level: 157 Qoa
03N21W31F05S Water Level: 158 Qoa
02N22W03F02S Water Level: 106 Qoa
03N21W31L01S Water Level: 155 Qoa
03N21W32C-b Water Level: 164 Qoa
02N22W02K09S Water Level: 138 Qoa
03N21W31F04S Water Level: 155 Qoa
02N22W03K02S Water Level: 134 Qoa
02N22W11A01S Water Level: 92 Qoa
03N21W31F03S Water Level: 160 Qoa
03N21W32C-c Water Level: 165 Qoa
02N22W11J85S Water Level: 81 Qoa
5 Foot Contours
5,000 0 5,000
feet
N S E W
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours Contour Interval = 5 ft.
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2000 Qoa Only.wor
Water Level Elevation Contour Map April 2000 Undifferentiated Alluvium Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343


10,000'
5,000'
Note: Groundwater gradient (i) is calculated in units of feet of groundwater elevation change per foot of horizontal distance over a length of 10,000 feet and in the western 5,000 feet of distance.
Santa Paula Settlement Boundary
RCS Cross Section Lines
A
A'
B
B'
"Fault Zone"
03N21W11E03S
Water Level: 217
Qoa/San Pedro
03N21W09R04S
Water Level: 208
San Pedro
03N21W11F03S
Water Level: 229
Qoa/San Pedro
03N21W16H05S
Water Level: 196
San Pedro
i = (226-200)/10,000 = 0.0026
03N21W15G01S
Water Level: 207
San Pedro
03N21W19G01S
Water Level: 164
San Pedro
03N21W19G04S
Water Level: 163
San Pedro
03N21W16K03S
Water Level: 198
San Pedro
03N21W20J03S
Water Level: 187
San Pedro
i = (209-200)/5,000 = 0.0018
03N21W30F01S
Water Level: 165
Qoa/San Pedro
03N22W36H01S
Water Level: 157
Qoa/San Pedro
i = (166-150)/10,000 = 0.0016
i = (158-150)/5,000 = 0.0016
02N22W03M02S
Water Level: 101
San Pedro
02N22W03M03S
Water Level: 101
San Pedro
02N22W02K07S
Water Level: 146
Qoa/San Pedro
02N22W09K03S
Water Level: 28
San Pedro
02N22W02R05S
Water Level: 94
Qoa/San Pedro
02N22W09K04S
Water Level: 34
Qoa/San Pedro
02N22W09K05S
Water Level: 98
San Pedro
02N21W07L03S
Water Level: 58
San Pedro
5 Foot Contours
5,000
0
5,000
feet
N
S
E
W
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours Contour Interval = 5 ft.
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2000 San Pedro and Hybrid.wor
Projection: Custom Projection
Water Level Elevation Contour Map
April 2000
San Pedro
Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

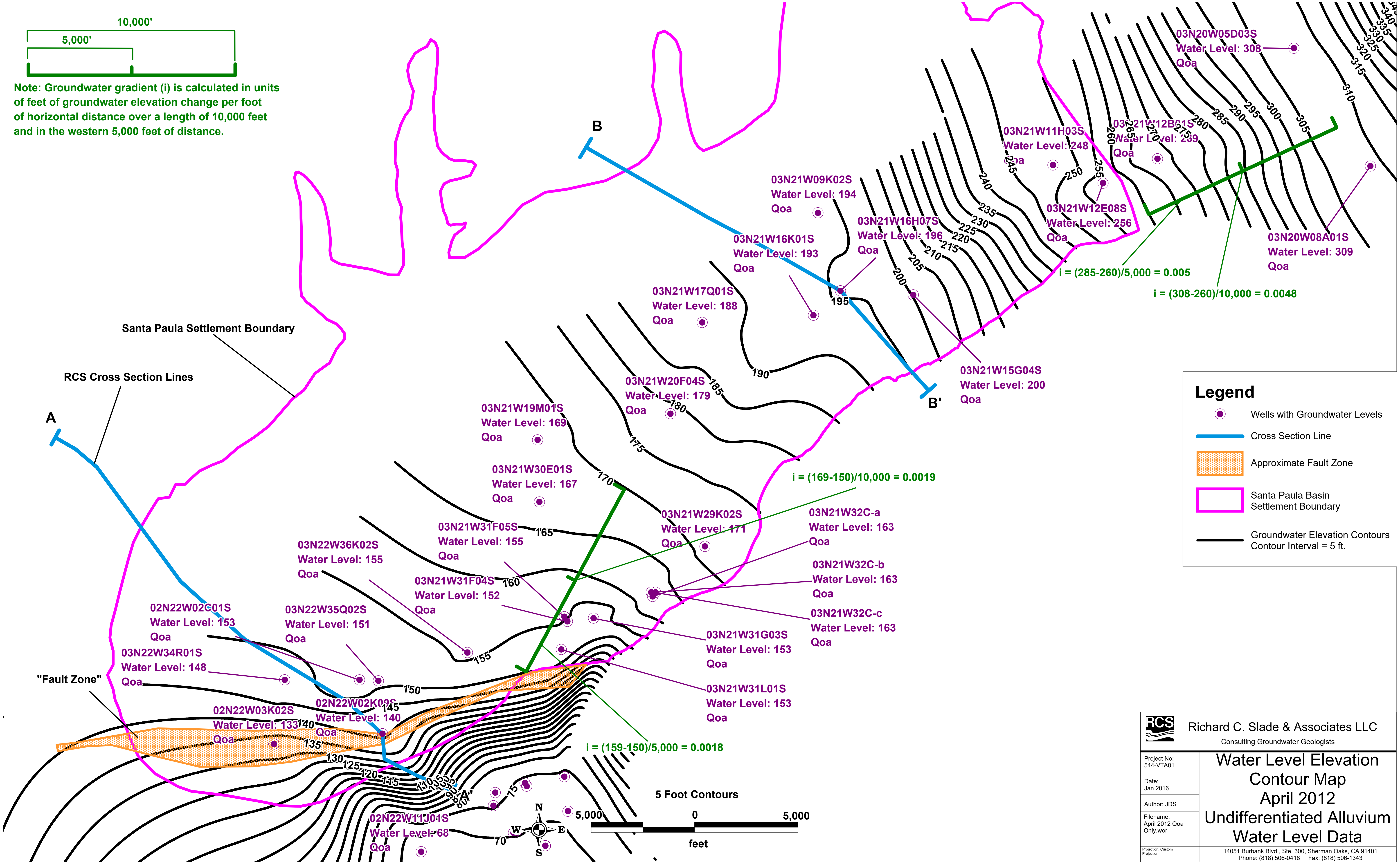

Santa Paula Settlement Boundary
RCS Cross Section Lines
A
A'
B
B'
"Fault Zone"
03N20W05D03S
Water Level: 304
Qoa
03N20W05D01S
03N21W11H03S
Water Level: 254
Qoa
03N21W01P02S
Water Level: 263
Qoa
03N20W08B02S
Water Level: 308
Qoa
03N21W11F04S
Water Level: 224
San Pedro
03N21W09K02S
Water Level: 195
Qoa
03N21W16H07S
Water Level: 195
Qoa
Water Level: 200
Qoa
03N21W11J01S
Water Level: 247
Qoa
03N21W17Q01S
Water Level: 187
Qoa
Water Level: 176
Qoa
03N21W19R01S
Water Level: 176
Qoa
03N21W30E01S
Water Level: 164
Qoa
03N21W29K02S
Water Level: 173
Qoa
03N21W32C-a
Water Level: 164
Qoa
03N21W32C-b
Water Level: 165
Qoa
03N21W32C-c
Water Level: 164
Qoa
03N22W36H01S
Water Level: 152
Qoa/San Pedro
03N21W31F05S
Water Level: 153
Qoa
03N22W36K05S
Water Level: 151
Qoa
03N21W31G03S
Water Level: 152
Qoa
03N21W31F04S
Water Level: 152
Qoa
02N22W03K02S
Water Level: 128
Qoa
02N22W03M02S
Water Level: 97
San Pedro
03N21W31L01S
Water Level: 150
Qoa
02N22W02K07S
Water Level: 142
Qoa/San Pedro
02N22W01P01S
Water Level: 93
San Pedro
02N22W11A01S
Water Level: 93
Qoa
02N22W12E04S
Water Level: 84
Qoa/San Pedro
Water Level: 25
Qoa/San Pedro
5 Foot Contours
5,000
0
5,000
feet
N
S
E
W
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours
Contour Interval = 5 ft.
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2010 All.wor
Water Level Elevation Contour Map
April 2010
All Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343


10,000'
5,000'
Note: Groundwater gradient (i) is calculated in units of feet of groundwater elevation change per foot of horizontal distance over a length of 10,000 feet and in the western 5,000 feet of distance.
B
A
B'
A'
Santa Paula Settlement Boundary
RCS Cross Section Lines
"Fault Zone"
03N20W05D03S Water Level: 304 Qoa
03N21W01P02S Water Level: 263 Qoa
03N21W11H03S Water Level: 254 Qoa
03N21W09K02S Water Level: 195 Qoa
03N21W16H07S Water Level: 195 Qoa
Water Level: 200 Qoa
03N21W11J01S Water Level: 247 Qoa
03N20W08B02S Water Level: 308 Qoa
i = (305-255)/10,000 = 0.005
i = (285-255)/5,000 = 0.006
03N21W17Q01S Water Level: 187 Qoa
Water Level: 176 Qoa
03N21W19R01S Water Level: 176 Qoa
03N21W30E01S Water Level: 164 Qoa
03N21W29K02S Water Level: 173 Qoa
i = (172-145)/10,000 = 0.0027
03N21W31F05S Water Level: 153 Qoa
03N21W32C-a Water Level: 164 Qoa
03N21W32C-b Water Level: 165 Qoa
03N21W32C-c Water Level: 164 Qoa
02N22W02C01S Water Level: 151 Qoa
03N22W35Q02S Water Level: 146 Qoa
03N22W36K05S Water Level: 151 Qoa
03N21W31G03S Water Level: 152 Qoa
03N22W34R01S Water Level: 150 Qoa
03N21W31L01S Water Level: 150 Qoa
03N21W31F04S Water Level: 152 Qoa
02N22W03K02S Water Level: 128 Qoa
Water Level: 140 Qoa
i = (156-145)/5,000 = 0.002
Water Level: 93 Qoa
Water Level: 77 Qoa
5 Foot Contours
5,000 0 5,000
feet
N S E W
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours Contour Interval = 5 ft.
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2010 Qoa Only.wor
Water Level Elevation Contour Map April 2010 Undifferentiated Alluvium Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343

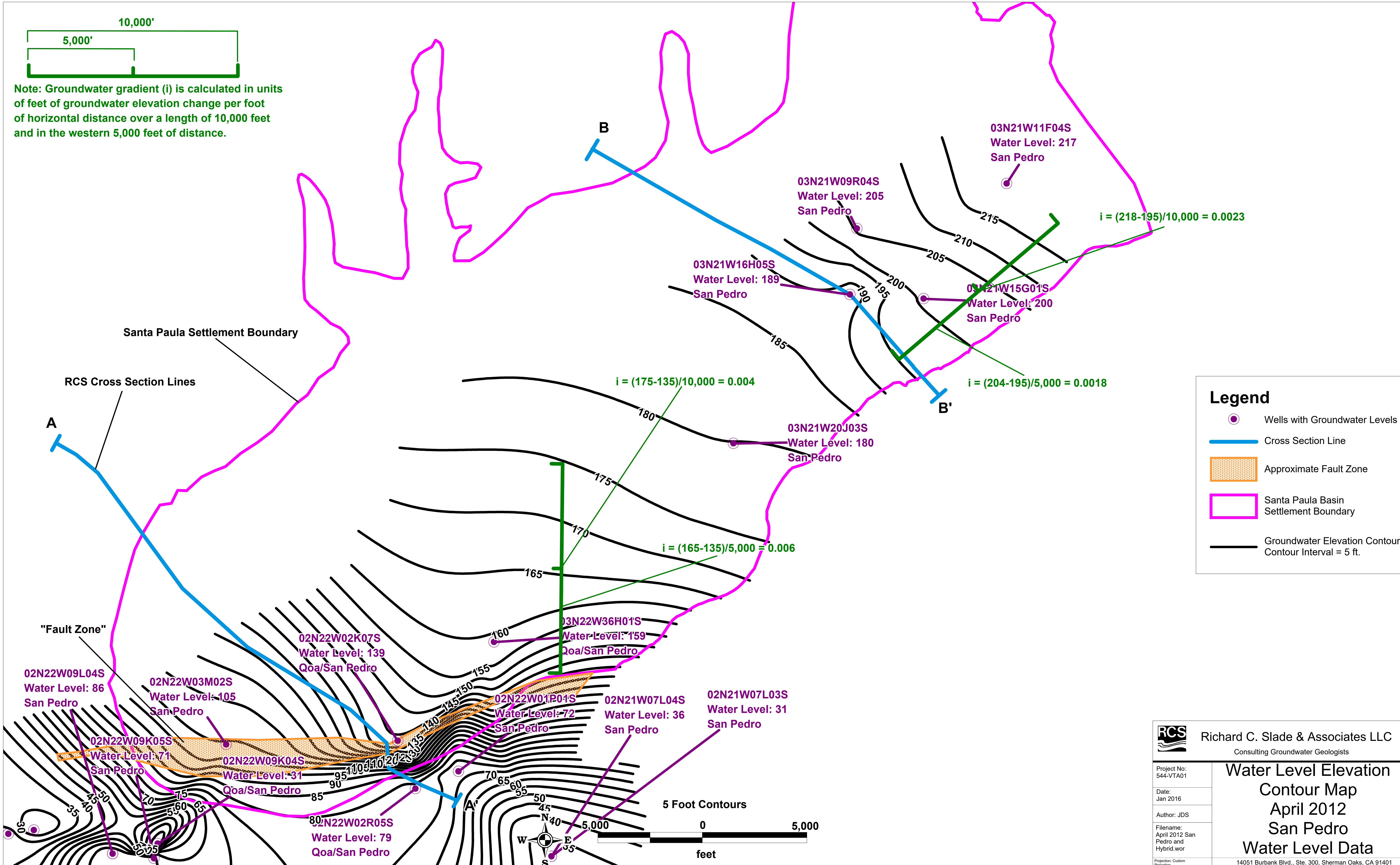

10,000'
5,000'
Note: Groundwater gradient (i) is calculated in units of feet of groundwater elevation change per foot of horizontal distance over a length of 10,000 feet and in the western 5,000 feet of distance.
Santa Paula Settlement Boundary
RCS Cross Section Lines
A
A'
B
B'
"Fault Zone"
03N21W11F04S
Water Level: 224
San Pedro
03N21W16H05S
Water Level: 192
San Pedro
03N21W15G01S
Water Level: 201
San Pedro
03N22W36H01S
Water Level: 152
Qoa/San Pedro
02N22W08G01S
Water Level: 24
San Pedro
02N22W03M02S
Water Level: 97
San Pedro
02N22W02K07S
Water Level: 142
Qoa/San Pedro
02N22W01P01S
Water Level: 93
San Pedro
02N21W07L04S
Water Level: 50
San Pedro
02N22W02R05S
Water Level: 94
Qoa/San Pedro
02N22W09L03S
Water Level: 58
San Pedro
02N22W12E04S
Water Level: 84
Qoa/San Pedro
02N22W09K04S
Water Level: 25
Qoa/San Pedro
i = (224-195)/10,000 = 0.0039
i = (215-195)/5,000 = 0.004
i = (163-145)/10,000 = 0.0018
i = (154-145)/5,000 = 0.0018
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours Contour Interval = 5 ft.
5 Foot Contours
5,000
0
5,000
feet
N
S
E
W
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2010 San Pedro and Hybrid.wor
Water Level Elevation Contour Map
April 2010
San Pedro
Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343



Santa Paula Settlement Boundary
RCS Cross Section Lines
A
A'
B
B'
"Fault Zone"
03N21W11F04S
Water Level: 217
San Pedro
03N21W12E08S
Water Level: 256
Qoa
03N20W08A01S
Water Level: 309
Qoa
03N21W09K02S
Water Level: 194
Qoa
03N21W09R04S
Water Level: 205
San Pedro
03N21W12B01S
Water Level: 269
Qoa
03N21W16H07S
Water Level: 196
Qoa
03N21W15G04S
Water Level: 200
Qoa
03N21W11H03S
Water Level: 248
Qoa
03N21W17Q01S
Water Level: 188
Qoa
03N21W16K01S
Water Level: 193
Qoa
03N21W20F04S
Water Level: 179
Qoa
03N21W19M01S
Water Level: 169
Qoa
03N21W20J03S
Water Level: 180
San Pedro
03N21W30E01S
Water Level: 167
Qoa
03N21W32C-a
Water Level: 163
Qoa
03N21W29K02S
Water Level: 171
Qoa
02N22W02K07S
Water Level: 139
Qoa/San Pedro
03N22W36H01S
Water Level: 159
Qoa/San Pedro
03N21W32C-b
Water Level: 163
Qoa
02N22W02G01S
Water Level: 153
Qoa
03N21W32C-c
Water Level: 163
Qoa
02N22W02K09S
Water Level: 140
Qoa
03N21W31G03S
Water Level: 153
Qoa
02N22W03M02S
Water Level: 105
San Pedro
03N22W34R01S
Water Level: 148
Qoa
03N22W35Q02S
Water Level: 151
Qoa
03N21W31F05S
Water Level: 155
Qoa
03N22W36K02S
Water Level: 155
Qoa
03N21W31L01S
Water Level: 153
Qoa
03N21W31F04S
Water Level: 152
Qoa
02N22W03K02S
Water Level: 133
02N22W02R05S
Water Level: 79
Qoa/San Pedro
02N22W11J01S
Water Level: 68
Qoa
5 Foot Contours
5,000
0
5,000
feet
N
W
E
S
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours
Contour Interval = 5 ft.
DRAFT
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2012 All.wor
Water Level Elevation Contour Map
April 2012
All Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343



10,000'
5,000'
Note: Groundwater gradient (i) is calculated in units of feet of groundwater elevation change per foot of horizontal distance over a length of 10,000 feet and in the western 5,000 feet of distance.
B
B'
A
A'
Santa Paula Settlement Boundary
RCS Cross Section Lines
"Fault Zone"
03N20W05D03S
Water Level: 308
Qoa
03N21W11H03S
Water Level: 248
Qoa
03N21W12B01S
Water Level: 269
Qoa
03N21W09K02S
Water Level: 194
Qoa
03N21W12E08S
Water Level: 256
Qoa
03N21W16H07S
Water Level: 196
Qoa
03N20W08A01S
Water Level: 309
Qoa
03N21W16K01S
Water Level: 193
Qoa
i = (285-260)/5,000 = 0.005
i = (308-260)/10,000 = 0.0048
03N21W17Q01S
Water Level: 188
Qoa
03N21W15G04S
Water Level: 200
Qoa
03N21W20F04S
Water Level: 179
Qoa
03N21W19M01S
Water Level: 169
Qoa
03N21W30E01S
Water Level: 167
Qoa
i = (169-150)/10,000 = 0.0019
03N21W29K02S
Water Level: 171
Qoa
03N21W32C-a
Water Level: 163
Qoa
03N21W31F05S
Water Level: 155
Qoa
03N22W36K02S
Water Level: 155
Qoa
03N21W32C-b
Water Level: 163
Qoa
03N21W31F04S
Water Level: 152
Qoa
03N21W32C-c
Water Level: 163
Qoa
02N22W02C01S
Water Level: 153
Qoa
03N22W35Q02S
Water Level: 151
Qoa
03N21W31G03S
Water Level: 153
Qoa
03N22W34R01S
Water Level: 148
Qoa
03N21W31L01S
Water Level: 153
Qoa
02N22W03K02S
Water Level: 133
Qoa
02N22W02K09S
Water Level: 140
Qoa
i = (159-150)/5,000 = 0.0018
02N22W11J01S
Water Level: 68
Qoa
5 Foot Contours
5,000
0
5,000
feet
N
W
E
S
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours Contour Interval = 5 ft.
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2012 Qoa Only.wor
Water Level Elevation Contour Map April 2012 Undifferentiated Alluvium Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343



10,000'
5,000'
Note: Groundwater gradient (i) is calculated in units of feet of groundwater elevation change per foot of horizontal distance over a length of 10,000 feet and in the western 5,000 feet of distance.
B
B'
A
A'
Santa Paula Settlement Boundary
RCS Cross Section Lines
"Fault Zone"
i = (218-195)/10,000 = 0.0023
i = (204-195)/5,000 = 0.0018
i = (175-135)/10,000 = 0.004
i = (165-135)/5,000 = 0.006
03N21W11F04S
Water Level: 217
San Pedro
03N21W09R04S
Water Level: 205
San Pedro
03N21W16H05S
Water Level: 189
San Pedro
03N21W15G01S
Water Level: 200
San Pedro
03N21W20J03S
Water Level: 180
San Pedro
03N22W36H01S
Water Level: 159
Qoa/San Pedro
02N22W02K07S
Water Level: 139
Qoa/San Pedro
02N22W09L04S
Water Level: 86
San Pedro
02N22W03M02S
Water Level: 105
San Pedro
02N22W01P01S
Water Level: 72
San Pedro
02N21W07L04S
Water Level: 36
San Pedro
02N21W07L03S
Water Level: 31
San Pedro
02N22W09K05S
Water Level: 71
San Pedro
02N22W09K04S
Water Level: 31
Qoa/San Pedro
02N22W02R05S
Water Level: 79
Qoa/San Pedro
215
210
205
200
195
190
185
180
175
170
165
160
155
150
145
140
135
130
125
120
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
5 Foot Contours
5,000
0
5,000
feet
N
E
S
W
Legend
Wells with Groundwater Levels
Cross Section Line
Approximate Fault Zone
Santa Paula Basin Settlement Boundary
Groundwater Elevation Contours Contour Interval = 5 ft.
RCS
Richard C. Slade & Associates LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan 2016
Author: JDS
Filename: April 2012 San Pedro and Hybrid.wor
Projection: Custom Projection
Water Level Elevation Contour Map
April 2012
San Pedro
Water Level Data
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
Phone: (818) 506-0418 Fax: (818) 506-1343


Data Key:
Ca Mg Na
HCO3 SO4 Cl
25 0 25 meq/l
Most Recent Data From:
2010 - 2014
2000 - 2009
1990 - 1999
Data Offset from Well Location:
Data at Well Location:
Santa Paula Settlement Basin Boundary
03N21W09K04S Perfs: 260-402' Qoa/San Pedro
03N21W09R04S Perfs: 360-756' San Pedro
03N21W09R05S Perfs: 320-760' San Pedro
03N21W15C06S Perfs: 452-653' San Pedo
03N21W15C02S Perfs: 176-322' Qoa
03N21W16H05S (USGS S.P.S. 2)
03N21W15G01S (USGS S.P.S. 1)
03N21W11E03S Perfs: 100-453' Qoa/San Pedro
03N21W11J02S Perfs: 260-700' Qoa/San Pedro
03N21W11A01S Depth: 470' Perfs: Unknown Likely Qoa/San Pedro
03N21W01N02S Perfs: 240-350'
03N21W01P08S Perfs: 160-260'
03N21W06N02S Perfs: 240-350'
03N21W12H01S Perfs: 74-150'
03N21W12F03S Perfs: 120-284'
03N21W12E04S Perfs: 120-284'
03N21W12E08S Perfs: 120-285'
Wells in this region are perforated in Qoa
03N21W19G01S Perfs: 456-566' San Pedro
03N21W30F01S Perfs: 260-424' Qoa/San Pedro
03N21W30H04S Perfs: 100-400' Qoa/San Pedro
03N21W29N01S Depth: 504' Perfs: Unknown Likely Qoa/San Pedro
03N22W36K07S Depth: 1,485' Perfs: Unknown Likely San Pedro
03N22W35Q01S Perfs: 232-724' Qoa/San Pedro
02N22W02K09S Perfs: 300-400' Qoa/San Pedro
02N22W03E01S Perfs: 266-723' Qoa/San Pedro
02N22W03L01S Perfs: 175-400' Qoa
Depth: 70' 170' 310' 550'
10/30/2013
10/20/2009
10/11/1999
Qoa
San Pedro
Depth: 80' 280' 390' 540' 680'
10/29/2013
10/19/2009
10/12/1999
Qoa
San Pedro
N W E S
1 mile
RCS RICHARD C. SLADE & ASSOCIATES LLC
Consulting Groundwater Geologists
Project No: 544-VTA01
Date: Jan. 2016
Author: JDS
Filename: Stiff Map.cdr
Stiff Water Quality Diagram Map Santa Paula Basin
14051 Burbank Blvd., Ste. 300, Sherman Oaks, CA 91401
S. California: (818) 506-0418 N. California: (707) 963-3914

Appendix G

DPWM Methodology and Documentation

Table G-1. Summary of General DPWM Input Values

Parameter	Variable	Value	Units	Comment
Field capacity	head_fc	102	cm	1/10 bar
Wilting point	head_wp	61,293	cm	60 bar
Elevation of reference weather station	Elev_ref	763	ft msl	Ojai Count Fire Station
Lapse rate for air temperature (dry adiabatic lapse rate)	CTcor	–2.6	°C/km	PRISM mean annual maximum air temperatures for 1971-2000 Normal period
Average elevation for basin	elevavg	1,300	ft msl	Average of USGS DEM cells in the basin
Average latitude for basin	Latavg	34.45	degrees	Approximate basin midpoint
Adjustment coefficient in Hargreaves' radiation formula	Krs	0.19	°C – 0.5	
Evaporation layer depth	Ze	0.15	meters	Depth of the surface soil layer that is subject to drying by way of evaporation; upper end of range in Allen et al., 1998, p. 144 (ranges from 0.10 to 0.15 meter)
Readily evaporable water	REW	8	mm	Upper end of range for loamy sand (Allen et al., 1998, Table 19)
Initial capillary head node 1	IC1	61,293	cm	Set to wilting point (60 bar)
Initial capillary head node 2	IC2	61,293	cm	Set to wilting point (60 bar)
Initial capillary head node 3	IC3	61,293	cm	Set to wilting point (60 bar)
Initial capillary head node 4	IC4	102	cm	Set to field capacity (1/10 bar)
Depletion factor	p	0.5	—	Varies 0 to 1 but typically ranges from 0.30 for shallow rooted plants at high values of ET_c (>8 mm/d) to 0.70 for deep rooted plants at low values of ET_c (<3 mm/d) with 0.5 in common use
Minimum snowmelt factor	MFMIN	2	mm/d/°C	Minimum expected to occur on December 21 (Schroeder et al., 1994)
Maximum snowmelt factor	MFMAX	5.2	mm/d/°C	Maximum expected to occur on June 21 (Schroeder et al., 1994)
Minimum transpiration coefficient (K_c) for dry surface soil (upper 0.10 to 0.15 meter) with no vegetation cover	Kc_min	0	—	0 recommended by Allen et al. (1998) for arid environments

cm = Centimeters
ft msl = Feet above mean sea level
°C/km= Degree Celsius per kilometer

PRISM = Parameter-elevation regressions on independent slopes model
USGS = U.S. Geological Survey
DEM = Digital elevation model

mm = Millimeters
ET_c = Crop evapotranspiration
— = Unitless
mm/d/°C = Millimeters per day per degree Celsius

Table G-2. Soils Data
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Map Unit Symbol	Saturated Hydraulic Conductivity		Van Genuchten Parameters		Water Content (cm^3/cm^3)		Depth (m)
	(m/s)	(ft/d)	alpha (1/cm)	n	Saturated	Residual	
AcA	2.80E-05	7.94	1.90E-02	1.34	0.348	0.033	20
AcC	2.80E-05	7.94	3.22E-02	1.4	0.384	0.047	5
AnC	2.80E-05	7.94	3.22E-02	1.4	0.384	0.047	5
AsF	9.20E-05	26.08	5.18E-02	1.45	0.332	0.023	1.65
AuB	9.00E-06	2.55	1.11E-02	1.46	0.413	0.069	5
AuC2	9.00E-06	2.55	1.11E-02	1.46	0.413	0.069	5
AuD	9.00E-06	2.55	1.11E-02	1.46	0.413	0.069	5
BdG	8.30E-05	23.53	1.00E-02	1.1	0.1	0.00	0.15
CaE2	9.00E-06	2.55	3.14E-02	1.35	0.345	0.042	0.41
CaF	9.00E-06	2.55	1.11E-02	1.46	0.413	0.069	0.36
Cd	1.60E-05	4.54	3.11E-02	1.33	0.36	0.04	20
CfD2	2.70E-06	0.77	1.15E-02	1.29	0.393	0.061	0.66
CfE	2.70E-06	0.77	1.15E-02	1.29	0.393	0.061	0.76
CfF2	2.70E-06	0.77	1.15E-02	1.29	0.393	0.061	0.66
CfG2	2.70E-06	0.77	1.28E-02	1.29	0.389	0.06	0.66
CgG2	2.70E-06	0.77	1.15E-02	1.29	0.393	0.061	0.66
CrC	2.80E-05	7.94	3.00E-02	1.37	0.381	0.055	5
CsD	2.80E-05	7.94	5.63E-02	1.55	0.302	0.033	20
CyC	9.10E-07	0.26	1.77E-02	1.27	0.474	0.094	5
Cz	9.10E-07	0.26	1.35E-02	1.18	0.412	0.065	20
Dbd	9.10E-07	0.26	1.77E-02	1.27	0.474	0.094	1.27
DbE	9.10E-07	0.26	1.77E-02	1.27	0.474	0.094	1.27
DbF	6.20E-07	0.18	1.08E-02	1.19	0.426	0.067	1.02
Fd	8.30E-05	23.53	1.45E-02	2.68	0.43	0.045	20
Gaa	9.00E-06	2.55	1.21E-02	1.34	0.368	0.045	20
GaC	9.00E-06	2.55	1.10E-02	1.48	0.404	0.062	5
GbC	9.00E-06	2.55	1.12E-02	1.47	0.406	0.064	5
GcB	9.00E-06	2.55	6.09E-03	1.6	0.458	0.079	5
GrF	1.20E-05	3.40	3.85E-02	1.36	0.351	0.038	0.2
GsE	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	0.82
GsF	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	0.77
GsG	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	0.77
GxG	9.20E-05	26.08	6.09E-03	1.6	0.458	0.079	5
HaG	4.00E-06	1.13	3.74E-02	1.34	0.352	0.055	0.36

cm^3/cm^3 = Cubic centimeters per cubic centimeter
m/s = Meters per second
ft/d = Feet per day
m = Meters

Table G-2. Soils Data
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Map Unit Symbol	Saturated Hydraulic Conductivity		Van Genuchten Parameters		Water Content (cm^3/cm^3)		Depth (m)
	(m/s)	(ft/d)	alpha (1/cm)	n	Saturated	Residual	
HuD2	3.70E-06	1.05	1.57E-02	1.26	0.357	0.052	20
HuE3	3.20E-06	0.91	1.06E-02	1.28	0.359	0.046	20
IrG	8.30E-05	23.53	1.00E-02	1.1	0.1	0.00	0.15
KmD2	9.00E-06	2.55	3.15E-02	1.39	0.381	0.051	5
LaF	8.30E-05	23.53	1.45E-02	2.68	0.43	0.045	20
LeD2	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	0.92
McA	9.20E-05	26.08	4.26E-02	1.4	0.323	0.02	20
McC	9.20E-05	26.08	4.26E-02	1.4	0.323	0.02	20
MeA	9.20E-05	26.08	4.26E-02	1.4	0.323	0.02	20
MfA	5.40E-05	15.31	2.00E-02	1.37	0.319	0.021	20
MhF	9.00E-06	2.55	1.11E-02	1.46	0.413	0.069	0.38
MkG	5.80E-06	1.64	1.22E-02	1.31	0.384	0.054	0.46
MoA	9.00E-06	2.55	1.09E-02	1.47	0.411	0.067	5
MoC	9.00E-06	2.55	1.09E-02	1.47	0.411	0.067	5
MrC	9.00E-06	2.55	1.09E-02	1.47	0.411	0.067	5
MsA	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	5
MsB	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	5
NaE2	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	0.77
NaG	1.40E-06	0.40	1.43E-03	1.29	0.403	0.064	0.76
OhA	9.00E-06	2.55	2.71E-02	1.38	0.386	0.051	5
OhC2	9.00E-06	2.55	2.71E-02	1.38	0.386	0.051	5
OhD2	9.00E-06	2.55	2.71E-02	1.38	0.386	0.051	5
OsD2	9.00E-06	2.55	3.15E-02	1.39	0.381	0.051	5
OsE2	9.00E-06	2.55	3.15E-02	1.39	0.381	0.051	5
Pa	2.70E-06	0.77	1.13E-02	1.26	0.374	0.055	20
PcA	3.40E-05	9.64	1.73E-02	1.34	0.346	0.035	20
PcC	3.40E-05	9.64	1.75E-02	1.34	0.351	0.035	20
PsA	6.00E-05	17.01	3.38E-02	1.36	0.33	0.027	20
PxG	9.20E-05	26.08	3.53E-02	3.96	0.378	0.049	20
RcC	2.30E-06	0.65	2.13E-03	1.23	0.346	0.052	20
RcD2	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	5
RcE2	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	5
Rw	9.20E-05	26.08	6.09E-03	1.6	0.458	0.079	5
SaA	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	5

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ft/d = Feet per day
m = Meters

Table G-2. Soils Data
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Map Unit Symbol	Saturated Hydraulic Conductivity (m/s)	Saturated Hydraulic Conductivity (ft/d)	Van Genuchten Parameters alpha (1/cm)	Van Genuchten Parameters n	Water Content (cm^3/cm^3) Saturated	Water Content (cm^3/cm^3) Residual	Depth (m)
SaC	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	5
SbF	5.20E-05	14.74	3.47E-02	1.35	0.342	0.033	20
ScD2	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	1.27
ScE2	2.50E-06	0.71	1.13E-02	1.26	0.385	0.058	1.52
ScF2	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	1.27
ScG	2.10E-06	0.60	1.17E-02	1.25	0.387	0.059	1.14
Sd	2.80E-05	7.94	4.25E-02	1.64	0.387	0.038	5
SeG	6.50E-06	1.84	4.43E-02	1.38	0.402	0.09	0.64
She	9.00E-06	2.55	3.17E-02	1.39	0.384	0.048	1.27
ShF2	7.40E-06	2.10	1.60E-02	1.37	0.355	0.029	1.24
SnG	9.00E-06	2.55	1.09E-02	1.47	0.411	0.067	0.2
SoF	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	0.82
SoG	2.70E-06	0.77	1.33E-02	1.4	0.429	0.079	0.82
SsE2	9.00E-06	2.55	1.10E-02	1.48	0.404	0.062	0.82
SvF2	9.00E-06	2.55	1.10E-02	1.48	0.404	0.062	0.82
SwA	9.00E-06	2.55	1.12E-02	1.47	0.406	0.064	5
SwC	9.00E-06	2.55	7.96E-03	1.35	0.371	0.05	20
SxA	2.70E-06	0.77	1.07E-02	1.28	0.393	0.061	20
SxC	2.70E-06	0.77	1.07E-02	1.28	0.393	0.061	20
SzC	2.70E-06	0.77	1.46E-02	1.37	0.437	0.083	5
SzD	2.70E-06	0.77	1.46E-02	1.37	0.437	0.083	5
TeF	5.00E-06	1.42	1.45E-01	3	0.1	0	5
W	8.30E-05	23.53	1.45E-01	2.68	0.43	0.045	20
ZmC	9.00E-06	2.55	8.37E-03	1.52	0.409	0.063	5
ZmD2	6.60E-06	1.87	9.42E-03	1.36	0.375	0.049	20
17	1.60E-05	4.54	1.38E-02	1.44	0.4	0.061	0.81
26	2.80E-05	7.94	3.10E-02	1.39	0.384	0.049	0.31
30	2.80E-05	7.94	4.40E-02	1.39	0.344	0.039	0.33
50	2.80E-05	7.94	4.66E-02	1.41	0.357	0.035	20
51	9.00E-06	2.55	5.46E-02	1.51	0.285	0.048	0.58
9	2.80E-05	7.94	2.57E-02	1.39	0.387	0.051	0.36
M-W	8.30E-05	23.53	1.45E-01	2.68	0.43	0.045	20
CrC	2.80E-05	7.94	3.00E-02	1.37	0.381	0.055	5
CsD	2.80E-05	7.94	5.63E-02	1.55	0.302	0.033	20

cm^3/cm^3 = Cubic centimeters per cubic centimeter
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m = Meters

Table G-2. Soils Data

Map Unit Symbol	Saturated Hydraulic Conductivity		Van Genuchten Parameters		Water Content (cm^3/cm^3)		Depth (m)
	(m/s)	(ft/d)	alpha (1/cm)	n	Saturated	Residual	
KmD2	9.00E-06	2.55	3.15E-02	1.39	0.381	0.051	5
OhC2	9.00E-06	2.55	2.71E-02	1.38	0.386	0.051	5
OhD2	9.00E-06	2.55	2.71E-02	1.38	0.386	0.051	5
OsD2	9.00E-06	2.55	3.15E-02	1.39	0.381	0.051	5
OsE2	9.00E-06	2.55	3.15E-02	1.39	0.381	0.051	5
NaF	2.70E-06	0.77	7.92E-03	1.51	0.458	0.085	0.77
Imperv	1.00E-07	0.03	4.42E-02	1.71	0.355	0.039	5
Wash	1.00E-06	0.28	6.09E-03	1.6	0.458	0.079	5

cm^3/cm^3 = Cubic centimeters per cubic centimeter
m/s = Meters per second
ft/d = Feet per day
m = Meters

Table G-3. Geologic Units

Map Unit Symbol	Saturated Hydraulic Conductivity	
	(m/s)	(ft/d)
Qf	5.00E-06	1.42
Qha	5.00E-06	1.42
Qhf	3.53E-07	0.10
Qhfy	5.00E-06	1.42
Qht	9.20E-05	26.08
Qlp	3.53E-09	1.00E-03
Qls	3.53E-06	1.00
Qoa	5.00E-06	1.42
Qpa	5.00E-06	1.42
Qpa1	5.00E-06	1.42
Qpa2	5.00E-06	1.42
Qpf	5.00E-06	1.42
Qpf1	5.00E-06	1.42
Qpf2	5.00E-06	1.42
Qs	3.53E-05	10.01
Qsb	3.53E-09	1.00E-03
Qsbc	3.53E-09	1.00E-03
Qw	9.20E-05	26.08
Tcd	1.06E-10	3.00E-05
Tcw	3.53E-09	1.00E-03
Tj	1.06E-10	3.00E-05
Tm	3.53E-10	1.00E-04
Tma	3.53E-09	1.00E-03
Tmash	1.06E-10	3.00E-05
Tmb	3.53E-10	1.00E-04
Tmyl	3.53E-10	1.00E-04
Tmyu	3.53E-10	1.00E-04
Tp	3.53E-09	1.00E-03
Ts	3.53E-09	1.00E-03
Tsq	1.06E-10	3.00E-05
Tv	3.53E-09	1.00E-03
Tjsh	1.06E-10	3.00E-05
Tmas	6.18E-10	1.75E-04
Tjs	3.53E-09	1.00E-03

Table G-4. Vegetation Mean Rooting Depth and Plant Height

Vegetation	Mean Maximum Plant Height (m)	Mean Rooting Depth (m)
California Central Valley and Southern Coastal Grassland	0.91	0.5
California Central Valley Mixed Oak Savanna	7.62	10.7
California Central Valley Riparian Woodland and Shrubland	10.67	4
California Coastal Closed-Cone Conifer Forest and Woodland	12.19	3.5
California Coastal Live Oak Woodland and Savanna	7.62	10.7
California Coastal Redwood Forest	12.19	3.5
California Lower Montane Blue Oak-Foothill Pine Woodland and Savanna	7.62	10.7
California Maritime Chaparral	3.05	22.9
California Mesic Chaparral	3.05	22.9
California Mesic Serpentine Grassland	0.91	0.5
California Montane Jeffrey Pine-(Ponderosa Pine) Woodland	12.19	3.5
California Montane Woodland and Chaparral	12.19	3.5
Central and Southern California Mixed Evergreen Woodland	12.19	3.5
Cultivated Cropland	3	0.5
Developed, High Intensity	0.91	0.5
Developed, Low Intensity	0.91	0.5
Developed, Medium Intensity	0.91	0.5
Developed, Open Space	0.91	0.5
Great Basin Pinyon-Juniper Woodland	7.62	4.57
Inter-Mountain Basins Big Sagebrush Shrubland	10.67	4
Inter-Mountain Basins Shale Badland	0.1	0.15
Mediterranean California Dry-Mesic Mixed Conifer Forest and Woodland	12.19	3.5
Mediterranean California Foothill and Lower Montane Riparian Woodland	10.67	4
Mediterranean California Mesic Serpentine Woodland and Chaparral	6.1	3.99
Mediterranean California Mixed Evergreen Forest	12.19	3.5
Mediterranean California Southern Coastal Dune	0.91	0.5
Mojave Mid-Elevation Mixed Desert Scrub	2.59	2.1
North American Warm Desert Bedrock Cliff and Outcrop	0.1	0.15
Sonora-Mojave Creosotebush-White Bursage Desert Scrub	2.59	2.1
Sonora-Mojave Semi-Desert Chaparral	2.59	2.1
Southern California Coastal Scrub	2.59	2.1
Southern California Dry-Mesic Chaparral	3.05	22.9
Southern California Oak Woodland and Savanna	7.62	10.7
Temperate Pacific Freshwater Emergent Marsh	0.91	0.5
Temperate Pacific Freshwater Mudflat	0.91	0.5
Temperate Pacific Tidal Salt and Brackish Marsh	0.91	0.5

Table G-5. Irrigation

Crop	Irrigation (inches/yr)
Avocado	40
Citrus	38
Nursery - Flowers	67
Misc. Veg Single Crop - Spr	23
Nursery Container	66
Strawberries	36
Celery	19.5
Raspberries	67
Tomatoes - Peppers	34
Blueberries	39
Sod	59

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1. Introduction

This manual documents the Distributed Parameter Watershed Model (DPWM). The DPWM is a soil-water balance model that estimates the daily water balance components of precipitation, transpiration, evaporation, net infiltration (e.g., recharge), snow accumulation, snow melt, sublimation, run-on and runoff.

A soil-water balance model is a tool that allows one to evaluate the magnitude of various components of the hydrologic cycle as it is applied to the soil. Such models have been available for many years (e.g., Leavesley et al., 1983) and applied in arid areas (Flint et al., 2004; Flint and Flint, 2007). These models generally simulate water within a certain depth of soil and recognize topography, the hydraulic properties of soil and bedrock, and meteorological data in order to distribute precipitation among snow sublimation, evapotranspiration, runoff, soil moisture storage, and deep percolation. In the model, basin surface is discretized so that the water balance is computed over relatively small areas. It is assumed that the deep percolation below the root zone, sometimes referred to as net infiltration, will eventually become groundwater recharge. These models can be useful predictors of the amount and spatial distribution of recharge at the basin scale.

DPWM is based on the model developed by Sandia National Laboratory (2007) for Yucca Mountain (MASSIF) and similar in concept to water balance models used by the USGS (e.g., BCM [Flint and Flint, 2007], INFIL [Hevesi et al., 2003]). The DPWM uses a daily time step over variable grid cell sizes that typically range up to 72,900 square meters (m^2) (270 meters by 270 meters) but can be any size that the user specifies. The model generally relies on the widely accepted FAO-56 procedure for computing actual evapotranspiration (AET) from the reference evapotranspiration (ET_0) estimated with the Penman-Monteith method (Allen et al., 1998; Allen et al 2005). Water budget components accounted for in the model include precipitation, bare soil evaporation, transpiration, runoff, runon, snow accumulation, snow melt, snow sublimation, soil water storage, and net infiltration. A bedrock boundary is placed at the bottom of cells with shallow soil depths that will restrict infiltration when the saturated hydraulic conductivity of the bedrock is less than that of the soil. Unlike the USGS BCM model, DPWM accounts for the routing of runoff through the watershed. Cells that intersect washes are divided into two cells: one small cell containing the wash soils and one large cell with the interwash properties.

The FAO-56 method (Allen et al., 1998) computes a reference evapotranspiration value using the Penman-Monteith equation that represents evapotranspiration from an extensive surface of green grass of uniform height, actively growing and adequately watered. The reference evapotranspiration is modified for any agricultural or natural vegetation type using crop coefficients (K_{cb}). A coefficient of 1.0 represents the reference grass vegetation. Coefficients less than 1 represent less dense vegetation, while coefficients greater than 1 represent dense vegetation. The FAO-56 method supplies equations for computing crop coefficients for natural vegetation using site-specific climate data and a measure of the vegetation density (e.g., leaf area index [LAI]). Further adjustments to the crop coefficient provided by FAO-56 include stomatal resistance adjustments that account for the ability of desert vegetation to conserve water.

1.1 Description of Water Balance Methodology

To conduct the water balance, the watershed is divided into grid cells. In each cell, the soil profile is divided into three layers with four nodes. The upper layer (Layer 1) has bare soil evaporation and transpiration, and its thickness is based on the maximum depth of bare soil evaporation (“evaporation layer depth” [Z_e] in FAO-56 [Allen et al., 1998]). Layer 1 is divided into two nodes (Nodes 1 and 2). Node 1 is the bare soil fraction of the cell where evaporation is dominant, and Node 2 is the fraction of the cell surface covered by vegetation canopy where transpiration is dominant. Bare soil evaporation does not occur in Node 2, but transpiration occurs to some degree in both Nodes 1 and 2. The areas of Nodes 1 and 2 are adjusted over the year as the vegetation grows, peaks, and then declines based on the basal transpiration coefficient (K_{cb}).

The second layer (Layer 2 and Node 3) is the remainder of the root zone for the vegetation type; its thickness is the maximum rooting depth minus the thickness of Layer 1. Transpiration is dominant in Layer 2, but some diffuse evaporation also occurs.

The final layer (Layer 3) is below the root zone and does not have any transpiration or evaporation. Its thickness is the depth to bedrock minus the thicknesses of Layers 1 and 2. In cells with deep alluvium, the thickness is limited to 5 meters minus the root layer thicknesses. Drainage from Layer 3 is limited by the bedrock saturated hydraulic conductivity when less than the soil saturated hydraulic conductivity.

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2. Model Description

The following model description describes the operation of DPWM, the input and output text file formats, and then provides detailed descriptions of the functions used in DPWM.

2.1 Compiling and Executing DPWM

The DPWM was written in the C/C++ computer language. The code is relatively easy to understand for anyone experienced with computer languages, in that it is simply composed of function calls, if-then statements, arithmetic expressions, and for-loops. Executables have been compiled in release mode with Microsoft Visual C++ version 7.1.6030. Microsoft compilers (available for free at http://www.microsoft.com/express/vc/) have also been used to successfully compile DPWM. The DPWM is executed at the command line. All input and output files have the same root name with different extensions. The DPWM will query the user to enter the root name for a simulation or the user can use the DOS redirection command to enter the root name automatically from a text file (e.g., DPWM < root.txt).

2.2 Input Files

There are ten input files for the DPWM, four of which are optional. All files are standard ASCII text files that can be edited with any text editing software. The nomenclature for the input file extension names is “i” for input followed by a two-letter abbreviation for the input file type (e.g., ipm for the input parameter file).

2.2.1 Input Parameter File (.ipm)*

The parameter input file has several input blocks that represent the soil, vegetation, bedrock, and general model parameter values. The file can be either space or tab delimited. Extra spaces and/or tabs at the ends of lines should be removed to prevent input errors. The input should be confirmed by checking an echo of the input in the *.chk file. The text below describes the setup of ipm for the field capacity version of DPWM.

2.2.1.1 Block A – Basic Information

- CellPrint – Logical for printing output files. 1 = true and output files are generated. 0 = false and only final results are printed. Output files are typically suppressed for stochastic simulations.

- CalWY – The initial water year (e.g., 1980).

- Sindex – The index number for the soil type found in ephemeral streams (e.g., washes or arroyos) and corresponding with Block B. The Sindex has an origin of 1. Cells with areas smaller than specified in the MaxWashArea will be assigned hydraulic properties based on Sindex.

- Vindex – The index number for the vegetation type representing bare rock. The VIndex has an origin of 1. If bare rock is not found in the vegetation data, VIndex should be set to a value greater than the number of vegetation types. The VIndex is used to assign a minimal soil depth equal to the evaporation layer thickness to the cell.

- MaxWashArea – The maximum wash area for a model cell in square meters. Cells with this area or less are assigned the wash soil hydraulic properties but retain the surrounding soil depth.

- BalanceModel – DPWM can use a field capacity (fc), van Genuchten-Mualem (vgm), or Richard’s equation (re) modeling approach. At present, only the field capacity model is fully implemented and so BalanceModel should be set to fc.

- FC_head_cm – The absolute value of the field capacity capillary pressure head in centimeters of water. The typical field capacity values of 1/10 bar and 1/3 bar are equivalent to 102 cm and 341 cm, respectively.

- WP_head_cm – The absolute value of the wilting point capillary pressure head in centimeters of water. Agricultural vegetation typically has a wilting point of 15 bars

(15,323 cm) but desert vegetation in the southwest can extract water down to 60 bars (61,293 cm).

- Ncells – The number of cells in the model and should correspond with the watershed file (iws)

- Nveg – the number of vegetation types found in Block D of the ipm file.

- Nsoils – the number of soil types found in Block B of the ipm file including the wash soil.

- Nrock – the number of rock types found in Block C of the ipm file.

- Ndays – the number of days for the simulation and should correspond with the climate file (icl)

- Nyear – the number of water years in the simulation.

- Nstations – the number of climate stations used for precipitation. Typically only one station is used.

- Nlayer – the number of layers in the model. Typically NLayer should be set to 3.

- Nexits – The total number of surface flow exits to track in the model. If multiple surface water exits do not exist or do not need to be tracked separately, Nexits should be set to 1. Multiple surface flow exits can be designated with sequential negative numbers in the watershed (iws) and downstream receptor (idn) files starting with -1 (e.g., -1, -2, -3, etc.). Nexits is then set to the total number of exits.

- Kdew_amp, Kdew_wave, Kdew_Xoff and Kdew_Yoff – Harmonic function parameters for varying the dew point offset with the day of year as described in the KdewOffset_fcn. If Kdew_Yoff is negative, the dew point offset is constant (ºC) and equal to the absolute value of Kdew_Yoff and the remaining harmonic function parameters are ignored.

- Elev_avg_m – The average elevation in the basin in meters.

- Elev_ref_m – The elevation of the reference climate station in meters. If multiple stations exist as specified in Nstations, then multiple values are present on this line.

- Lat_avg – the average latitude in decimal degrees for the basin.

- CTcor – The absolute value of the dry temperature lapse rate with elevation (ºC/m). Lapse rates of about -7.5 ºC/km (-7.5E-03 ºC/m) are commonly observed in the PRISM mean annual maximum air temperature data. Maidment 1993 reports a dry temperature lapse rate of -10ºC/km, which was used as the nominal value for present day conditions at Yucca Mountain (SNL 2007). A saturated adiabatic lapse rate ranging from 6.9ºC/km at 0ºC to 3.6ºC/km at 30ºC at sea level can be used under conditions of condensation (SNL 2007 after Rosenberg et al 1983). A value is given for CTcor but is not used if PRISM temperature data are implemented.

- Cprecipcor – The precipitation lapse rate with elevation (1/m). A value is given but is not used if PRISM is implemented. Cprecipcor is estimated by regression of the observed mean annual precipitation (MAP) and elevation at climate stations in the area. The regression parameters are used to estimate MAP at the reference location. The slope (mm/km) from the regression is then divided by the estimate at the reference location (mm). The nominal present day value of Cprecipcor used at Yucca Mountain was 6.3%/100m, which would be inputted as 6.28E-04 in the ipm file (SNL 2007).

- CWindcor – The mean daily wind speed lapse rate with elevation (m/s/m). Zero can be given if it is assumed that wind speed does not vary with elevation.

- Ks_exp – exponent coefficient for relating the transpiration stress factor (Ks) to the water level in the root zone. If less than zero, the linear transpiration stress equation (equation 84 in Allen et al 1998) is implemented.

- LAI_exp – exponent coefficient for estimating the Kcb transpiration coefficient from leaf area index (LAI) (equation in Allen et al 1998). The nominal value for this coefficient is -0.7.

- K_rs – The Hargreaves' coefficient for estimating incoming solar radiation ($^{\circ}C^{-0.5}$). Typically ranges from 0.16 to 0.19 (Allen et al 1998) and a nominal value of 0.19 $^{\circ}C^{-0.5}$ was used for Yucca Mountain (SNL 2007). K_rs can be estimated from observed solar radiation data.

- Ze – Evaporation layer thickness in meters. Typically the evaporation layer is 10 to 15 cm (Allen et al 1998; p. 144).

- REW – Readily evaporable water in millimeters. This is the quantity of water that can be readily evaporated from upper evaporation layer in the model (Allen et al 1998; p. 144). REW ranges from 2 – 7 mm in sands to 8 – 12 mm in clay. A uniform value is given here for the model.

- p – Average fraction of the total available soil water that can be depleted before moisture stress occurs (Allen et al 1998; p. 162). The value of p ranges from 0.3 for shallow rooted plants at high rates of ET (> 8 mm/d) to 0.7 for deep rooted plants at low rates of ET (< 3 mm/d) with a typical value of 0.5 for many crops (Allen et al 1998).

- Kc_min – The minimum basal transpiration coefficient. Typically set to zero in arid climates.

- Kcln – Turbidity coefficient for solar radiation in Allen et al 2005, eq. D.2 (unitless). 1.0 recommended for clean air and <=0.5 for extremely turbid, dusty or polluted air.

- Fc_switch – The area fraction covered by vegetation in a cell. Determines distribution between nodes 1 and 2 in layer 1. If negative, the vegetation area varies with the transpiration coefficient (Kcb) as given in Allen et al 1998 (eq. 76; p. 149).

- Ze_Rock –This is the storage component for cell identified as bare rock by VIndex in units of meters. Typically, this is set equal to Ze_m

- MFMIN – minimum snow melt factor as given in the HELP model for December 21 or a constant melt factor if the MASSIF snow model is implemented. Typically set to 2mm/ºC.

- MFMAX – maximum snow melt factor as given in the HELP model for June 21. Typically set to 5.2mm/ºC. If zero, the MASSIF snow model for snowmelt is implemented.

- SUBPAR1 – sublimation fraction. In the MASSIF snow model, this is a constant value for the season that occurs on the day snow fall (0.15 reported for Colorado and used in the Yucca Mountain model). In the INFIL snow model, this is the fraction of daily reference evapotranspiration that occurs as sublimation for below freezing conditions.

- SUBPAR2 – daily sublimation fraction of reference evapotranspiration for above freezing temperatures. If zero, the MASSIF snow model for sublimation is implemented.

- IC_1_cm, IC_2_cm, IC_3_cm, IC_4_cm – Initial capillary pressure heads in centimeters. Although IC_4_cm is given here, it is set equal to the field capacity value by DPWM.

- Duration_slope – Relation between precipitation daily quantity and duration of precipitation. If negative, the duration of precipitation is obtained from the climate input file (icl).

- Precip_adj – Uniform adjustment to precipitation. Typically set to 1 unless sensitivity to precipitation is being tested.

- Temp_adj – Uniform adjustment to minimum and maximum air temperature. Typically set to 1 unless sensitivity to temperature is being tested.

- bLAI – If TRUE, LAI data are provided for each grid cell in the imt file.

- bMETRIC – If TRUE, read ETrF data from the imt file. bLAI and bMETRIC cannot both be true.

- bBCM – if TRUE, runoff is not routed downstream as is implemented in the USGS BCM model.

- bPRISM_PPT – If TRUE, read PRISM mean annual precipitation data for each grid in the ipz file. Cprecipcor is not used.

- bPRISM_TEMP – If TRUE, read PRISM monthly temperature data. CTcor is not used.

- bPRISM_MON – If TRUE, read PRISM data for each month of simulation. Cprecipcor is not used.

- bAlbedo – If TRUE, read cell specific albedo data from the watershed file.

- bRH – If TRUE, read relative humidity data from the input climate file (icl)

- bDPO – If TRUE, dew point offset is provided in climate file (icl) rather than estimating with a harmonic function or using a constant offset.

- bMETRIC_Sat – if TRUE, directly insert moisture data from METRIC into the model.

- bSat_Reset – If TRUE, water contents are reset to the initial condition at the beginning of each year. Typically used if running non-sequential water years in one simulation.

- bDataAssim – If TRUE, data assimilation routines are implemented.

- bGDD – if TRUE, growing degree day (GDD) method for estimating crop coefficients is implemented. Additional polynomial coefficients are provided in the vegetation block of the IPM file. If both bGDD and bLAI are TRUE, bGDD is used rather than bLAI.

2.2.1.2 Block B – Soil Data

Soil data are provided in the order as specified in the soil index of the watershed file. For example, a cell in the watershed file with soil index 5 will refer to the data on the 5th line of Block B in the ipm file.

- Soil Name (no spaces)

- Soil saturated hydraulic conductivity (m/s). Typical values range from 5.6E-08 m/s for silty clay to 8.2E-05 m/s for sand (Carsel and Parrish, 1988).

- Van Genuchten curve parameter alpha (1/cm). Typical values range from 0.005 1/cm for silty clay to 0.145 1/cm for sand (Carsel and Parrish, 1988).

- Van Genuchten curve parameter n (unitless). Should be greater or equal to 1.0. Typical values range from 1.09 for silty clay to to 2.68 for sand (Carsel and Parrish, 1988).

- Saturated volumetric water content (unitless). Similar in value to total porosity. Typical values range from 0.36 for silty clay to 0.46 for silt (Carsel and Parrish, 1988).

- Residual water content (unitless). Typical values range from 0.034 for silt to 0.1 for sandy clay (Carsel and Parrish, 1988).

- Soil depth (m). The depth to a restrictive layer (e.g., bedrock). For deep soils where there is no restrictive layer present, the soil depth can be represented with a depth greater than the maximum rooting depth of vegetation.

2.2.1.3 Block C – Bedrock Data

Bedrock data are ordered to relate to the bedrock index number given in the watershed file (Rock index 5 in the watershed file refers to data on line 5 in block C of the ipm). For the purpose of DPWM, the term “bedrock” refers to any geologic unit underlying the soil layer, which may refer to unconsolidated or consolidated media.

- Name (no spaces)

- Bulk saturated hydraulic conductivity of the bedrock considering fractures (m/s)

2.2.1.4 Block D – Vegetation Data

Vegetation data are ordered to relate to the bedrock index number given in the watershed file (e.g., vegetation index 5 in the watershed file refers to line 5 of Block D in the ipm file).

The first Nveg number of lines in Block D provide the following parameters

- Name (no spaces)

- H_plant – mean maximum plant height in meters. Values greater than 2 meters do not influence evapotranspiration calculations (e.g, Allen et al 1998, Chapter 9).

- Zr_m – mean maximum rooting depth in meters.

- LAI_ini – leaf area index at the initiation of growth in the spring. Not used if bLAI, bMETRIC, or bGDD are implemented.

- LAI_mid – peak leaf area index during the middle of the growing season. Not used if bLAI, bMETRIC, or bGDD are implemented.

- LAI_late – late season leaf area index. Not used if bLAI, bMETRIC, or bGDD are implemented.

- rl_ini – mean leaf resistance for the vegetation at the initiation of growth (s/m). Nominal values of 100 s/m indicate no adjustment to transpiration coefficients (Allen et al 1998, p. 191).

- rl_mid – mid-season mean leaf resistance for the vegetation (s/m). Nominal values of 100 s/m indicate no adjustment to transpiration coefficients (Allen et al 1998, p. 191).

- rl_late – late season mean leaf resistance for the vegetation (s/m). Nominal values of 100 s/m indicate no adjustment to transpiration coefficients (Allen et al 1998, p. 191).

- Develop_start – day of calendar year for start of vegetation growth development. Days of the year prior to Develop_start use LAI_ini for leaf area index. Between Develop_start and Mid_start, values are linearly interpolated from LAI_ini to LAI_mid. Not used if bLAI, bMETRIC, or bGDD are implemented.

- Mid_start – start of mid season. Between Mid_Start and Mid_end, leaf area index values are set to LAI_min. Not used if bLAI, bMETRIC, or bGDD are implemented.

- Late_start – End of midseason and start of vegetation decline. Leaf area index values are linearly interpolated between LAI_mid and LAI_late for days of the calendar year between Late_start and Late_end. Not used if bLAI, bMETRIC, or bGDD are implemented.

- Late_end – Day of calendar year for the end of the season. Leaf area index values are set to LAI_late for remainder of calendar year. Not used if bLAI, bMETRIC, or bGDD are implemented.

If the Growing Degree Days method is implemented (bGDD = TRUE), Nveg additional lines are provided with the six coefficients for the 5^{th} order polynomial relating growing degree days and the transpiration coefficient (Kcb; Brower 2008).

2.2.2 Input Climate File (.icl)*

The climate input file has climate data for the reference location in the watershed. Columns are as follows:

- Month
- Day of month [DOM]
- Water year

- Day of water year [DOWY]
- Precipitation in millimeters (mm) [PRECIP]. Multiple columns if more than one reference weather station as specified by Nstations in the IPM file.
- Maximum daily temperature in °C [TMAX]
- Minimum daily temperature in °C [TMIN]
- Wind speed in meters per second (m/s) [WIND]
- Duration of precipitation in hours [DURATION]
- Daily maximum relative humidity (%) [RHMAX_Daily] if bRH is TRUE
- Daily minimum relative humidity (%) [RHMIN_Daily] if bRH is TRUE
- Daily dew point offset (°C) [DPO_Station] if bDPO is TRUE

The file is in a space delimited format.

2.2.3 Input Watershed File (.iws)*

The watershed input file has the cell location and elevation along with the types of soil, vegetation and bedrock. Columns are as follows:

- Cell ID [Cell_ID]
- UTM easting in NAD83 meters [POINT_X]
- UTM northing in NAD83 meters [POINT_Y]
- Elevation of cell in meters [ELEV_METER]
- Cell ID of downstream cell that receives runoff [DWNSTRM_ID]
- Slope of cell in degrees [SLOPE_DEG]
- Aspect of cell [ASPECT]
- Soil type index with array origin at 1 [Soil_Index]
- Bedrock type index with array origin at 1 [Rock_Index]
- Vegetation type with array origin at 1 [Veg_Index]
- Area of cell in meters squared [Area]

- Width of wash in meters [WashWidth]

- Albedo of soil at cell [Albedo] if bAlbedo is true.

This file must be ordered with upstream cell above downstream cell.

2.2.4 Input Downstream Receptor File (*.idn)

The downstream contributor file instructs the DPWM how to route runoff. The rows of the IDN file must correspond with iws file. Columns are as follows:

- C/C++ array index with 0 origin [RankJ]
- Cell ID [Cell_ID]
- Cell ID of downstream cell that will receive runon [DWNSTREAM_ID]
- C/C++ array index of downstream cell with 0 origin [Dwnstrm_J]

Index values must correspond with positions in the watershed file (*.iws). The second line in this file (first line after header) corresponds with array index 0.

2.2.5 Input Daily Observation File for Specified Cells (*.iob)

The input file identifies individual cells to monitor daily water balance. The first line is the number of cells to monitor. Subsequent lines have cell IDs. Daily output of monitored cells is in the output file *.ocd.

2.2.6 Input Observation File for Specified Times (*.iot)

The input file identifies times to output water balance for entire watershed. The first line is the number of output times. Subsequent lines have water year, month, and day of month to generate output. Output for each cell on the specified output days can be found in the *.oct file.

2.2.7 Input METRIC/LAI data at specified Times (*.imt)

This input file contains estimates of the METRIC estimate of the evaporative fraction (bMETRIC = TRUE) or the leaf area index (bLAI = true) for days of the water year. The first line of the file has the number of days with METRIC or LAI observations (nday). The second line contains the day of the water year where METRIC or LAI observations are available. The remainder of the file contains ncell number of rows and nday number of columns with METRIC or LAI data. The rows must be in the same order as found in the input watershed file (IWS). This file is optional and is only needed if bMETRIC or bLAI are true.

2.2.8 Input annual PRISM data (*.ipz)

This file contains mean annual estimates of precipitation for each grid cell from PRISM (bPRISM_PPT = TRUE) and monthly estimates of minimum and maximum air temperature for each grid cell from PRISM (bPRISM_TEMP = TRUE). The first line of the file contains the cell identification numbers for cells that represent the reference climate station and the mean elevation of the basin. The second line is a header file. The remaining columns have precipitation, monthly entries for mean minimum air temperature, and monthly entries for mean maximum air temperature. The number and order of lines should correspond with the input watershed file (IWS). If bPRISM_PPT is true and bPRISM_TEMP is false, then there is only one column of data. This file is optional and is only needed if bPRISM_PPT or bPRISM_TEMP are true.

2.2.9 Input monthly PRISM data (*.izm)

This file contains the monthly estimate of precipitation from PRISM for each grid cell in the model for the simulation period. The first column contains the cell identification numbers and all subsequent columns correspond to each month of simulation. There should be a column of precipitation data for each month of simulation (e.g., 120 columns for a 10 year simulations) so this file can quickly become quite large. This file is optional and is only needed if bPRISM_MON is true.

2.2.10 Input Data Assimilation data (*.ida)

This file contains a matrix of data for implementing data assimilation routines in DPWM. The first column contains the cell identification numbers, the second column contains weights for each grid cells, and the remaining columns contain factors that can be used to modify soil parameters on a cell by cell basis (e.g., soil depth). This file is optional and is only read if bDataAssim is TRUE. If the file does not exist, DPWM will prompt for a default data assimilation factor and will assign weights of 1 to all cells to generate the file.

2.2.11 Input Irrigation data

This file contains irrigation data on a daily or monthly basis for specified model cells. Irrigation is specified as a rate in mm/day for the duration of the day or month. The first line specifies if the data are in monthly or daily format and the number of cells that have irrigation. The following lines specify the cell identification numbers for the cells that have irrigation. The rows following the cell identification list give the rate off irrigation for the cells with one row for each cell and one column for each month or day. Monthly or daily irrigation data are applied repeatedly for each simulated year. Irrigation is applied only to the non-wash portions of each specified cell.

2.3 Output Files

Output files provide the mass balance components (precipitation, evaporation, transpiration, net infiltration, runoff, storage, snowpack level, and error) for the water balance calculations at the watershed or cell level and at either daily, annual, or other specified time intervals. Generally the nomenclature for output file extensions is “o” for output, “c” for cell or “w” for watershed, and “d” for daily, “a” for annual or “s” for simulation period (e.g., owd is mass balance components for the watershed on a daily basis).

2.3.1 Output Watershed Daily Mass Balance (*.owd)

This output file contains the daily water balance for the entire watershed on a lumped basis. Columns are as follows:

- Day of run [Day]
- Total precipitation in cubic meters [Precip]
- Change in water stored for watershed in cubic meters [dStorage]
- Change in water stored in the snowpack in cubic meters [dSnow]
- Evapotranspiration for watershed in cubic meters [ET]
- Net infiltration for watershed in cubic meters [Infil]
- Runoff at Toquop Gap in cubic meters [RunoffExit]
- Mass balance for model in cubic meters [Masscheck]

- Percent mass balance error

- Total runoff generated in the watershed in cubic meters (not part of the watershed mass balance).

- Total runon generated in the watershed in cubic meters (not part of the watershed mass balance).

- Percent of watershed covered in snow.

- Runoff from each watershed exit in cubic meters.

2.3.2 Output Cell Annual Mass Balance (.oca)*

This output file has the annual water balance for each cell in the watershed. Columns are as follows:

- Cell ID [ID]
- Water year [Year]
- UTM Zone 11 easting in NAD83 meters [UTM83_X]
- UTM Zone 11 northing in NAD83 meters [UTM83_Y]
- Precipitation volume for year on cell in cubic meters [Precip]
- Actual evapotranspiration in cubic meters [AET]

- Net infiltration in cubic meters [Infil]
- Runoff in cubic meters [Runoff]
- Runon in cubic meters [Runon]
- Total change in water stored in soil in cubic meters [dWlevel]
- Total change of water in snowpack in cubic meters [dSnow]
- Sublimation in cubic meters
- Snowmelt in cubic meters
- Snowfall in cubic meters
- Area of cell in square meters [Area]

The file is in a tab delimited format.

2.3.3 Output for Specified Cells Daily Mass Balance (.ocd)*

This file has the daily water balance for individual cells specified in the input file *.iob. There are 70 columns of data as follows:

- Day of run [Day]
- Cell ID [CellID]
- Change in water stored in soil in cubic meters [dWlevel]
- Daily precipitation in cubic meters [Precip]
- Daily transpiration in cubic meters [Trans]
- Daily evaporation in cubic meters [Evap]
- Daily runon in cubic meters [Runon]
- Daily runoff in cubic meters [Runoff]
- Daily net infiltration in cubic meters [Infil]
- Daily sublimation in cubic meters
- Daily water balance error in cubic meters [Balance]
- Actual evapotranspiration in mm [AET_mm]
- Reference evapotranspiration in mm [RefET_mm]
- Transpiration water stress coefficient Ks

- Basal Transpiration coefficient Kcb [Kcb]
- Evaporation water stress coefficient Kr
- Evaporation coefficient Ke
- Maximum Kc [Kcmax]
- Vegetation canopy cover fraction (fc)
- Kcb for full vegetation cover
- Minimum relative humidity
- Precipitation in mm
- Net infiltration in mm
- Runoff in mm
- Runoff due to saturation of model cells in mm
- Runoff due to exceedances of soil saturated hydraulic conductivity in mm
- Runon in mm
- Transpiration in mm
- Evaporation in mm
- Maximum actual evapotranspiration in mm
- Snow in mm
- Change in snowpack in mm
- Snowmelt in mm
- Sublimation in mm
- Change in soil water storage in mm
- Ra_hor -- extraterrestrial radiation on a horizontal surface for a 24-hr period (MJ m^{-2} d^{-1})
- Rso_hor -- clear sky solar radiation over the 24-hr period (MJ m^{-2} d^{-1})
- Rsm_hor -- estimated 'measured' solar radiation on a horizontal surface using Hargreaves' method (MJ m^{-2} d^{-1}).
- Rsm_inc -- total radiation received by the inclined surface (MJ m^{-2} d^{-1})
- Rs_eqhor -- horizontal projection (equivalent) of total radiation received by surface (MJ m^{-2} d^{-1})
- Rns -- horizontal equivalent for net short wave radiation on the incline (MJ m^{-2} d^{-1})
- Rnl -- net outgoing long wave radiation (MJ m^{-2} d^{-1})

- Rn -- net radiation on the inclined surface projected to a horizontal projection (input to the Penman-Monteith equation). (MJ m^{-2} d^{-1})
- Reference precipitation in mm (multiple columns if more than one reference station)
- Daily minimum reference air temperature (C)
- Daily maximum reference air temperature (C)
- Reference wind speed (m/s)
- Reference elevation (m)
- Dew point offset (C)
- Wind speed at cell (m/s)
- Dew point temperature at cell (C)
- Daily minimum air temperature at cell (C)
- Daily average air temperature at cell (C)
- Daily maximum air temperature at cell (C)
- Dew point temperature for watershed (C)
- Daily minimum air temperature for average elevation in watershed (C)
- Daily average air temperature for average elevation in watershed (C)
- Daily maximum air temperature for average elevation in watershed (C)
- Elevation of cell in meters
- Slope of land surface at cell (degrees)
- Azimuth of land surface at cell
- k_Rs – Hargreaves' coefficient
- Average latitude of watershed (degrees)
- Albedo of cell
- Mean leaf resistance (s/m) at cell
- Adjustment to Kcb from stomatal resistance (Fr)
- Leaf area index at cell
- Evapotranspiration fraction (EToF)
- Root zone water level in mm
- Relative saturation of root zone (Sroot)
- Average root zone water content where transpiration begins reduction due to water stress (Qp)

- Average water content in the root zone (Qroot)
- Depletion water level in the evaporation layer in mm (De)
- Depletion water level in the root zone in mm (Dr)
- Growing degree days (C)
- Number of daylight hours

2.3.4 Output Watershed Annual Mass Balance (.owa)*

This file has the water balance for the entire lumped watershed on an annual basis. Results are given in cubic meters for each water year and then averaged. Output of results are repeated at the bottom of the file in acre-feet. Columns are as follows:

- Water year [Year]
- Total annual precipitation on watershed in cubic meters [Precip]
- Actual evapotranspiration for entire watershed in cubic meters [AET]
- Total net infiltration (e.g., recharge) for watershed in cubic meters [Infil]
- Runoff from watershed at Toquop Gap in cubic meters for year [GapRunoff]
- Change in water storage for year over watershed in cubic meters [dStorage]
- Change in snow pack for year over watershed in cubic meters
- Sublimation in cubic meters
- Mass balance error for watershed in percent [MBE%]
- Runoff from mountain block onto alluvium (e.g., mountain front runoff as described in Wilson and Guan [2004]) in cubic meters for year [MF_Runoff]
- Precipitation on mountain block in cubic meters for year
- Net infiltration in washes in cubic meters for year.

2.3.5 Output All Cells at Specified Times (.oct)*

This file contains the water balance for specified days for the entire watershed. Columns are as follows:

- Cell ID [ID]
- Water year [Year]
- Month [Month]
- Day of month [Day]
- UTM easting for zone 11 and NAD83 in meters [UTM83_Xm]
- UTM northing for zone 11 and NAD83 in meters [UTM83_Ym]
- Area of cell in square meters [Area_m2]
- Precipitation in mm
- Net infiltration in mm
- Runoff in mm
- Runoff from saturation of cell profile in mm
- Runoff from exceedances of soil saturated hydraulic conductivity in mm
- Runon in mm
- Transpiration in mm
- Evaporation in mm
- Snow in mm
- Change in show pack in mm
- Sublimation in mm
- Change in storage in mm
- Reference evapotranspiration in mm
- Minimum relative humidity (%)
- Evapotranspiration fraction
- Leaf area index
- Crop coefficient
- Mass balance
- Ra_hor -- extraterrestrial radiation on a horizontal surface for a 24-hr period (MJ m^{-2} d^{-1})
- Rso_hor -- clear sky solar radiation over the 24-hr period (MJ m^{-2} d^{-1})
- Rsm_hor -- estimated 'measured' solar radiation on a horizontal surface using Hargreaves' method (MJ m^{-2} d^{-1}).
- Rsm_inc -- total radiation received by the inclined surface (MJ m^{-2} d^{-1})

- Rs_eqhor -- horizontal projection (equivalent) of total radiation received by surface (MJ m^{-2} d^{-1})
- Rns -- horizontal equivalent for net short wave radiation on the incline (MJ m^{-2} d^{-1})
- Rnl -- net outgoing long wave radiation (MJ m^{-2} d^{-1})
- Rn -- net radiation on the inclined surface projected to a horizontal projection (input to the Penman-Monteith equation). (MJ m^{-2} d^{-1})
- Wind speed at cell (m/s)
- Dew point temperature (C)
- Daily minimum air temperature at cell (C)
- Daily average air temperature at cell (C)
- Daily maximum air temperature at cell (C)
- Elevation of cell (meters)
- Mean leaf resistance (s/m)
- Transpiration coefficient for stomatal resistance
- Root zone depletion water level (Dr) in mm
- Root zone relative saturation (Sroot)

2.3.6 Output Runoff (ORO)

This output file contains monthly total runoff (acre-feet) for the observation cells.

2.3.7 Output soil moisture (OSM)

Output relative root zone saturation for each cell at each observation time. Each column contains the relative root saturation for all of the model cells for the given observation time. These values can be compared to root zone moisture estimates from METRIC. Average values of relative root zone saturation for various combinations of soil, rock and vegetation type are given at the bottom of the file.

2.3.8 Output simulation averages for each cell (OCS)

This file gives the average water balance components for each cell averaged over the simulation period. The columns are:

- Cell_ID number
- UTM easting coordinates in meters
- UTM northing coordinates in meters
- Elevation of cell in meters
- Average precipitation in mm/yr
- Average actual evapotranspiration in mm/yr
- Average net infiltration in mm/yr
- Average runoff in mm/yr
- Average in runon in mm/yr
- Average change in soil moisture storage (mm/yr)
- Average change in snow pack (mm/yr)
- Average sublimation (mm/yr)
- Average snowmelt (mm/yr)
- Average portion of precipitation occurring as snowfall (mm/yr)

- Available water -- average quantity of water available for surface infiltration (mm/yr) calculated as precipitation + runon – runoff.

- Percent net infiltration computed as mean net infiltration / available water.

- Area (square meters)

2.3.9 Water balance tracking file (bal)

This file tracks the water balance of the cell with the maximum mass balance error.

2.3.10 Echo of Input and Output of Calculated Input Values (check.txt or .chk)

This file echoes input data and outputs calculated input values. The file will flag errors in the run

2.4 Initializing Routines

After DPWM loads the input data and opens the output files for writing, the *initialize* subroutine is called to calculate additional parameters. Input file units are converted to units of mm and days. The cdepth_fcn is called for each cell to calculate the thicknesses of the nodes from the total soil depth, as follows:

$$Thick_{1-4} = cdepth\_fcn(Depth, Ze, Zr_{veg}) \tag{1}$$

where $Thick_{1-4}$ = the thickness of Nodes 1 through 4 (mm)
Depth = the soil depth specified for the soil type of the cell converted to mm
Ze = the evaporation layer thickness (mm)
Zr = the rooting depth of the vegetation at the cell (mm)

If the vegetation index indicates that the cell is bare rock, the depth is set to the evaporation depth (Ze) to allow for surface storage and evaporation and the soil hydraulic conductivity is set to the bedrock hydraulic conductivity. For cells that are washes, the hydraulic properties of the soil are set to those specified for washes.

The maximum water level in each cell node is set based on the saturated water content and node thickness, as follows:

$$\theta s\_level_{1-4} = \theta s \cdot Thick_{1-4} \tag{2}$$

where θs_level_{1-4} = the water level equivalent to saturation in the node (mm)

θs = the saturated water content from the soil type at the cell

The water contents associated with the field capacity and wilting point capillary pressure heads are computed, as follows:

$$\begin{aligned} \theta_{FC} &= vg\_head\_to\_wc(\theta r, \theta s, \alpha, n, h_{FC}) \\ \theta_{WP} &= vg\_head\_to\_wc(\theta r, \theta s, \alpha, n, h_{WP}) \end{aligned} \tag{3}$$

where θ_{FC} = the field capacity water content

θ_{WP} = the wilting point water content, θr is the residual water content

θs = the saturated water content

α and n = the van Genuchten curve fitting parameters

h_{FC} = the field capacity capillary pressure head (cm) specified by the user

h_{WP} = the wilting point capillary pressure head (cm) specified by the user

The water levels equivalent to the field capacity and wilting point water contents are calculated as follows:

$$\begin{aligned} FC_{1-4} &= Thick_{1-4} \cdot \theta_{FC} \\ WP_{1-4} &= Thick_{1-4} \cdot \theta_{WP} \end{aligned} \tag{4}$$

where FC_{1-4} = the water level equivalent to the field capacity water content for Nodes 1 through 4 (mm)

$WP_{1\text{-}4}$ = the water level equivalent to the wilting point water content for Nodes 1 through 4 (mm)

The FAO-56 parameters for total evaporable water (TEW) and total available water (TAW) are computed for each cell based on the equations in Allen et al. (1998), as follows:

$$TEW = \left(\theta_{FC} - 0.5 \cdot \theta_{WP}\right) \cdot Thick_1$$
$$TAW = \left(\theta_{FC} - \theta_{WP}\right) \cdot \left(Thick_1 + Thick_3\right) \tag{5}$$

where θ_{FC} = the field capacity water content

θ_{WP} = the wilting point water content

$Thick_1$ = the thickness of Layer 1 from Node 1 (Nodes 1 and 2 in Layer 1 have the same thickness and either could have been used here)

$Thick_3$ = the thickness of Layer 2 from Node 3

The initial water levels in each node of each cell are set based on the user specified capillary pressure heads in each node, as follows:

$$\theta_{1-4} = vg\_head\_to\_wc\left(\theta r, \theta s, \alpha, n, h_{i,1-4}\right)$$
$$Wlevel_{1-4} = \theta_{1-4} \cdot Thick_{1-4} \tag{6}$$

where $\theta_{1\text{-}4}$ = the water content in Nodes 1 through 4 in each cell

θr = the residual water content

θs = the saturated water content

α and n = the curve fitting parameters

$hi_{,1\text{-}4}$ = the initial capillary pressure head for Nodes 1 through 4 specified by the user

Typically, the initial water levels are set to the wilting point in Nodes 1 through 3 and to field capacity in Node 4. The water in Node 4 is stagnant (will not drain or evapotranspire) when set at or below the field capacity.

After the initial properties have been calculated, they are printed to the output file check.txt or *.chk for verification.

2.5 Main Program Routine

The main program routine is the daily water balance calculation for each cell and for each day. For each day of the simulation, the program loops through all of the cells as ordered in the watershed file. The cells in the watershed file must be ordered so that no cell is below a cell that is downstream (the program checks that the order is correct and if not correctly ordered will stop execution).

Before the cell calculations, the program calculates the dewpoint offset (Koffset) if not given in the ICL file by using a harmonic function fit (KdewOffset_fcn), maximum relative humidity (TdewFromRHmax_and_Tmin), or a constant offset in IPM.

The routine for each cell for the day is as follows:

- Estimate minimum, mean and maximum air temperatures at the cell and for the average elevation in the watershed using either the temperature lapse rate in IPM or based on PRISM (T_elev_PRISM or T_elev_cor_fcn).

- Estimate the Growing Degree Days as the cumulative difference for each day between the mean air temperature at the cell and the minimum threshold temperature (TETMIN).

- Correct the windspeed for the elevation of the cell from the reference station.

- Adjust precipitation from reference station to cell elevation and location based on the precipitation lapse rate (Precip_elev_cor_fcn), the mean annual PRISM estimates of precipitation (Precip_elev_PRISM), or using the monthly estimate of precipitation from PRISM (PPT_PRISM_Monthly_fcn).

- Calculate the evaporation and transpiration coefficients (e.g., “crop” coefficients) in the subroutine AET_Fraction.

- Estimate the reference evapotranspiration adjusted for the slope and azimuth of the cell (RefET_fcn).

- Estimate the snow hydrology components using either the MASSIF (Snow_MASSIF), MASSIF and HELP (Snow_MASSIFHELP) or INFIL and HELP (Snow_INFILHELP) methodologies. If the MFMIN and MFMAX factors are less than or equal to zero in the IPM file, the snow hydrology functions are not implemented.

- Add the cumulative runon from upstream cells to the water available at the surface. The volume of runon is adjusted for the cell area.

- Estimate the quantity of runoff resulting from exceeding the saturated hydraulic conductivity of the soil. The saturated hydraulic conductivity of the soil is adjusted downwards to account for the fraction of the day when precipitation or snowmelt occurs. If there is snowmelt, the fraction of day for water available at the soil surface is set to 12 hours.

- The water balance routine DPWM_FC is implemented to estimate changes in soil water storage, evaporation, transpiration, net infiltration and additional runoff from exceeding the storage capacity of the soil.

- The volume of runoff is transferred to the downstream cell

The main program stores the cell balances for the day and prints daily balances to OCD and OCT output files. At the end of the daily balance for all of the cells, balances are summed for the watershed and printed to the OWD output file. At the end of the simulation, annual and average output files OWA, ORO, OSM, OCS and OCA are generated.

2.6 Balance Functions

2.6.1 BalanceFC_Kcb_fcn

This function calculates water redistribution between nodes for a cell using the field capacity method, and computes runoff and net infiltration. If precipitation or snowmelt occurs on a particular day, BalanceFC_Kcb_fcn is called twice—first for the duration of the precipitation/melting event and then for the balance of the day. If no precipitation or melting occurs, water in excess of the field capacity may yet exist in one or more nodes due to precipitation or melting on a previous day. For this case, BalanceFC_Kcb_fcn is called once for the entire day.

The initial step in the function is to reduce the soil and bedrock saturated hydraulic conductivities for the fraction of the day for the calculation, as follows:

$$\begin{aligned} Ksoil_{frac} &= Ksoil \cdot fracDt \\ Krock_{frac} &= Krock \cdot fracDt \end{aligned} \tag{7}$$

where $Ksoil_{frac}$ = the reduced soil hydraulic conductivity (mm)
Ksoil = the soil saturated hydraulic conductivity (mm/d)
fracDt = the fraction of the day for the balance calculation (day)
$Krock_{frac}$ = the reduced bedrock saturated hydraulic conductivity (mm)
Krock = the bedrock saturated hydraulic conductivity (mm/d)

The next step is to calculate the amount of water that can drain from Node 1 if the water level in Node 1 exceeds field capacity. Drainage is the minimum of the difference between the water level and field capacity or the reduced soil hydraulic conductivity. The water level in Node 1 is reduced for any drainage that occurs from Node 1, as follows:

$$\begin{aligned} Drain_1 &= \min(Ksoil_{frac}, Wlevel_1 - FC_1) \geq 0 \\ Wlevel_1 &= Wlevel_1 - Drain_1 \end{aligned} \tag{8}$$

where $Drain_1$ = the drainage from Node 1 (mm)

$Ksoil_{frac}$ = the reduced soil saturated hydraulic conductivity (mm)

$Wlevel_1$ = the water level in Node 1 (mm)

FC_1 = the water level equivalent of field capacity (mm)

Next, the drainage from Node 2 is calculated if the water level in Node 2 is greater than field capacity. Drainage is the minimum of the water level and field capacity drainage or the adjusted soil hydraulic conductivity, as follows:

$$\begin{aligned} Drain_2 &= \min(Ksoil_{frac}, Wlevel_2 - FC_2) \geq 0 \\ Wlevel_2 &= Wlevel_2 - Drain_2 \end{aligned} \tag{9}$$

where $Drain_2$ = the drainage from Node 2 (mm)

$Ksoil_{frac}$ = the adjusted soil saturated hydraulic conductivity (mm)

$Wlevel_2$ = the water level in Node 2 (mm)

FC_2 = the water level equivalent of field capacity (mm)

If drainage from Node 2 is less than the adjusted soil hydraulic conductivity and there is water in Node 1 in excess of the saturated water content water level (θs_level1), the excess water in Node 1 is transferred to Node 2 and drainage from Node 2 is recomputed, as follows:

$$\begin{aligned} Wlevel_2 &= Wlevel_2 + Drain_2 \\ \Delta Wlevel\_\max_1 &= Wlevel_1 - \theta s\_level_1 \\ \Delta Wlevel\_\max_2 &= Ksoil_{frac} - \max(Wlevel_2 - FC_2, 0) \\ \Delta Wlevel_2 &= \min\left(\Delta Wlevel\_\max_1 \frac{1-f_c}{f_c}, \Delta Wlevel\_\max_2\right) \\ Wlevel_2 &= Wlevel_2 + \Delta Wlevel_2 \\ Drain_2 &= Wlevel_2 - FC_2 \geq 0 \\ Wlevel_2 &= Wlevel_2 - Drain_2 \\ Wlevel_1 &= Wlevel_1 - \Delta Wlevel_2 \frac{f_c}{1-f_c} \end{aligned} \tag{10}$$

Similarly, if there is excess water in Node 2 and drainage in Node 1 is not at the maximum, water is transferred from Node 2 to Node 1 and Node 1 drainage is recomputed, as follows:

$$
\begin{aligned}
&Wlevel_1 = Wlevel_1 + Drain_1 \\
&\Delta Wlevel\_\max_2 = Wlevel_2 - \theta s\_level_2 \\
&\Delta Wlevel\_\max_1 = Ksoil_{frac} - \max(Wlevel_1 - FC_1, 0) \\
&\Delta Wlevel_1 = \min\left(\Delta Wlevel\_\max_2 \frac{f_c}{1-f_c}, \Delta Wlevel\_\max_1\right) \\
&Wlevel_1 = Wlevel_1 + \Delta Wlevel_1 \\
&Drain_1 = Wlevel_1 - FC_1 \geq 0 \\
&Wlevel_1 = Wlevel_1 - Drain_1 \\
&Wlevel_2 = Wlevel_2 - \Delta Wlevel_1 \frac{1-f_c}{f_c}
\end{aligned}
\tag{11}
$$

Then the drainage from Nodes 1 and 2 in Layer 1 is added to the water level in Layer 2 (Node 3), as follows:

$$
Wlevel_3 = Wlevel_3 + (1 - f_c)Drain_1 + f_c \cdot Drain_2 \tag{12}
$$

Water in excess of field capacity Layer 2 (Node 3) is added to Layer 3 (Node 4), as follows:

$$
\begin{aligned}
&Drain_3 = Wlevel_3 - FC_3 \geq 0 \\
&Drain_3 = \min(Drain_3, Ksoil_{frac}) \\
&Wlevel_3 = Wlevel_3 - Drain_3 \\
&Wlevel_4 = Wlevel_4 + Drain_3
\end{aligned}
\tag{13}
$$

Water in excess of field capacity in Layer 3 (Node 4) becomes net infiltration, as follows:

$$
\begin{aligned}
&Drain_4 = \min(Wlevel_4 - FC_4, Ksoil_{frac}, Krock_{frac}) \geq 0 \\
&Wlevel_4 = Wlevel_4 - Drain_4 \\
&Infil = Drain_4
\end{aligned}
\tag{14}
$$

After net infiltration has been computed, any water in excess of the saturated water content in the layers is passed back up to the overlying layer. If water is in excess of the saturated water content in Layer 3 (Node 4), the excess water is added to Layer 2 (Node 3), as follows:

$$\begin{aligned} Wlevel_3 &= Wlevel_3 + \left(Wlevel_4 - \theta s\_level_4\right) \\ Wlevel_4 &= \theta s\_level_4 \end{aligned} \tag{15}$$

If water is in excess of the saturated water content in Layer 2 (Node 3), it is passed back up to Layer 1 and is proportioned between Nodes 1 and 2 based on the original drainage, as follows:

$$\begin{aligned} \Delta Wlevel_3 &= Wlevel_3 - \theta s\_level_3 \\ Wlevel_3 &= \theta s\_level_3 \\ Wlevel_1 &= Wlevel_1 + \frac{Drain_1}{\left[(1-f_c)Drain_1 + f_c \cdot Drain_2\right]} \cdot \Delta Wlevel_3 \\ Wlevel_2 &= Wlevel_2 + \frac{Drain_2}{\left[(1-f_c)Drain_1 + f_c \cdot Drain_2\right]} \cdot \Delta Wlevel_3 \end{aligned} \tag{16}$$

If the water level of Node 1 is greater than the saturation limit and the water level of Node 2 is below the saturation limit, the excess water in Node 1 is transferred to Node 2 up to the capacity of Node 2 before computing runoff, as follows:

$$\begin{aligned} \Delta Wlevel\_\max_1 &= Wlevel_1 - \theta s\_level_1 \\ \Delta Wlevel_2 &= \min\left(\Delta Wlevel\_\max_1 \frac{1-f_c}{f_c}, \theta s\_level_2 - Wlevel_2\right) \\ Wlevel_2 &= Wlevel_2 + \Delta Wlevel_2 \\ Wlevel_1 &= Wlevel_1 - \Delta Wlevel_2 \frac{f_c}{1-f_c} \end{aligned} \tag{17}$$

Similarly, if the water content in Node 2 is greater than the saturated water content and the water level in Node 1 is less than the saturated water content, the excess water in Node 2 is passed to Node 1 up to the saturated water content of Node 1 before computing runoff, as follows:

$$
\begin{aligned}
&\Delta Wlevel\_\max_2 = Wlevel_2 - \theta s\_level_2 \\
&\Delta Wlevel_1 = \min\left(\Delta Wlevel\_\max_2 \frac{f_c}{1-f_c}, \theta s\_level_1 - Wlevel_1\right) \\
&Wlevel_1 = Wlevel_1 + \Delta Wlevel_1 \\
&Wlevel_2 = Wlevel_2 - \Delta Wlevel_1 \frac{1-f_c}{f_c}
\end{aligned}
\tag{18}
$$

Water in excess of the saturated water content in Nodes 1 and 2 is transferred to runoff, as follows:

$$
\begin{aligned}
&Runoff = Wlevel_1 - \theta s\_level_1(1 - f_c) \\
&Wlevel_1 = \theta s\_level_1 \\
&Runoff = Runoff + (Wlevel_2 - \theta s\_level_2) f_c \\
&Wlevel_2 = \theta s\_level_2
\end{aligned}
\tag{19}
$$

The function returns the water levels in each of the nodes, runoff, and net infiltration.

2.6.2 DPWM_FC

The DPWM_FC function adds the water that infiltrates the soil surface to the water balances of the top layer of the cell (nodes 1 and 2). The function then calls the GroupBalance and ET_Kcb_fcn routines to compute the changes in soil water storage, net infiltration, runoff and evapotranspiration. DPWM_FC then tracks the total change in soil water storage and computes the relative root zone saturation (Sroot) that corresponds with METRIC. The Sroot computation is as follows:

If Kcb is greater than Kc_min, then transpiration is active and Sroot is computed based on the stress water level in the entire root zone thickness.

$$
\begin{aligned}
&Root\_Wlevel = Wlevel_1(1 - f_c) + Wlevel_2\, f_c + Wlevel_3 \\
&MaxRoot\_Wlevel = \theta s\_level_1 + \theta s\_level_3 \\
&Stress\_Wlevel = (FC\_Wlevel_1 + FC\_Wlevel_3) - \\
&\qquad p[(FC\_Wlevel_1 + FC\_Wlevel_3) - (WP\_Wlevel_1 + WP\_Wlevel_3)]
\end{aligned}
\tag{20}
$$

If Kcb is less than or equal to Kc_min, transpiration is inactive and only layer 1 is used for computing the stress water level:

$$
\begin{aligned}
&Root\_Wlevel = Wlevel_1(1 - f_c) + Wlevel_2\, f_c \\
&MaxRoot\_Wlevel = \theta s\_level_1 \\
&Stress\_Wlevel = (FC\_Wlevel_1) - p[(FC\_Wlevel_1 - WP\_Wlevel_1)]
\end{aligned}
\tag{21}
$$

Where Root_Wlevel is the quantity of water available for transpiration or evaporation, MaxRoot_Wlevel is the saturated capacity of the layers 1 and/or 2, and the Stress_Wlevel is the water level in layer 1 and/or 2 where the transpiration begins reduction due to water stress. The water levels are converted to average water contents and the relative saturation (Sroot) is computed:

$$
\begin{aligned}
&\theta_p = Stress\_Wlevel / MaxRoot\_Wlevel * \theta s \\
&\theta_{root} = Root\_Wlevel / MaxRoot\_Wlevel * \theta s \\
&\theta wp = Wilt\_Layer_1 / \theta s\_Wlevel_1 * \theta s \\
&S_{root} = \frac{\theta_{root} - \theta_{wp}}{\theta_p - \theta_{wp}}
\end{aligned}
\tag{22}
$$

Sroot is limited to values between 0 and 1. The output of Sroot is limited to be no less than the minimum reported by METRIC (~0.09).

2.6.3 GroupBalance

The *GroupBalance* function calls the balance model for the fraction of the day where precipitation, if any, occurs and for the non-precipitation fraction of the day. The function returns the total net infiltration and runoff for the cell for the day and updates the water levels in each node based on the balance model results.

2.6.4 WATERSHED_TABLE

This function linearly interpolates values of LAI from given values over the water year.

2.7 Climate Functions

Code for the climate functions are contained in the file climate.cpp.

2.7.1 CellP_fcn

This function calculates the atmospheric pressure at a cell for a given elevation (Allen et al., 1998, Equation 7):

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{23}$$

where P = the atmospheric pressure (kPa)
z = the elevation above sea level in meters

2.7.2 KdewOffset_fcn

This function calculates the dewpoint offset based on the day of the year. In arid climates, the dewpoint temperature is typically less than the daily minimum temperature. The DPWM allows for either a constant dewpoint offset from the daily minimum temperature or a harmonic fit to observed dewpoint offset from measurements of minimum relative humidity and temperature. The harmonic fit equation is as follows:

$$Ko = \left(A \cdot \sin\left(\frac{2\pi}{L} (DOY - V) \right) \right) + C \qquad (24)$$

where A, L, V, and C = the fitted parameters of the harmonic function supplied by the user
DOY = the day of the year

If C is specified by the user as negative, the harmonic fit is not used and the absolute value of C is used as a constant offset.

2.7.3 PPT_PRISM_Monthly_fcn

This function uses the estimate of precipitation provided by PRISM for the month and year at the given cell (PPT_PRISM_Month). The monthly value is portioned into daily values based on the quantity of monthly precipitation that occurs at a reference station for the given day.

PPT_Cell = PPT_PRISM_Month * (PPT_Ref_Daily / PPT_Ref_Month) (25)

2.7.4 Precip_Elev_PRISM

This function uses the mean annual estimate of precipitation at the cell versus the reference station that is estimated by PRISM. The annual difference in precipitation between the two locations estimated by PRISM is divided into a daily value based on the quantities of daily and annual precipitation measured at the reference station. The quantity of precipitation cannot be less than zero.

PPT_Cell = (PPT_Ref_Daily + (PPT_Ref_Daily / PPT_Ref_Annual) * (PPT_PRISM_Cell - PPT_PRISM_Ref) (26)

Where PPT_Cell is the daily total precipitation at the cell (mm), PPT_Ref_Daily is the daily total precipitation at the reference station, PPT_Ref_Annual is the annual total precipitation at the reference station, PPT_PRISM_Cell is the mean annual precipitation estimated by PRISM for the cell, and PPT_PRISM_Ref is the mean annual precipitation estimated by PRISM for the reference station. Mean annual estimates of precipitation from PRISM are converted from values of inches in the input file IPZ to mm.

2.7.5 Precip_elev_cor_fcn

This function is the MASSIF implementation for adjusting the daily rate of precipitation for elevation in the watershed. This function estimates the precipitation at a cell for a given elevation based on the reference precipitation value for the day supplied by the climate file. The correction to precipitation for elevation is based on the slope of the correlation between precipitation and elevation supplied by the user. The elevation correction for precipitation is as follows:

$$P_{cell} = P_{ref}\left(1 + \left(elev_{cell} - elev_{ref}\right)Cprecip\right) \tag{27}$$

where P_{cell} = the daily precipitation at the cell (mm)

P_{ref} = the reference precipitation supplied in the user file (mm)

$elev_{cell}$ = the elevation of the cell (m) supplied in the watershed file

$elev_{ref}$ = the elevation of the reference precipitation supplied in the parameter input file (m)

Cprecip = the correlation between precipitation and elevation (mm/m)

Although negative values for daily precipitation are not expected, this function is set to zero if the result is negative. The value of Cprecip is estimated by linear regression of observed mean annual precipitation (MAP) at climate stations. The slope of the regression equation is used to predict the MAP at the reference location. Cprecip is then the linear regression slope divided by the predicted MAP. The standard error of the lapse rate is obtained by the standard error of the regression slope parameter divided by the predicted MAP at the reference location. The nominal lapse rate for Yucca Mountain was 6.3%/100m (6.28E-04) with a standard error of

0.7%/100m. If the predicted precipitation is negative, the precipitation for the day at the cell is set to zero.

2.7.6 Psych_fcn

This function calculates the psychrometric constant, as follows (Allen et al., 1998, Equation 8):

$$\gamma = \frac{c_p P}{\varepsilon \lambda} \tag{28}$$

where γ = the psychrometric constant (kPa/°C)

c_p = the specific heat at constant pressure (1.013×10^{-3} MJ/(kg°C))

P = the atmospheric pressure

ε = the ratio of molecular weight of water vapor to dry air (0.622)

λ = the latent heat of vaporization (2.45 MJ/kg)

2.7.7 RH_min_fcn

This function calculates the daily minimum relative humidity from the daily dewpoint and maximum temperatures, as follows (Allen et al., 1998, Equation 10):

$$RH_{\min} = \frac{e0(Tdew)}{e0(T\max)} \cdot 100 \tag{29}$$

where RH_{min} = the daily minimum relative humidity

e0 = the function described above

Tdew = the daily dewpoint temperature (°C)

Tmax = the maximum daily temperature (°C)

2.7.8 T_dew_fcn

This function calculates the daily dewpoint temperature from the daily minimum temperature:

$$Tdew = T\min - Ko \tag{30}$$

where Tdew = the daily dewpoint temperature

Tmin = the daily minimum temperature from the climate input file

Ko = the dewpoint offset calculated from KdewOffset_fcn

2.7.9 T_elev_PRISM

This function uses PRISM monthly estimates of mean minimum and maximum air temperature at the cell and reference location. The offset is:

$$\text{Offset} = \text{Temp\_PRISM\_Cell} - \text{Temp\_PRISM\_Ref} \tag{31}$$

The offset is applies to the minimum and maximum temperatures from the reference station to obtain the temperature at the cell. This function also returns the mean daily air temperature as the simple average of the minimum and maximum air temperature and returns the dew point temperature from T_dew_fcn. This function is only used if bPRISM_TEMP is true in the input file IPM.

2.7.10 T_elev_cor_fcn

This function returns the minimum, maximum, average, and dewpoint temperatures for a cell. The minimum and maximum temperatures are estimated for the elevation of the cell from the reference minimum and maximum temperatures, as follows:

$$Tcell = Tref - \left(elev_{cell} - elev_{ref}\right)C\_Tcor \tag{32}$$

where Tcell = the minimum or maximum temperature for the cell (°C)

Tref = the corresponding minimum or maximum reference temperature (°C)

$elev_{cell}$ = the elevation of the cell (m)

$elev_{ref}$ = the elevation of the reference temperature (m)

C_Tcor = the correlation between temperature and elevation

The average daily temperature for the cell is the average of the minimum and maximum temperatures estimated. The dewpoint temperature is calculated from the minimum daily temperature using the function *T_dew_fcn*.

2.7.11 TdewFromRHmax_and_Tmin

This function returns the dew point temperature based on the daily maximum relative humidity (RHmax)and the daily minimum air temperature (Tmin; Allen et al 2005).

$$Tdew = \frac{237.3\log\left(\frac{RH_{\max}}{100}\exp\left(\frac{17.27T_{\min}}{237.3+T_{\min}}\right)\right)}{17.27-\log\left(\frac{RH_{\max}}{100}\exp\left(\frac{17.27T_{\min}}{237.3+T_{\min}}\right)\right)} \tag{33}$$

2.7.12 e0

This function calculates the mean saturation vapor pressure as a function of air temperature (Allen et al., 1998, Equation 11):

$$e0 = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \tag{34}$$

where e0 = the saturation vapor pressure at the air temperature T (kPa)
T = the air temperature (°C)

2.7.13 ea_RH

This function estimates the actual vapor pressure (ea) in units of kPa from relative humidity and/or air temperature. If the daily minimum relative humidity is available, the function returns (Allen et al 1998, eq. 17):

$$e_a = \frac{e0(T_{\min})\dfrac{RH_{\max}}{100} + e0(T_{\max})\dfrac{RH_{\min}}{100}}{2} \tag{35}$$

If the minimum relative humidity is not available, this function returns (Allen et al 1998, eq 18)

$$e_a = e0(T_{\min})\frac{RH_{\max}}{100} \tag{36}$$

2.8 Evapotranspiration Functions

The evapotranspiration functions are contained in the ET.cpp and RefET.cpp files.

2.8.1 AET_Fraction

This function computes the transpiration coefficients based on leaf area index (LAI), METRIC, or growing degree days (GDD). LAI data can be supplied for each vegetation stage in the IPM file by vegetation type or from satellite data at regular intervals for each cell in the IMT file. Intermediate values of LAI are linearly interpolated using the WATERSHED_Table function.

Prior to selecting the LAI, METRIC or GDD method, this function computes air pressure at the cell with CellP_fcn, the psycrometric constant with Psych_fcn, the saturation slope with slope_es, the minimum relative humidity with RH_min_fcn, and the Kcb coefficient for full vegetation with KcbFull_fcn. Next, adjustments for stomatal control are estimated by linearly interpolating the rl values from the DPWM input file IPM using the TABLE_linear function and then calling the function for the resistance correction factor in Fr_fcn. Finally, the daily adjustment to Kcb for wind speed, relative humidity and plant height is estimated (Allen et al 1998, eq 62 and 100):

$$adjust = \left[0.04(u_2 - 2) - 0.004 \cdot (RH_{\min} - 45)\right]\left(\frac{h_{plant}}{3}\right)^{1/3} \tag{37}$$

2.8.1.1 LAI by Cell

If leaf area index (LAI) data are supplied for each cell in the imt file and bLAI is true in the IPM file, the AET_Fraction function will compute the crop coefficients as follows:

- The LAI for the cell is linearly interpolated from the supplied LAI table in the IMT file. If the LAI value is missing for the cell (indicated by a value less than or equal to zero), the LAI is set to 1.0. If the vegetation type for the cell is indicated to be rock, the LAI is set to zero.

- The Kcb is estimated by calling the LAI_to_Kcb function

- The Kcb is adjusted for stomatal control.

- If the average daily air temperature is less than or equal to the minimum or maximums for transpiration set in the IPM file (TETMIN or TETMAX), the Kcb is set to the value of Kc_min.

- The maximum Kcb (Kc_max) is computed from equation 72 in Allen et al 1998

- If the Kcb is greater than Kc_max, then the Kcb is set to Kc_max.

- If the fraction of ground cover is not constant, the fraction of ground cover is computed with equation 76 in Allen et al 1998.

- The evaporative fraction coefficient (Ke) is computed by calling the Ke_fcn function

- The single crop coefficient (Kc) is computed as the sum of Kcb and Ke.

2.8.1.2 METRIC EToF

If the evaporative fraction is supplied in the imt file from METRIC data, the daily value of EToF is linearly interpolated between measurements for the cell using WATERSHED_TABLE function. The procedure for the computing the crop coefficients is then:

- Kc is set equal to EToF estimated for the day and cell.
- Kc_max is computed from equation 72 in Allen et al 1998.
- The evaporative fraction (Ke) is the difference between Kc_max and Kc.
- The basal transpiration coefficient (Kcb) is the difference between Kc and Ke.
- If the average daily air temperature is less than or equal to the minimum or maximums for transpiration set in the IPM file (TETMIN or TETMAX), the Kcb is set to the value of Kc_min.
- If the fraction of ground cover is not constant, the fraction of ground cover is computed with equation 76 in Allen et al 1998.
- There is no stomatal adjustment made so Fr is set to 1.0
- The LAI is set to -999 for printing purposes.

2.8.1.3 Growing Degree Days

The growing degree days method for the crop coefficients computes the maximum crop coefficient (Kc_max) and then calls the Kcb_GDD function. The fraction of ground cover is computed with equation 76 in Allen et al 1998 and the evaporative fraction is computed with the Ke_fcn.

2.8.1.4 LAI by Vegetation Type and Growing Season

The procedure for estimating LAI by vegetation type and growing season is the same as for LAI by Cell except that LAI is linearly interpolated from input data in the IPM file.

2.8.2 Dc_fcn

This function calculates the depletion depth of the evaporative layer covered by vegetation canopy (Layer 1, Node 2).

$$Dc = \min\left(FC_2 - Wlevel_2, TEW\right) \geq 0 \tag{38}$$

where Dc = the depletion depth (mm)

FC_2 = the field capacity in Node 2

$Wlevel_2$ = the water level in Node 2

TEW = the total evaporable water

Depletion depth is a measurement of how far the water level in the node is below field capacity. When the water level in the cell is at or above field capacity, the depletion depth is zero. When the water level is at one-half the wilting point, the depletion depth is at a maximum equal to the total evaporable water (e.g., De_{max} = TEW = (FC – ½WP) in units of mm).

2.8.3 De_fcn

This function calculates the depletion depth of the bare soil fraction of the evaporative layer (Layer 1, Node 1):

$$De = \min\left(FC_1 - Wlevel_1, TEW\right) \geq 0 \tag{39}$$

where De = the depletion depth (mm)

FC_1 = the field capacity in Node 1

$Wlevel_1$ = the water level in Node 1

TEW = the total evaporable water

2.8.4 Dr_fcn

This function calculates the root zone depletion depth:

$$\begin{aligned} Dr &= \left[FC_1(1-f_c)+FC_2 f_c + FC_3\right]-\left[Wlevel_1(1-f_c)+Wlevel_2 f_c + Wlevel_3\right] \geq 0 \\ Dr &= \min(Dr, TAW) \end{aligned} \tag{40}$$

where Dr = the root zone depletion depth

FC = the field capacity for the specified node

f_c = the vegetation canopy cover fraction

Wlevel = the water level in the specified node

TAW = the total available water for transpiration in the root zone

Dr is always greater than zero and less than or equal to TAW.

2.8.5 ET_Kcb_fcn

The ET_Kcb_fcn calculates the amount of transpiration and evaporation from the cell for the day. If there is no soil or evaporative layer thickness, the evaporation and transpiration are set to zero. Otherwise, the transpiration and evaporation are computed. The depletion depth is calculated using the De_fcn for the bare soil fraction of Layer 1 (Node 1):

$$De = De\_fcn(FC_1, Wlevel_1, TEW) \tag{41}$$

where De = the depletion depth

FC_1 = the water level equivalent to field capacity in Node 1

$Wlevel_1$ = the water level in Node 1

TEW = the total evaporable water

Next, if the water level in Node 1 is greater than one-half the wilting point and there is no snow present, the evaporation from Node 1 is computed:

$$
\begin{aligned}
&Kr = Kr\_fcn(De, REW, TEW)\\
&Ke = Ke\_fcn(Kr, Kc_{\max}, Kcb, f_c)\\
&Evaporation = \min(Ke \cdot RefET, (Wlevel_1 - 0.5WP_1)(1 - f_c))
\end{aligned}
\tag{42}
$$

where Kr = the dimensionless evaporation reduction coefficient

REW = the readily evaporable water

Ke = the soil evaporation coefficient

Kc_{max} = the maximum basal transpiration coefficient

Kcb = the basal transpiration coefficient

f_c = the canopy cover coefficient

RefET = the potential reference evapotranspiration

WP1 = the water level equivalent to the wilting point in Node 1

The evaporation is subtracted from the water level in Node 1, as follows:

$$
Wlevel_1 = Wlevel_1 - \frac{Evaporation}{1 - f_c}
\tag{43}
$$

Next, transpiration is computed for Layers 1 and 2 (Nodes 1 through 3). The maximum transpiration possible from each node is calculated as follows:

$$
\begin{aligned}
&Transpire\_\max_1 = Wlevel_1 - WP_1 \geq 0\\
&Transpire\_\max_2 = Wlevel_2 - WP_2 \geq 0\\
&Transpire\_\max_3 = Wlevel_3 - WP_3 \geq 0
\end{aligned}
\tag{44}
$$

where $Transpire\_max_1$ through $Transpire\_max_3$ = the maximum transpirations from Nodes 1 through 3

$Wlevel_1$ through $Wlevel_3$ = the water levels in Nodes 1 through 3

WP_1 through WP_3 = the water level equivalents for the wilting point in Nodes 1 through 3.

The total maximum transpiration (Transpire_max) from the model cell is:

$$Transpire\_\max = Transpire\_\max_1 (1 - f_c) + Transpire\_\max_2 \cdot f_c + Transpire\_\max_3 \quad (45)$$

Transpiration is not limited to the canopy covered fraction and occurs in Layers 1 and 2 (Nodes 1 through 3) over the entire area of the cell. If Transpire_max is greater than zero, the actual total transpiration is computed. First the depletion depth for the root zone is calculated:

$$Dr = Dr\_fcn(FC_{1-3}, Wlevel_{1-3}, TAW, f_c) \quad (46)$$

Next, the unadjusted evapotranspiration is computed as follows (Allen et al., 1998, Equation 69):

$$ET_c = (K_e + Kcb)\, RefET \quad (47)$$

The water stress coefficient is as follows:

$$Ks = Ks\_fcn(Dr, TAW, ET_c, p) \quad (48)$$

where Ks = the transpiration reduction coefficient due to water stress

p = the fraction of the total available water (TAW) for transpiration that is readily available

Actual total transpiration is as follows:

$$Transpiration = \min(Ks \cdot Kcb \cdot RefET, Transpire\_\max) \quad (49)$$

The transpiration is then proportioned between the nodes using the extension to FAO-56 described by Allen et al. (2005b). If the water level in Node 1 is above the wilting point, Node 1 transpiration coefficient (Ktp) is:

$$Ktp = Ktp\_fcn(De, Dr, TEW, TAW, Thick) \quad (50)$$

where Thick = the thickness of each node

The transpiration from Node 1 is:

$$Transpiration_1 = \min(Ktp \cdot Transpiration, Transpire\_\max_1) \tag{51}$$

Similarly, the transpiration from the fraction of Layer 1 covered by the vegetation canopy (Node 2) is calculated as follows:

$$\begin{aligned} &Dc = Dc\_fcn(FC_2, Wlevel_2, TEW) \\ &Ktpc = Ktpc\_fcn(Dc, Dr, TEW, TAW, Thick) \\ &Transpiration_2 = \min(Ktpc \cdot Transpiration, Transpire\_max_2) \end{aligned} \tag{52}$$

The transpiration from the root zone (Layer 2, Node 3) is:

$$Transpiration_3 = \min(Transpiration - Transpiration_1(1 - f_c) - Transpiration_2 f_c, Transpire\_max_3) \tag{53}$$

Next, the total transpiration is recalculated:

$$Transpiration = Transpiration_1(1 - f_c) + Transpiration_2 f_c + Transpiration_3 \tag{54}$$

The water levels are adjusted for transpiration, as follows:

$$\begin{aligned} Wlevel_1 &= Wlevel_1 - Transpiration_1 \\ Wlevel_2 &= Wlevel_2 - Transpiration_2 \\ Wlevel_3 &= Wlevel_3 - Transpiration_3 \end{aligned} \tag{55}$$

The function returns the updated water levels, total transpiration, and total evaporation.

2.8.6 Fr_fcn

This function calculates the stomatal resistance correction factor, as follows (Allen et al., 1998, Equation 102):

$$Fr = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2 \frac{r_l}{100}\right)} \tag{56}$$

where Fr = the resistance correction factor

Δ = the slope of the saturation vapor pressure temperature relationship (kPa/°C)

u_2 = the mean daily wind speed at 2 meters above ground (m/s)

γ = the psychrometric constant (kPa/°C)

r_l = the mean leaf resistance (s/m)

The mean leaf resistance for the ET_0 reference grass and many agricultural crops is 100 s/m (Allen et al., 1998).

2.8.7 KcbFull_fcn

This function estimates the transpiration coefficient for natural vegetation with full ground cover during the peak of the growing season (Kcb_{full}). The first step is to estimate Kcb for full cover vegetation under sub-humid and calm wind conditions (Kcb_h), as follows (Allen et al., 1998):

$$Kcb_h = 1.0 + 0.1h \leq 1.20 \tag{57}$$

where h = the plant height

For vegetation greater than 2 meters in height, Kcb_h is limited to a value of 1.20 (Allen et al., 1998). Kcb_{full} is then estimated for the site climate conditions using Allen et al. (1998), Equation 100, as follows:

$$Kcb_{full} = Kcb_h + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \tag{58}$$

where u_2 = the daily mean wind speed (m/s)

RH_{min} = the daily minimum relative humidity

h = the plant height

2.8.8 KcbLAI_fcn

The basal transpiration coefficient is estimated from LAI as follows (Allen et al., 1998, Equation 97):

$$Kcb = Kc_{\min} + \left(Kcb_{full} - Kc_{\min}\right)\cdot\left(1 - \exp(-0.7 \cdot LAI)\right) \tag{59}$$

where Kc_{min} = the minimum Kc for bare soil (user input)

Kcb_{full} = the basal Kcb for peak plant height and cover (calculated in *Kcbfull_fcn*)

Kcb = the basal transpiration coefficient

The function then adjusts Kcb using the stomatal resistance adjustment as follows (Allen et al., 1998, p. 191-193):

$$Kcb = Kcb \cdot Fr \tag{60}$$

where Fr = the stomatal resistance correction factor (Allen et al., 1998, Equation 102) calculated in the function *Fr_fcn*

2.8.9 Kcb_GDD

This function computes the Kcb based on the number of growing degree days (GDD) in the season. The GDD is set to zero at the beginning of the year (January 1) and whenever the mean daily air temperature is above the minimum for transpiration (TETMIN), the difference is accumulated as the GDD value for the day. The Kcb is estimated from GDD data using a 5th order polynomial (Brower 2008):

$$Kcb = a_0 + a_1 GDD + a_2 GDD^2 + a_3 GDD^3 + a_4 GDD^4 + a_5 GDD^5 \quad (61)$$

The coefficients a0 through a5 are supplied for each vegetation type in the IPM file.

2.8.10 Ke_fcn

This function calculates the reduction in evaporation as the soil dries in the evaporative layer (Allen et al., 1998, Equation 71):

$$Ke = Kr\left(Kc_{\max} - Kcb\right) \leq f_{ew} Kc_{\max} \quad (62)$$

where Ke = the soil evaporation coefficient

Kr = the dimensionless evaporation reduction coefficient (calculated outside of this function by *Kr_fcn*)

Kc_{max} = the maximum value of Kc following rain or irrigation

Kcb = the basal crop coefficient

f_{ew} = the fraction of the soil that is both exposed and wetted

2.8.11 Kr_fcn

This function calculates the dimensionless evaporation reduction coefficient for the evaporative layer. If all of the water that is available for evaporation (TEW) has been depleted, then Kr is equal to zero. If the soil water in the evaporative layer exceeds the amount of readily evaporable water (REW), then Kr is equal to 1. Otherwise, Kr ranges from 0 to 1 based on the following equation (Allen et al., 1998, Equation 74):

$$Kr = \frac{TEW - De}{TEW - REW} \quad (63)$$

where De = the cumulative depth of evaporation (depletion) in the evaporative layer

REW = the readily evaporable water equal to the difference between the field capacity and one-half the wilting point

2.8.12 Ks_expfcn

This function returns the reduction factor for transpiration based on water stress of the vegetation. If the level of water in the root zone is less than the quantity of readily available water (RAW), the relative saturation in the root zone is computed as:

$$S = \frac{TAW - Dr}{TAW - RAW} \tag{64}$$

where TAW = the total available water for transpiration

Dr = the root zone depletion

RAW = the readily available water for transpiration

The transpiration reduction coefficient is then

$$Ks = \exp\left(Ks\_\exp\left(S - 1\right)\right) \tag{65}$$

where Ks_exp = the transpiration stress coefficient given in the IPM file

2.8.13 Ks_fcn

This function calculates the reduction in transpiration due to the depletion in water content in the root zone. The transpiration reduction coefficient (Ks) is calculated as follows (Allen et al., 1998, Equation 84):

$$Ks = \frac{TAW - Dr}{TAW - RAW} \tag{66}$$

where TAW = the total available water for transpiration
Dr = the root zone depletion
RAW = the readily available water for transpiration

RAW is computed from TAW as follows (Allen et al., 1998, Equation 83):

$$RAW = p \cdot TAW \tag{67}$$

where p = the average fraction of TAW that can be depleted from the root zone before moisture stress reduces ET

The value of p depends on the plant and the climate and ranges from 0.30 for shallow rooted plants under high ET to 0.70 for deep rooted plants with low ET. The DPWM adjusts the user-supplied value of p depending on ET, as follows (Allen et al., 1998):

$$p_{adj} = p + 0.04(5 - ET_c) \tag{68}$$

where p = the user-supplied value
ET_c = the potential ET for the given plant

The value of p_{adj} is constrained to be between 0.1 and 0.8. If the user supplied value of p is negative, the absolute value is used as a constant rather than adjusting p with equation 84.

2.8.14 Ktp_fcn

This function implements one of the extensions to the FAO-56 method described by Allen et al. (2005b) where transpiration is proportioned between the evaporative layer and root layer depending on the water contents of each layer and the rooting depth of the vegetation. The function Ktp_fcn is for bare soil node of Layer 1 (Node 1). The proportion of basal transpiration extracted from the evaporative layer is as follows (Allen et al., 2005b, Equation 29):

$$K_{tp} = \left(\frac{1 - \dfrac{De}{TEW}}{1 - \dfrac{Dr}{TAW}} \right) \left(\frac{Ze}{Zr} \right)^{0.6} \tag{69}$$

where De = the cumulative depletion in Node 1 (bare soil fraction of evaporative layer)

Dr = the cumulative depletion in Node 3 (root layer)

TEW = the total evaporable water

TAW = the total available water

Ze = the evaporation layer depth

Zr = the rooting depth

2.8.15 Ktpc_fcn

This function implements the extension to the FAO-56 method where transpiration is proportioned between the evaporative layer and root layer. This function is virtually the same as Ktp_fcn except that Ktpc_fcn is for the fraction of the evaporative layer that is covered by the plant canopy (Node 2). The proportion of basal transpiration extracted from the evaporative layer is calculated as follows (Allen et al., 2005b, Equation 29):

$$K_{tp} = \left(\frac{1 - \dfrac{Dc}{TEW}}{1 - \dfrac{Dr}{TAW}} \right) \left(\frac{Ze}{Zr} \right)^{0.6} \tag{70}$$

where Dc = the cumulative depletion in Node 2 (canopy covered fraction of evaporative layer)

Dr = the cumulative depletion in Node 3 (root layer)

TEW = the total evaporable water

TAW = the total available water

Ze = the evaporation layer depth

Zr = the rooting depth

2.8.16 LAI_daily_fcn

This function returns the leaf area index (LAI) linearly interpolated from data provided for the vegetation type in the IPM file. If the day of the calendar year is less than the start of development (Develop_Start), the LAI is set to the initial value (LAI_ini). Between the start of development and the start of the mid-season, the LAI is linearly interpolated between LAI_ini and the mid-season LAI (LAI_mid). Between the start of the mid-season and the end of the mid-season, the LAI is constant and set to the mid-season LAI. Between the end of the mid-season and the start of vegetation decline, the LAI is linearly interpolated between LAI_mid and LAI_late. After the start of the late season, the LAI is constant at the LAI_Late value.

2.8.17 LAI_to_Kcb

This function calculates the Kcb from leaf area index using equation 97 in Allen et al 1998. If the value of LAI is greater than 3 or if the estimated Kcb is greater than Kc_max, the function returns Kc_max.

2.8.18 slope_es_fcn

This function estimates the slope of the saturation vapor pressure curve (Allen et al., 1998, Equation 13):

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{\left(T+237.3\right)^2} \tag{71}$$

where D = the slope of the saturation pressure curve (kPa/°C)

T = the air temperature (°C)

2.8.19 TABLE_Linear

This function linearly interpolates between values similar to the method in LAI_daily_fcn.

2.8.20 Varying_f_c_fcn

This function maintains the water balance as the sizes of Nodes 1 and 2 change with changing canopy cover. Node 1 represents the bare soil area of the evaporative layer while Node 2 is the remaining area of the cell covered by vegetation canopy cover. As the canopy cover changes, the corresponding volumes of Nodes 1 and 2 change and water must be transferred to maintain the water balance.

If the canopy cover fraction (f_c) decreases, the water level in Node 1 increases, as follows:

$$Wlevel_1 = \frac{\left(1 - f_{c\_old}\right)Wlevel_{1\_old} + \left(f_{c\_old} - f_c\right)Wlevel_{2\_old}}{1 - f_c} \tag{72}$$

where $Wlevel_1$ = the new water level in Node 1 (mm)

f_{c_old} = the old canopy cover fraction

$Wlevel_{1\_old}$ = the old water level in Node 1 (mm)

$Wlevel_{2\_old}$ = the old water level in Node 2 (mm)

f_c = the new canopy cover fraction

The water level in Node 2 does not need to be changed when the canopy cover decreases to maintain the water mass balance in Layer 1.

If the canopy cover fraction increases, the water level in Node 2 increases, as follows:

$$Wlevel_2 = \frac{f_{c\_old} \cdot Wlevel_{2\_old} + \left(f_c - f_{c\_old}\right)Wlevel_{1\_old}}{f_c} \tag{73}$$

where $Wlevel_2$ = the new water level in Node 2 (mm)

f_{c_old} = the old canopy cover fraction
$Wlevel_{1\_old}$ = the old water level in Node 1 (mm)
$Wlevel_{2\_old}$ = the old water level in Node 2 (mm)
f_c = the new canopy cover fraction

The water level in Node 1 does not need to be changed when the canopy cover increases to maintain the water mass balance in Layer 1.

2.8.21 RefET_fcn

This function calculates the reference evapotranspiration adjusted for the slope and azimuth of the cell. Values of latitude, slope, and aspect provided in units of degrees are converted to radians at the beginning of RefET_fcn. The procedure is the same as that described by Allen and Trezza (2006).

Step 1: The mean daily dewpoint temperature is set to the reference dewpoint temperature:

$$Tdew = Tdew_{ref} \tag{74}$$

Step 2: The general, actual vapor pressure (ea) is calculated for use in the Penman-Monteith equation and for estimating precipitable water (W) over the watershed, as follows (Allen et al., 1998, Equation 14):

$$e_{a\_general} = 0.6108 \cdot \exp\left[\frac{17.27 \cdot Tdew}{Tdew + 237.3}\right] \tag{75}$$

$e_{a\_general}$ is in units of kPa. It is assumed that the entire air mass over the watershed has this actual vapor pressure.

Step 3: The inverse square relative distance between the earth and the sun (d_r) is then calculated for use in the Ra calculation, as follows (Allen et al., 1998, Equation 23):

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} DOY\right) \tag{76}$$

where DOY = the calendar day of the year between January 1 and December 31

Step 4: The declination of the earth (δ) is then calculated as follows (Allen et al., 1998, Equation 24):

$$\delta = 0.409 \sin\left[\frac{2\pi}{365} DOY - 1.39\right] \tag{77}$$

Step 5: The sunset hour angle (w_s) for a horizontal surface is then calculated as follows (Allen et al., 1998, Equation 25):

$$\omega_s = ar\cos\left[-\tan(Latitude)\tan(\delta)\right] \tag{78}$$

where latitude= the average latitude of the watershed

Step 6: Extraterrestrial radiation on a horizontal surface for a 24-hour period (Ra_hor) is calculated as follows (Allen et al., 1998, Equation 21):

$$R_{a\_hor} = \frac{12(60)}{\pi} G_{sc} d_r \left[\omega_s \cdot \sin(Latitude)\sin(\delta) + \cos(Latitude)\cos(\delta)\sin(\omega_s)\right] \tag{79}$$

where G_{sc} = the solar constant (0.0820 MJ/(m^2min))

Latitude = the average latitude of the watershed

Step 7: The sine of mean solar elevation over a 24-hour period weighted by extraterrestrial radiation is calculated as follows (Allen et al., 2005a, Equation D-5):

$$\sin\beta_{24} = \sin\left[0.85 + 0.3 Latitude \cdot \sin\left(\frac{2\pi}{365} DOY - 1.39\right) - 0.42(Latitude)^2\right] \geq 0.001 \tag{80}$$

The value of $\sin\beta_{24}$ is limited to values greater than 0.001 for numerical stability in Step 10.

Step 8: The mean atmospheric pressure for the reference weather station is calculated using the elevation of the weather station, as follows (Allen et al., 1998, Equation 7):

$$P_{ref} = 101.3\left(\frac{293 - 0.0065 Elev_{ref}}{293}\right)^{5.26} \tag{81}$$

where $Elev_{ref}$ = the reference elevation of the weather station

Step 9: Precipitable water (W) at the reference location is calculated as follows (Allen et al., 2005a, Equation D-3):

$$W = 0.14 \cdot e_{a\_general} \cdot P_{ref} + 2.1 \tag{82}$$

where W = the precipitable water over the watershed

Step 10: The 24-hour transmissivity for beam radiation is calculated as follows (Allen et al., 2005a, Equation D-2):

$$K_{Bo\_hor} = 0.98 \exp\left[\frac{-0.00146 P_{ref}}{K_{cln} \cdot \sin\beta_{24}} - 0.075\left(\frac{W}{\sin\beta_{24}}\right)^{0.4}\right] \tag{83}$$

where P_{ref} = the atmospheric pressure at the reference location (kPa)
W = the precipitable water in the atmosphere (mm)
Kcln = the atmospheric clearness (turbidity) coefficient

K_{cln} ranges from less than 0.5 for extremely turbid, dusty or polluted air to 1.0 for clean air.

Step 11: The 24-hour transmissivity for diffuse radiation is calculated as follows (Allen et al., 2005a, Equation D-4):

$$K_{Do\_hor} = 0.35 - 0.36 K_{Bo\_hor} \quad for\ K_{Bo\_hor} \geq 0.15$$
$$K_{Do\_hor} = 0.18 - 0.82 K_{Bo\_hor} \quad for\ K_{Bo\_hor} < 0.15 \tag{84}$$

Step 12: Clear sky solar radiation over the 24-hour period is calculated as follows (Allen et al., 2005a, Equation D-1):

$$R_{so\_hor} = \left(K_{Bo\_hor} + K_{Do\_hor}\right) R_{a\_hor} \tag{85}$$

Step 13: "Measured" solar radiation on a horizontal surface is estimated using Hargreave's method, as follows (Allen et al., 1998, Equation 50):

$$R_{sm\_hor} = k_{rs} \sqrt{T\max_{ref} - T\min_{ref}}\, R_{a\_hor} \leq R_{so\_hor} \tag{86}$$

where R_{sm_hor} = the estimated "measured" solar radiation (MJ/(m^{2}d))
k_{rs} = the adjustment coefficient (typically 0.16 to 0.19)
$Tmax_{ref}$ = the maximum daily temperature at the reference location (°C)
$Tmin_{ref}$ = the minimum daily temperature at the reference location (°C)

Step 14: The total short-wave transmissivity (also known as clearness index) associated with the "measured" R_s value is calculated as follows (Duffie and Beckman, 1980, Equation 2.9.2):

$$\tau_{sw\_hor} = \frac{R_{sm\_hor}}{R_{a\_hor}} \tag{87}$$

Step 15: The atmospheric transmissivity in Step 14 is partitioned into its diffusive and direct beam components. The procedure as described by Trezza and Allen (2006) is adapted from Duffie and Beckman (1980, 1991), who cite Orgill and Hollands (1977). Allen and Trezza (2006) rearranged the equations and made minor modifications to match measured transmissivity data at Yucca Mountain.

$$K_{D\_hor} = 0.12\tau_{sw\_hor} \quad for\ \tau_{sw\_hor} \geq 0.78$$
$$K_{D\_hor} = 1.557\tau_{sw\_hor} - 1.84(\tau_{sw\_hor})^2 \quad for\ 0.35 < \tau_{sw\_hor} < 0.78 \tag{88}$$
$$K_{D\_hor} = \tau_{sw\_hor} - 0.249(\tau_{sw\_hor})^2 \quad for\ \tau_{sw\_hor} \leq 0.35$$

Step 16: The actual direct beam transmissivity is calculated as the difference between total transmissivity and diffuse transmissivity, as follows (Allen, 1996, Equation 7):

$$K_{B\_hor} = \tau_{sw\_hor} - K_{D\_hor} \tag{89}$$

Step 17: The direct beam radiation on the horizontal surface is calculated based on the measured R_{sm_hor}, as follows:

$$I_{b\_hor} = K_{B\_hor} \cdot R_{a\_hor} \tag{90}$$

Step 18: The diffuse component of measured R_{sm_hor} for a horizontal surface is calculated as follows:

$$I_{d\_hor} = K_{D\_hor} \cdot R_{a\_hor} \tag{91}$$

Step 19: The albedo (α_T) is the value specified by the user or estimated for snow cover:

$$\alpha_T = albedo \tag{92}$$

Step 20: The ratio of beam radiation R_b on an incline to the beam radiation on a horizontal plane is calculated. Allen and Trezza (2006) suggest making a lookup table for many slope-aspect-day of year combinations, but the DPWM calculates the ratio exactly for the given slope-aspect and day of year combination.

Step 20a: The effective latitude for a given slope and aspect is calculated as described by Revfeim (1976) (Equation 2):

$$\varphi_{eff} = \arcsin\left[\cos(s)\sin(\varphi) + \sin(s)\cos(\gamma + \pi)\right] \tag{93}$$

where φ_{eff} = the effective latitude

s = the slope in radians

φ = the average latitude for the watershed in radians

γ = the surface aspect angle in radians

Step 20b: Check whether surface receives any direct beam radiation during the day. If the cell does not receive any direct beam radiation (i.e., during winter on extreme northerly slopes), Rb is zero and the remaining Step 20 sub-steps are skipped:

$$if\ \varphi_{eff} - \delta \geq \frac{\pi}{2} \quad then\ Rb = 0 \tag{94}$$

where δ = the declination from Step 4

Step 20c: Set up for the solution of daily integration limits for beam (direct) radiation using Duffie and Beckman (1991). Parameter A for the slope-aspect combination is calculated as follows:

$$A = \cos(s) + \tan(\varphi)\cos(\gamma)\sin(s) \tag{95}$$

where s = the slope in radians

φ = the latitude in radians

g = the surface aspect angle in radians

Step 20d: Parameter B for the slope-aspect combination and day of the year is calculated as follows:

$$B = \cos(\omega_s)\cos(s) + \tan(\delta)\sin(s)\cos(\gamma) \tag{96}$$

where w_s = the sunset hour angle from Step 5

s = the slope in radians

d = the solar declination from Step 4

g = the surface aspect angle in radians

Step 20e: Parameter C for the specified slope-aspect combination is calculated as follows:

$$C = \frac{\sin(s)\sin(\gamma)}{\cos(\varphi)} \tag{97}$$

Step 20f: The 24-hour integration limits on w_{sr} and w_{ss} for the Rb equation are calculated assuming that the sun appears only once during a 24-hour period:

$$|\omega_{sr}| = \min\left[\omega_s, ar\cos\left(\frac{A \cdot B + C\sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right)\right]$$
$$\omega_{sr} = \begin{cases} -|\omega_{sr}|\, if\ (A > 0\, and\ B > 0\ or\ A \geq B) \\ |\omega_{sr}|\ \ otherwise \end{cases}$$

$$|\omega_{ss}| = \min\left[\omega_s, ar\cos\left(\frac{A \cdot B - C\sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right)\right]$$
$$\omega_{sr} = \begin{cases} |\omega_{sr}|\, if\ (A > 0\, and\ B > 0\ or\ A \geq B) \\ -|\omega_{sr}|\ \ otherwise \end{cases} \tag{98}$$

The program checks that the square root term (A2 - B2 + C2) is positive and that the arcos terms are within the domain bounds of –1 to 1. If the square root term is negative, $w_{sr} = -w_s$ and $w_{ss} = w_s$. If one of the arcos terms is out of bounds, the respective integration limit is $w_{sr} = -w_s$ and/or $w_{ss} = w_s$. Another check is performed before calculating Rb to prevent negative values of Rb. Negative values for Rb may occur under conditions of very low sun angles during the day (e.g., winter) on north-facing slopes. Negative values of Rb are prevented by changing the signs for the integration limits:

$$\begin{aligned} &if\ (A < B)\ and\ \gamma > 0\ then\ \omega_{sr} = -\omega_{sr} \\ &f\ (A < B)\ and\ \gamma < 0\ then\ \omega_{ss} = -\omega_{ss} \end{aligned} \tag{99}$$

Step 20g: The beam adjustment ratio Rb is calculated as follows:

$$Rb = \frac{\begin{array}{l} \sin(\delta)\sin(\varphi)\cos(s)(\omega_{ss} - \omega_{sr}) \\ -\sin(\delta)\cos(\varphi)\sin(s)\cos(\gamma)(\omega_{ss} - \omega_{sr}) \\ +\cos(\delta)\cos(\varphi)\cos(s)(\sin(\omega_{ss}) - \sin(\omega_{sr})) \\ +\cos(\delta)\sin(\varphi)\sin(s)\cos(\gamma)(\sin(\omega_{ss}) - \sin(\omega_{sr})) \\ -\cos(\delta)\sin(s)\sin(\gamma)(\cos(\omega_{ss}) - \cos(\omega_{sr})) \end{array}}{2(\cos(\varphi)\cos(\delta)\sin(\omega_s) + \omega_s \sin(\varphi)\sin(\delta))} \tag{100}$$

Step 21: The direct beam on the inclined surface for a given slope-aspect combination is calculated using the Rb adjustment factor from Step 20:

$$I_b = I_{b\_hor} \cdot Rb \tag{101}$$

where I_{b_hor} is from Step 17. I_b and I_{b_hor} have units of MJ/(m^{2}d).

Step 22: The anisotropic index is equivalent to the actual direct beam transmissivity (K_{B_hor}):

$$A_t = K_{B\_hor} \tag{102}$$

where K_{B_hor} is from Step 16.

Step 23: The modulating function f is calculated as follows:

$$f = \sqrt{\frac{I_{b\_hor}}{R_{sm\_hor}}} \tag{103}$$

where I_{b_hor} is from Step 21 and R_{sm_hor} is from Step 13.

Step 24: The diffuse component for the inclined surface is calculated as follows:

$$I_d = I_{d\_hor}\left[(1-A_t)\left(\frac{1+\cos(s)}{2}\right)\left(1+f\cdot\sin^3(s/2)\right)+A_t Rb\right] \tag{104}$$

Step 25: The reflected radiation component for the inclined surface is calculated as follows:

$$I_r = R_{sm\_hor}\cdot\alpha_T\cdot\left(\frac{1-\cos(s)}{2}\right) \tag{105}$$

where α_T = the albedo of the terrain (Step 19)

s = the slope in radians

Step 26: The total radiation received by the inclined surface is calculated as follows:

$$R_{sm\_inc} = I_b + I_d + I_r \tag{106}$$

where I_b = the beam radiation on the incline (Step 21)

I_d = the anisotropic diffuse radiation on the incline (Step 24)

I_r = reflected radiation from lower-lying terrain (Step 25)

Step 27: Reproject R_{sm_inc} to a horizontal projection (equivalent), as follows:

$$R_{s(equiv)\_hor} = \frac{R_{sm\_inc}}{\cos(s)} \tag{107}$$

Step 28: The mean saturation vapor pressure associated with the lapsed daily extreme temperature for the cell is calculated as follows:

$$e_s = \frac{e0(T\max_{cell})+e0(T\min_{cell})}{2} \tag{108}$$

where $Tmax_{cell}$ = the maximum temperature for the cell (°C)
$Tmin_{cell}$ = the minimum temperature for the cell (°C)
e0 = the function described above

Step 29: The actual vapor pressure of the cell is limited to a value equal or greater than e_a from Step 2:

$$e_a = \min\left(e_{a\_general}, e_s\right) \tag{109}$$

Step 30: The slope of the saturation vapor pressure curve is calculated as follows:

$$\Delta = slope\_es\_fcn(Tavg_{cell}) \tag{110}$$

Step 31: The atmospheric pressure at the cell is calculated as follows:

$$P_{cell} = CellP\_fcn(Elev_{cell}) \tag{111}$$

Step 32: The psychrometric constant is calculated as follows:

$$\gamma_c = Psych\_fcn(P_{cell}) \tag{112}$$

Step 33: The horizontal equivalent for net short wave radiation on the incline is calculated as follows (Allen et al., 1998, Equation 38):

$$R_{ns} = \left(1 - \alpha_T\right) \cdot R_{s(equiv)hor} \tag{113}$$

Step 34: The net outgoing radiation is calculated as follows (Allen et al., 1998, Equation 39):

$$R_{nl} = \sigma\left[\frac{T\max_{cell,K}{}^4 + T\min_{cell,K}{}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_{sm\_hor}}{R_{so\_hor}} - 0.35\right) \tag{114}$$

where R_{nl} = the net outgoing longwave radiation (MJ/(m^{2}d)) on a horizontal equivalent projection

s = the Stefan-Boltzmann constant at 4.903 x 10^{-9} MJ K^{-4} M^{-2} day^{-1}

$Tmax_{cell,K}$ = the maximum absolute temperature at the cell (°K)

$Tmin_{cell,K}$ = the minimum absolute temperature at the cell (°K)

e_a = the actual vapor pressure at the grid cell (kPa)

R_{sm_hor} = the measured or calculated solar radiation on a horizontal surface (MJ m^{-2} day^{-1})

R_{sm_hor} = the calculated clear-sky radiation on a horizontal surface (MJ m^{-2} day^{-1})

The ratio of R_{sm_hor}/R_{so_hor} is limited to values less than or equal to 1.

Step 35: Net radiation on the inclined surface projected to a horizontal projection is calculated as follows (Allen et al., 1998, Equation 40):

$$R_n = R_{ns} - R_{nl} \tag{115}$$

Step 36: The reference evapotranspiration (ET_0) is calculated as follows (Allen et al., 1998, Equation 6):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma_c \dfrac{900}{Tavg_{cell} + 273} u_2(e_s - e_a)}{\Delta + \gamma_c(1 + 0.34u_2)} \tag{116}$$

where ET_0 = the reference evapotranspiration (mm/d) for an inclined surface but expressed on a horizontal basis

R_n = the net radiation at the incline (but horizontal projection) (MJ m^{-2} day^{-1})

G = the soil heat flux density, which is zero for daily time steps

$Tavg_{cell}$ = the average temperature at the cell (°C)

u_2 = the wind speed at a 2-meter height provided from user input (m/s)

e_s = the saturation vapor pressure (kPa)

e_a = the actual vapor pressure (kPa)

$e_s - e_a$ = the saturation vapor pressure deficit (kPa)

Δ = the slope of the vapor pressure curve (kPa/°C)

γ_c = the psychrometric constant (kPa/°C)

2.9 Snow Functions

In all of the snow functions, if the mean daily air temperature is below freezing and precipitation occurs, the precipitation occurs as snow and is added as it's water equivalent to the snow pack on the cell. Since air temperatures vary with elevation in the model, it is possible for precipitation to occur as snow in the higher elevations on a given day and as rain in the lower elevations. Any sublimation or snowmelt that occurs is removed from the snowpack. The quantity of sublimation or snowmelt is limited by the quantity of snowpack available.

2.9.1 Snow_INFILHELP

This function uses the sublimation function from the INFIL model (USGS 2008) and the snowmelt function from the HELP model Schroeder et al 1994. The INFIL sublimation methodology uses a fraction of the potential (or reference) evapotranspiration as the daily quantity of sublimation. If the temperatures are below freezing, the sublimation factor is set to SUBPAR1. If the temperatures are above freezing the sublimation factor is set to SUBPAR2.

Snow melt occurs when the temperatures are above freezing (0 C) based on equation 40 in the HELP model (Schroeder et al 1994). The rate of snow melt varies from MFMIN on December 21 to MFMAX on June 21.

2.9.2 Snow_MASSIFHELP

This function uses the MASSIF method for computing sublimation where the entire seasonal quantity of sublimation is removed from the snowpack on the day that the snowfall occurs at a specified fraction given by SUBPAR1 in the IPM file. Snow melt occurs when the temperatures are above freezing (0 C) based on equation 40 in the HELP model (Schroeder et al 1994). The rate of snow melt varies from MFMIN on December 21 to MFMAX on June 21.

2.9.3 Snow_MASSIF

This function uses the MASSIF method for computing sublimation and snow melt (SNL, 2007). The sublimation is computed for the snowfall on the day that the snow occurs as a specified fraction of the snowfall (SUBPAR1). The snowmelt occurs at a constant rate (MFMIN) based on the mean daily air temperature.

2.10 Soil Functions

2.10.1 Krel_fcn

This function calculates the relative permeability (K_{rel}) using the van Genuchten–Mualem equation. If the water content is less than the residual water content, K_{rel} is set to zero. Otherwise the relative permeability is calculated as follows (Selker et al., 1999):

$$K_{rel} = \sqrt{\frac{\theta - \theta r}{\theta s - \theta r}} \left[1 - \left(1 - \left(\frac{\theta - \theta r}{\theta s - \theta r} \right)^{\frac{1}{m}} \right)^{m} \right]^{2} \qquad (117)$$

where θ = the water content of the node (L^3/L^3)

θr = the residual water content (L^3/L^3)

θs = the saturated water content (L^3/L^3)

m = the dimensionless van Genuchten exponent

2.10.2 Ktheta_fcn

The *Ktheta_fcn* estimates the unsaturated hydraulic conductivity based on the relative permeability calculated by the function *Krel_fcn*. The unsaturated hydraulic conductivity as a function of water content [K(θ)] is estimated as follows:

$$K(\theta) = Ksat \cdot Krel\_fcn \tag{118}$$

where Ksat = the saturated hydraulic conductivity

If the water level is greater than the thickness of the layer, K(θ) is set to Ks. Assuming a unit gradient, the rate of drainage from the layer is equivalent to the unsaturated hydraulic conductivity. This function is used in the VGM balance model.

2.10.3 cdepth_fcn

This function calculates the depth of each layer in a cell based on the total thickness of the cell. If the total thickness of the cell is less than evaporation layer thickness (Ze, specified by user), the thickness of Layer 1 (Nodes 1 and 2) is set to the total thickness and the thicknesses of Layers 2 (Node 3) and 3 (Node 4) are set to zero. If the total thickness is greater than the evaporation layer thickness but less than the rooting depth, the thickness of Layer 1 is set to the evaporation layer thickness, the thickness of Layer 2 is set to the difference between the total soil thickness and the evaporation layer thickness, and Layer 3 thickness is set to zero. If the soil thickness is greater than the rooting depth, Layer 1 is set to the evaporation layer thickness, Layer 2 is set to the rooting depth minus the evaporation layer thickness, and Layer 3 is set to the total thickness minus the rooting depth. This function is called once for each cell during the calculation of initial properties.

2.10.4 vg_head_to_wc

This function calculates the water content for a given capillary pressure using the van Genuchten equation:

$$\theta = \frac{(\theta s - \theta r)}{\left(1 + [\alpha \cdot h_c]^n\right)^m} + \theta r \tag{119}$$

where θ = the water content (L^3/L^3)

θs = the saturated water content (L^3/L^3)

θr = the residual water content (L^3/L^3)

α and n = the van Genuchten curve fitting parameters (1/L and unitless, respectively)

m = the van Genuchten curve parameter calculated as m = 1 – 1/n

h_c = the capillary pressure (L)

This function is used to estimate water contents for the field capacity and wilting point pressure points.

2.10.5 vg_wc_to_head

This function calculates the capillary pressure for a given water content based on the van Genuchten equation. This equation is not directly used to calculate water balance components in the DPWM but is provided to output average capillary pressures associated with water contents in the cell nodes:

$$h_c = \frac{1}{\alpha}\left[\left(\frac{\theta - \theta r}{\theta s - \theta r}\right)^{-\frac{1}{m}} - 1\right]^{\frac{1}{n}} \tag{120}$$

where hc = the capillary pressure

α and n = the van Genuchten curve fitting parameters

m = the van Genuchten curve parameter estimated from n as m = 1 – 1/n

θ = the water content

θr = the residual water content

θs = the saturated water content

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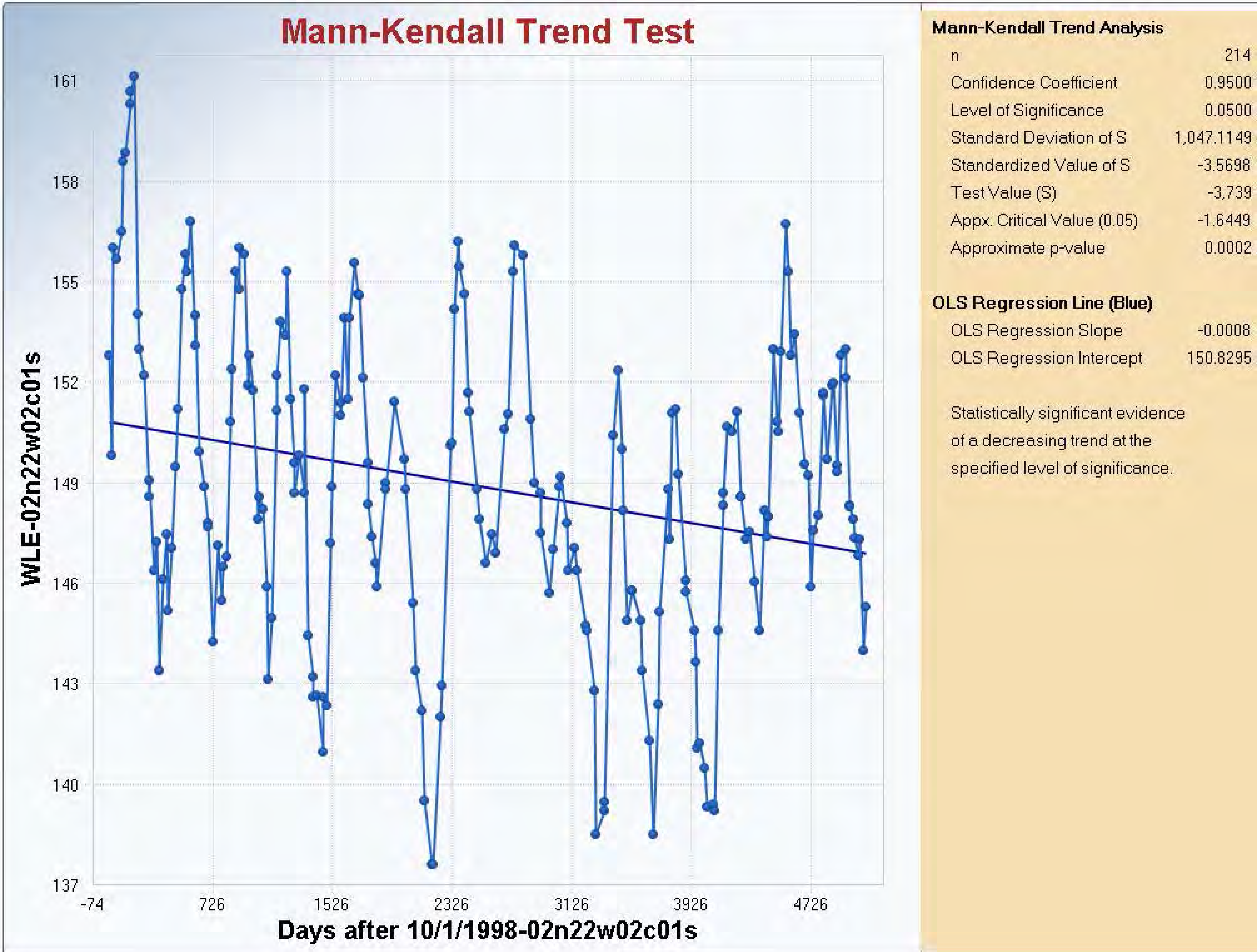
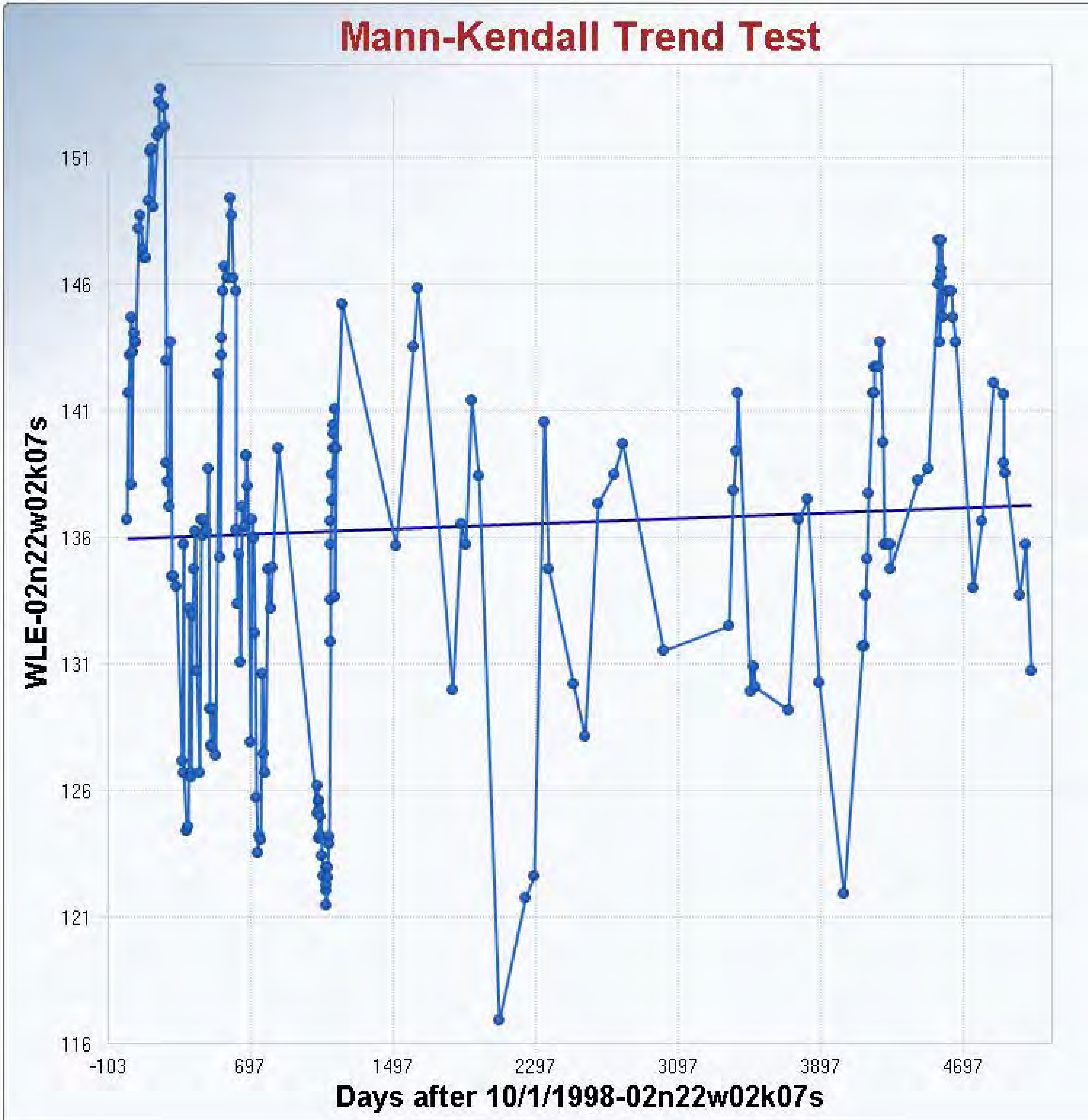
Appendix H

Groundwater Elevation Trend Analysis Graphs


Mann-Kendall Trend Test
161
158
155
152
149
146
143
140
137
-74
726
1526
2326
3126
3926
4726
WLE-02n22w02c01s
Days after 10/1/1998-02n22w02c01s
Mann-Kendall Trend Analysis
n 214
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 1,047.1149
Standardized Value of S -3.5698
Test Value (S) -3,739
Appx. Critical Value (0.05) -1.6449
Approximate p-value 0.0002
OLS Regression Line (Blue)
OLS Regression Slope -0.0008
OLS Regression Intercept 150.8295
Statistically significant evidence of a decreasing trend at the specified level of significance.



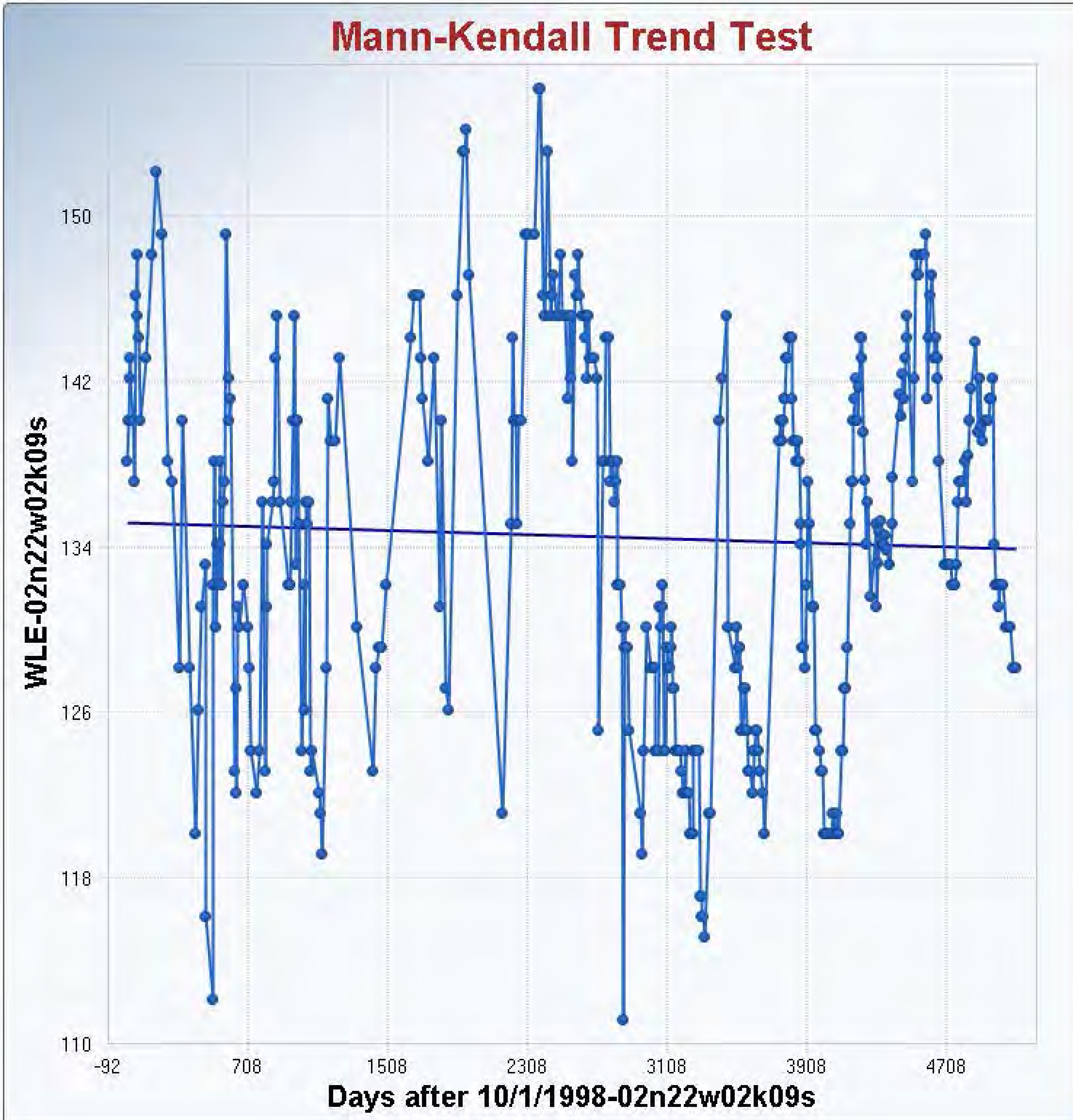
Mann-Kendall Trend Analysis

n	191
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	883.2363
Standardized Value of S	-0.9103
Test Value (S)	-805
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.1813

OLS Regression Line (Blue)

OLS Regression Slope	0.0003
OLS Regression Intercept	135.9825

Insufficient statistical evidence of a significant trend at the specified level of significance.



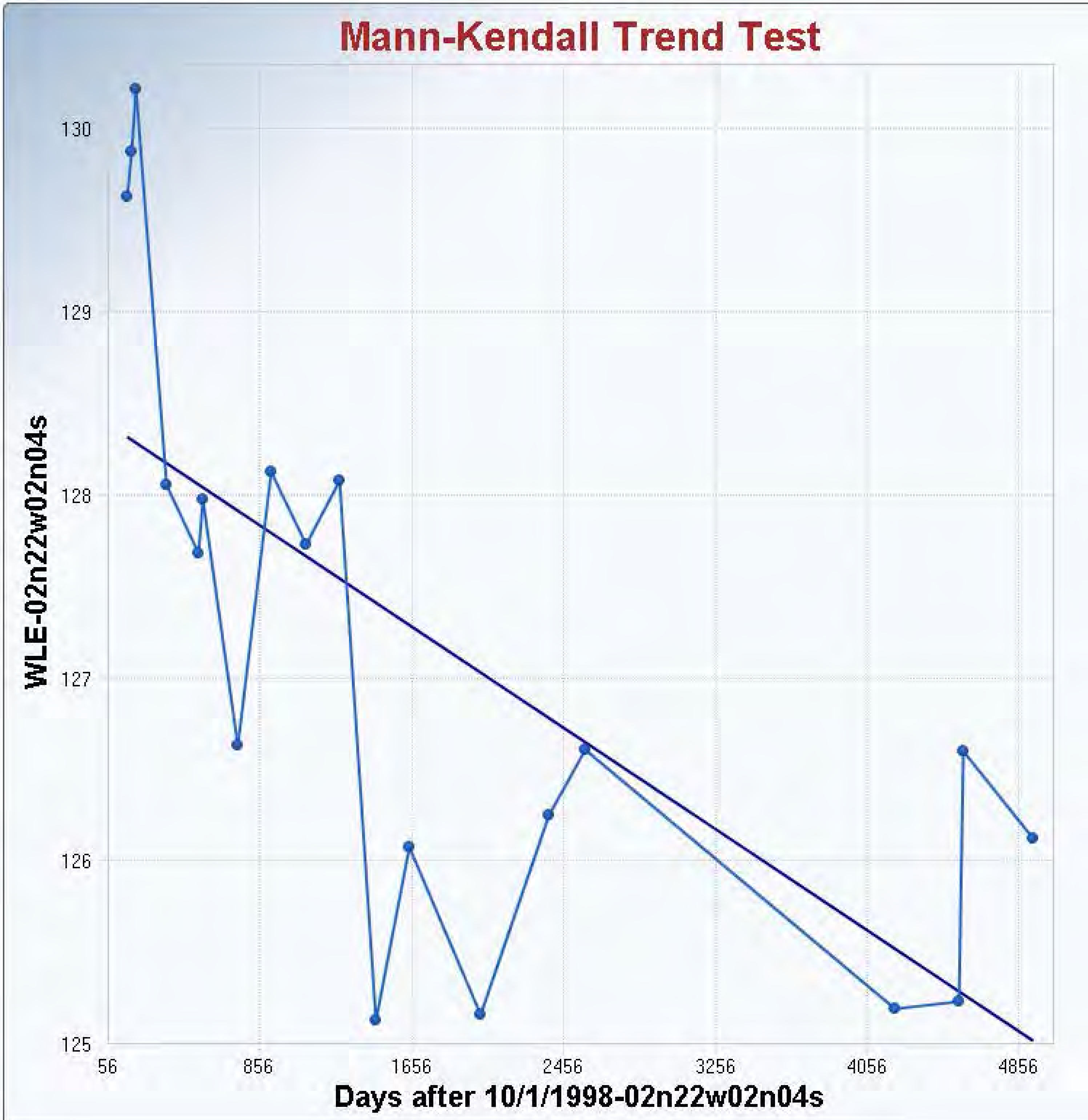
Mann-Kendall Trend Analysis

n	394
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	2,609.9156
Standardized Value of S	-0.9552
Test Value (S)	-2,494
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.1697

OLS Regression Line (Blue)

OLS Regression Slope	-0.0002
OLS Regression Intercept	135.3828

Insufficient statistical evidence of a significant trend at the specified level of significance.



Mann-Kendall Trend Analysis

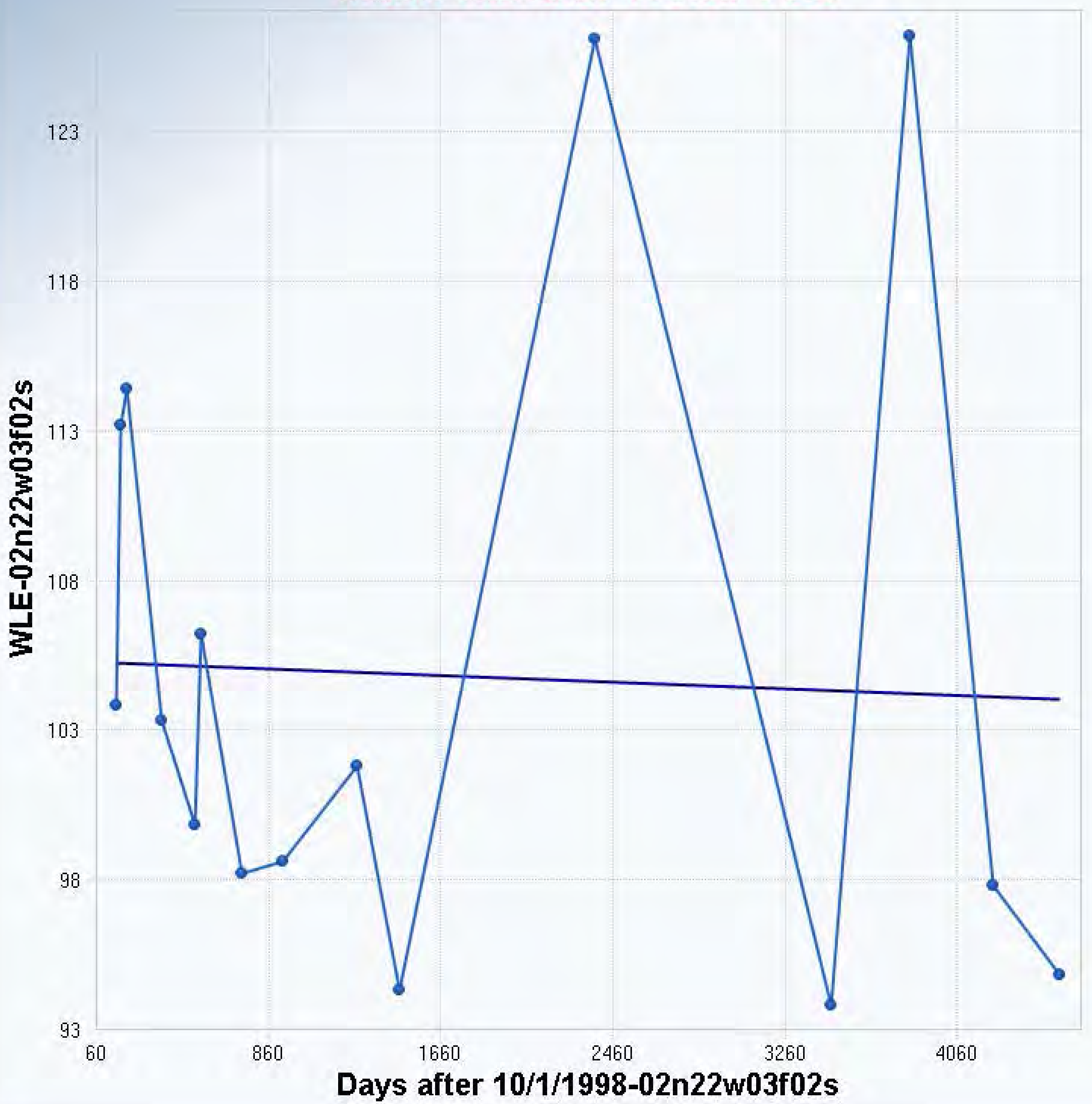
n	19
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	28.5832
Standardized Value of S	-3.1487
Test Value (S)	-91
Tabulated p-value	0.0010
Approximate p-value	0.0008

OLS Regression Line (Blue)

OLS Regression Slope	-0.0007
OLS Regression Intercept	127.9347

Statistically significant evidence of a decreasing trend at the specified level of significance.

Mann-Kendall Trend Test



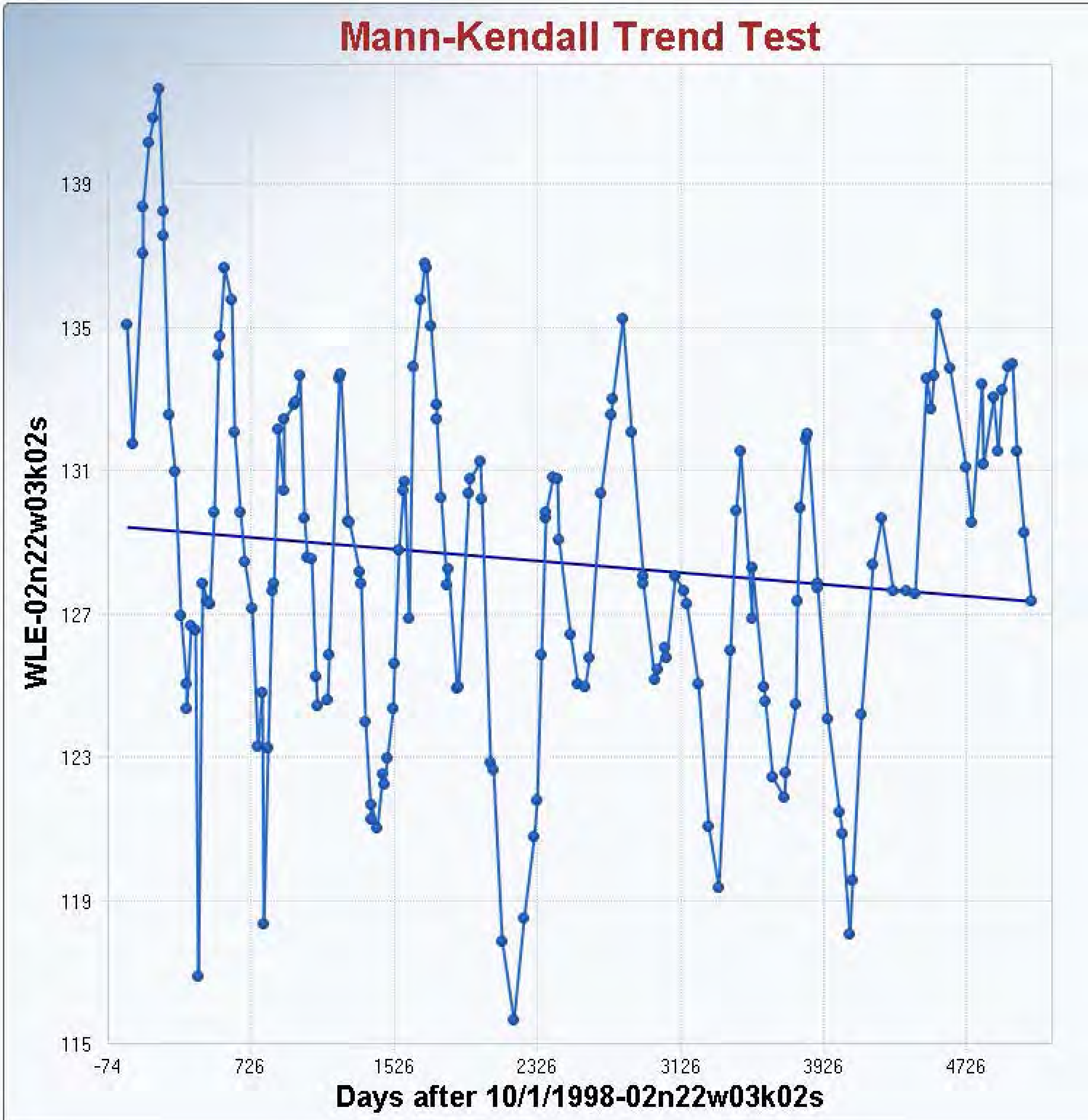
Mann-Kendall Trend Analysis

n	15
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	20.2073
Standardized Value of S	-1.5836
Test Value (S)	-33
Tabulated p-value	0.0570
Approximate p-value	0.0566

OLS Regression Line (Blue)

OLS Regression Slope	-0.0003
OLS Regression Intercept	104.9250

Insufficient statistical evidence of a significant trend at the specified level of significance.



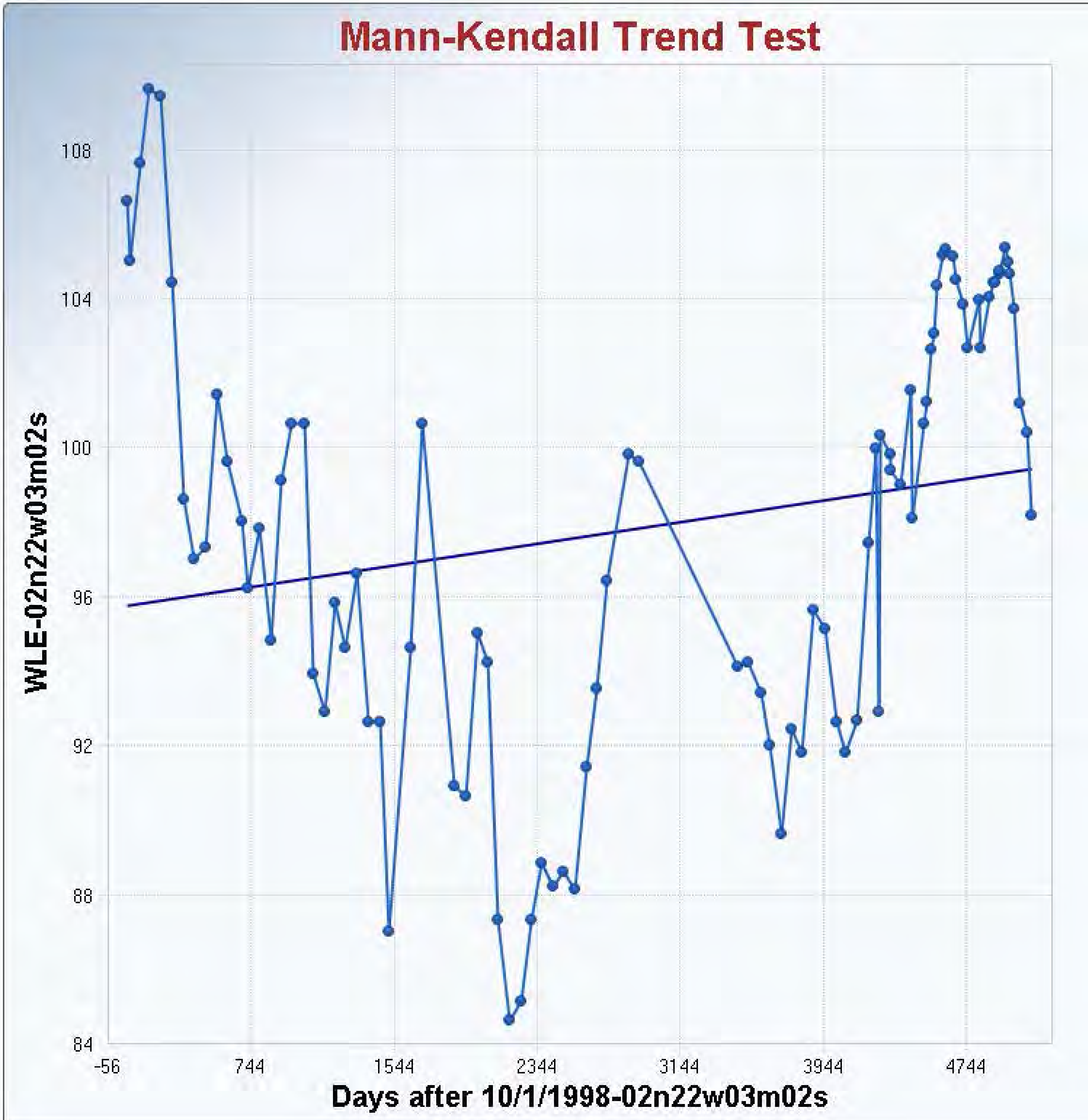
Mann-Kendall Trend Analysis

n	162
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	690.4276
Standardized Value of S	-1.4600
Test Value (S)	-1,009
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0721

OLS Regression Line (Blue)

OLS Regression Slope	-0.0004
OLS Regression Intercept	129.1533

Insufficient statistical evidence of a significant trend at the specified level of significance.



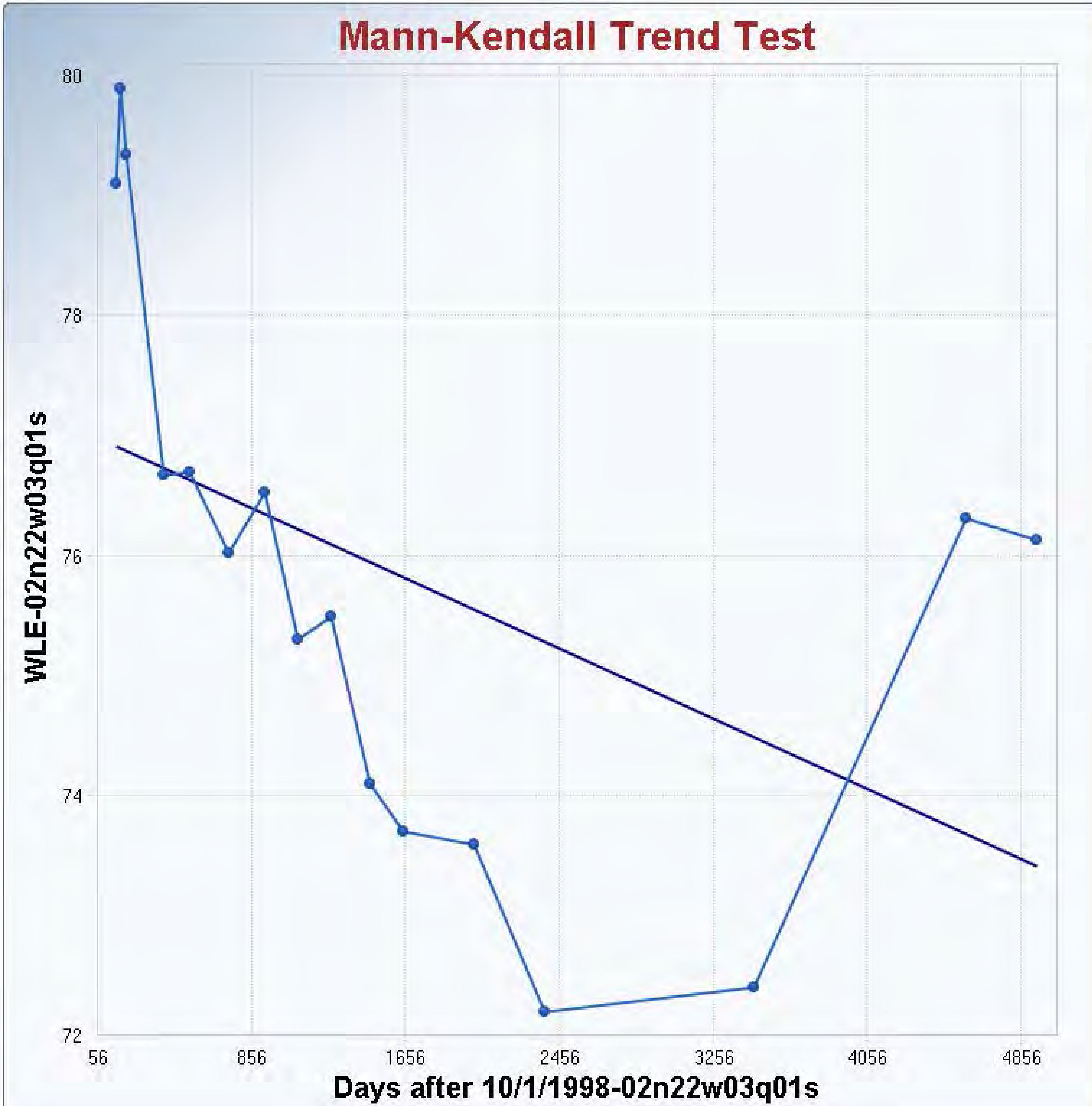
Mann-Kendall Trend Analysis

n	91
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	291.6585
Standardized Value of S	3.0481
Test Value (S)	890
Appx. Critical Value (0.05)	1.6449
Approximate p-value	0.0012

OLS Regression Line (Blue)

OLS Regression Slope	0.0007
OLS Regression Intercept	95.5862

Statistically significant evidence of an increasing trend at the specified level of significance.



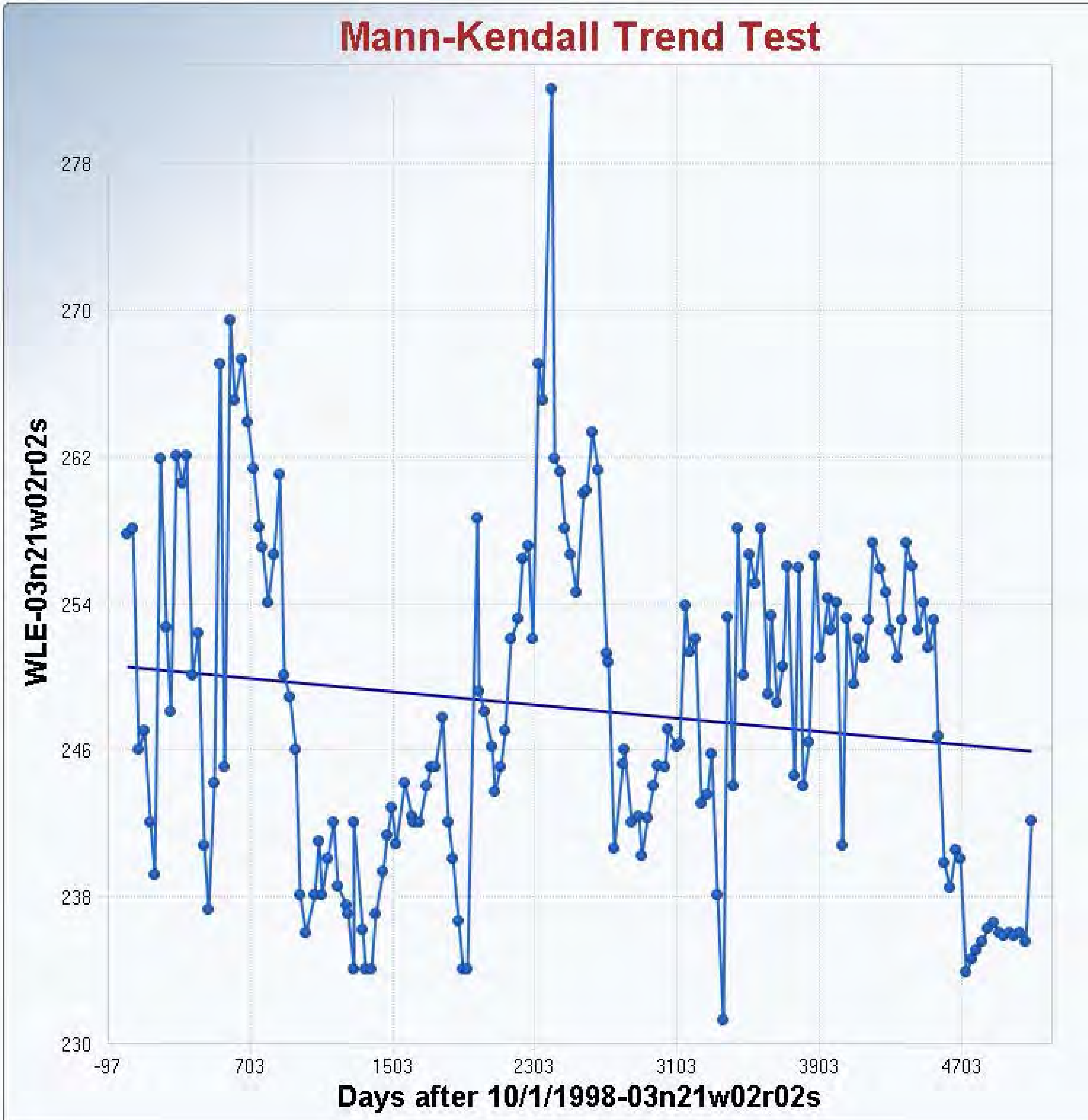
Mann-Kendall Trend Analysis

n	16
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	22.2111
Standardized Value of S	-3.3767
Test Value (S)	-76
Tabulated p-value	0.0000
Approximate p-value	0.0004

OLS Regression Line (Blue)

OLS Regression Slope	-0.0007
OLS Regression Intercept	76.7350

Statistically significant evidence of a decreasing trend at the specified level of significance.



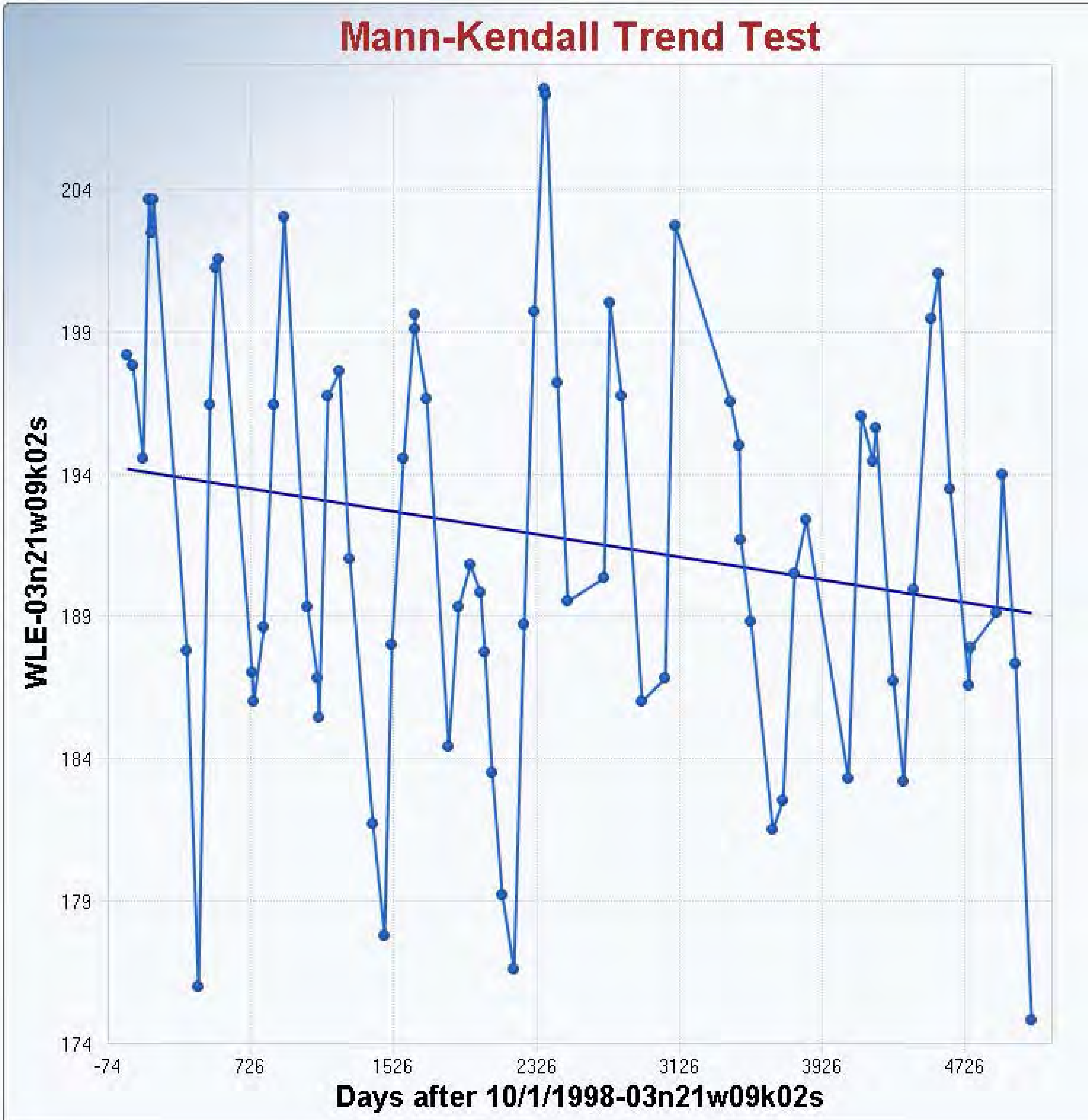
Mann-Kendall Trend Analysis

n	169
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	735.4305
Standardized Value of S	-1.3502
Test Value (S)	-994
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0885

OLS Regression Line (Blue)

OLS Regression Slope	-0.0009
OLS Regression Intercept	250.9184

Insufficient statistical evidence of a significant trend at the specified level of significance.



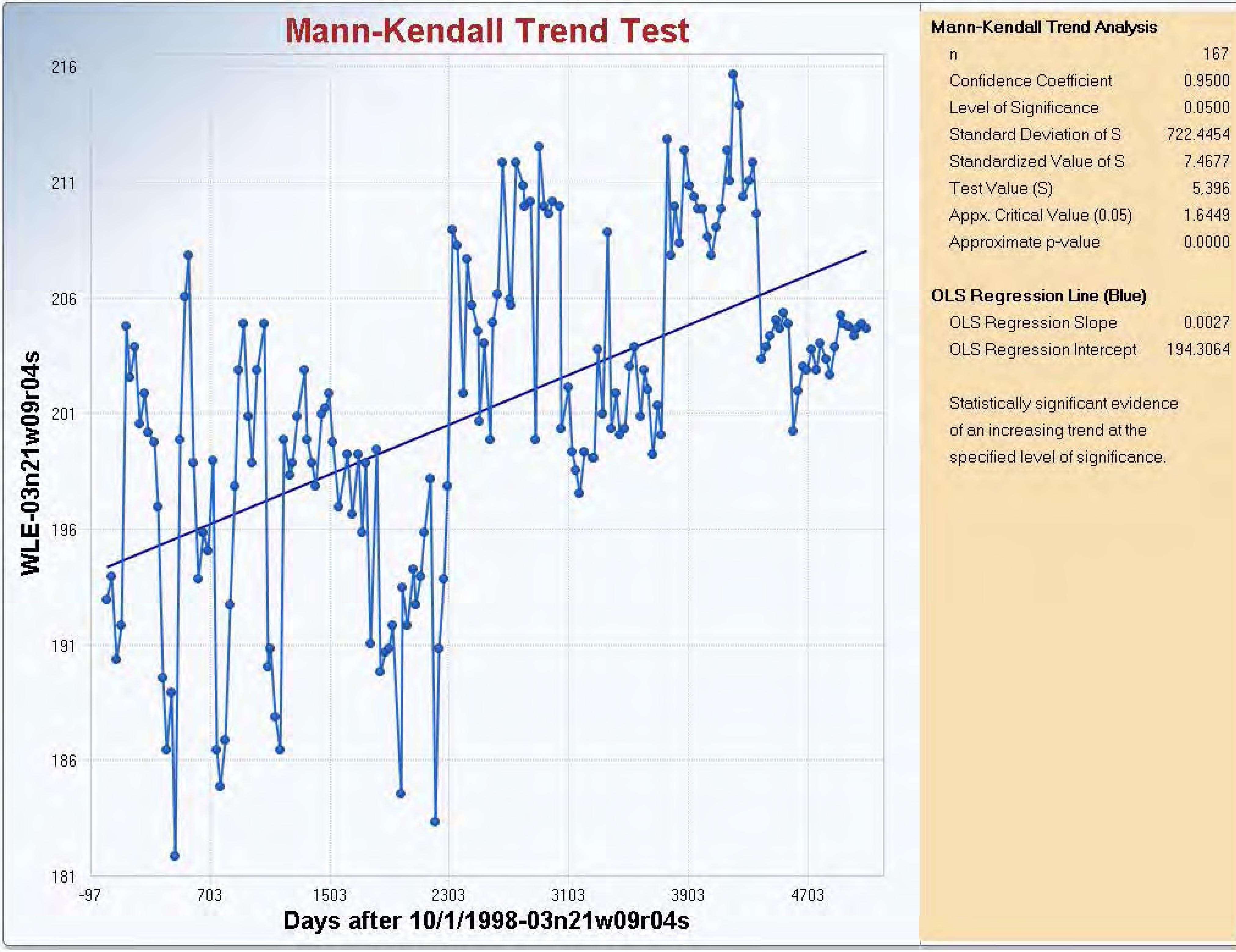
Mann-Kendall Trend Analysis

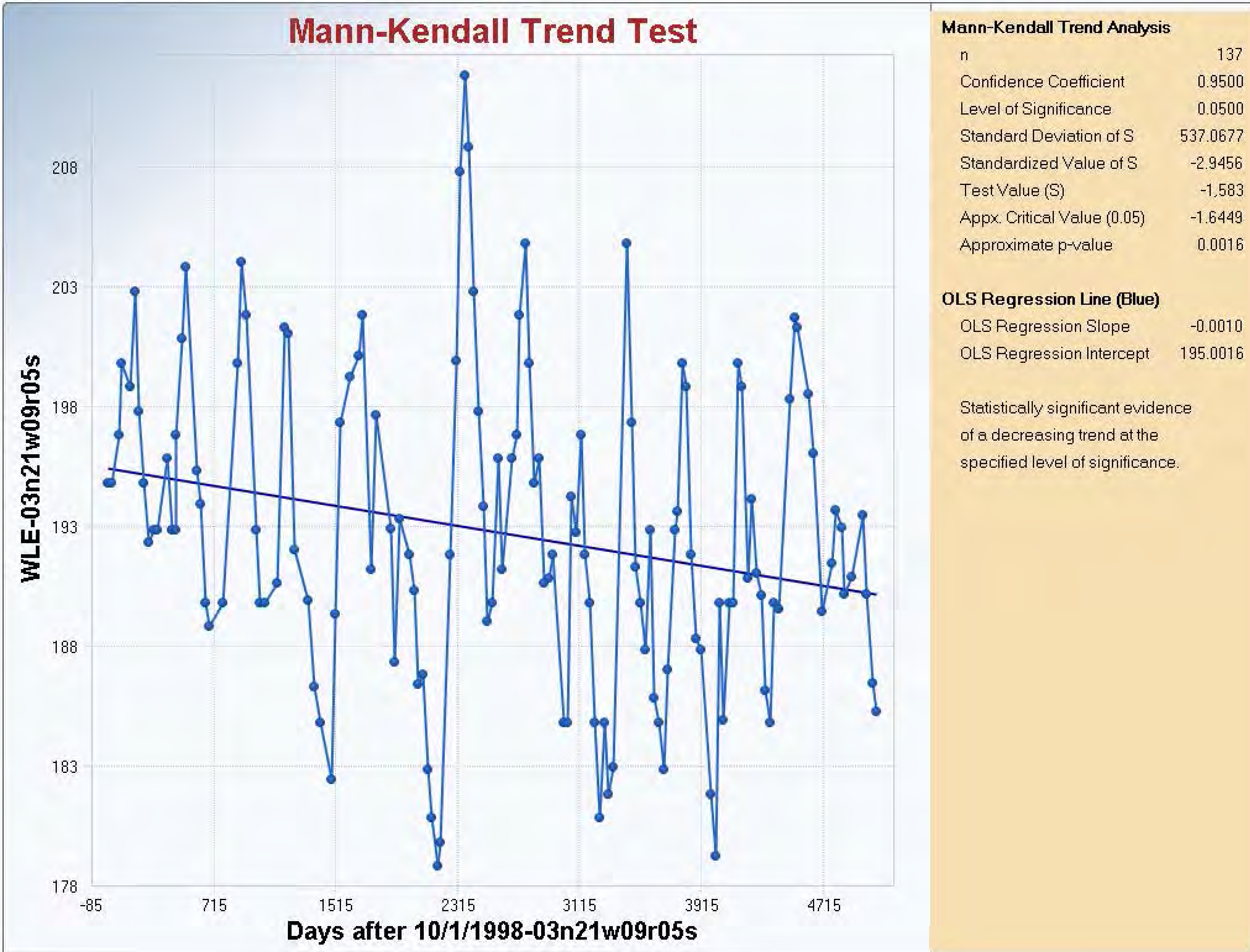
n	73
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	209.9667
Standardized Value of S	-1.7860
Test Value (S)	-376
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0370

OLS Regression Line (Blue)

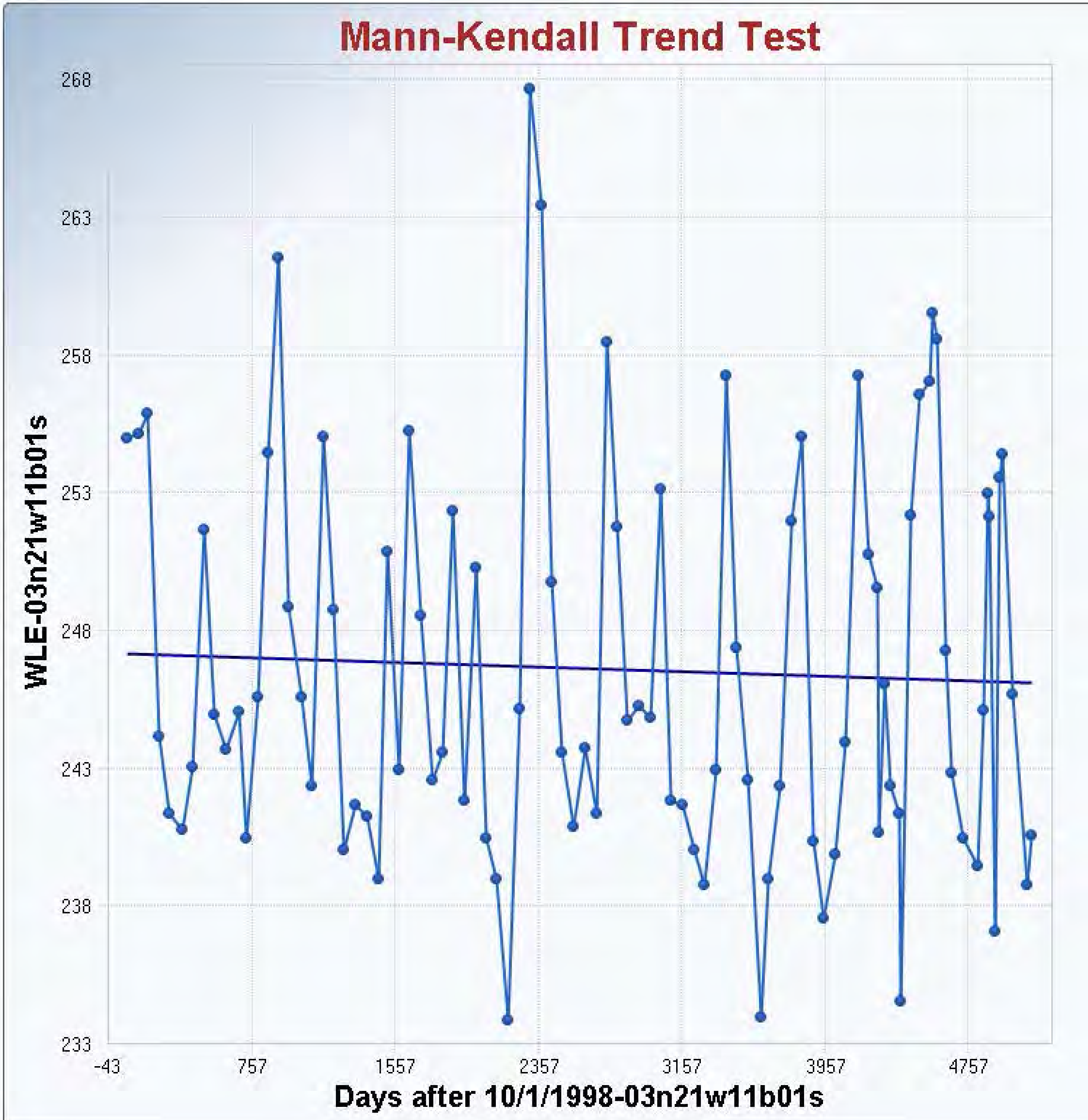
OLS Regression Slope	-0.0010
OLS Regression Intercept	194.3941

Statistically significant evidence of a decreasing trend at the specified level of significance.


Mann-Kendall Trend Test
WLE-03n21w09r04s
Days after 10/1/1998-03n21w09r04s
216
211
206
201
196
191
186
181
-97
703
1503
2303
3103
3903
4703
Mann-Kendall Trend Analysis
n 167
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 722.4454
Standardized Value of S 7.4677
Test Value (S) 5,396
Appx. Critical Value (0.05) 1.6449
Approximate p-value 0.0000
OLS Regression Line (Blue)
OLS Regression Slope 0.0027
OLS Regression Intercept 194.3064
Statistically significant evidence of an increasing trend at the specified level of significance.



Mann-Kendall Trend Test
208
203
198
193
188
183
178
-85
715
1515
2315
3115
3915
4715
WLE-03n21w09r05s
Days after 10/1/1998-03n21w09r05s
Mann-Kendall Trend Analysis
n 137
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 537.0677
Standardized Value of S -2.9456
Test Value (S) -1,583
Appx. Critical Value (0.05) -1.6449
Approximate p-value 0.0016
OLS Regression Line (Blue)
OLS Regression Slope -0.0010
OLS Regression Intercept 195.0016
Statistically significant evidence of a decreasing trend at the specified level of significance.



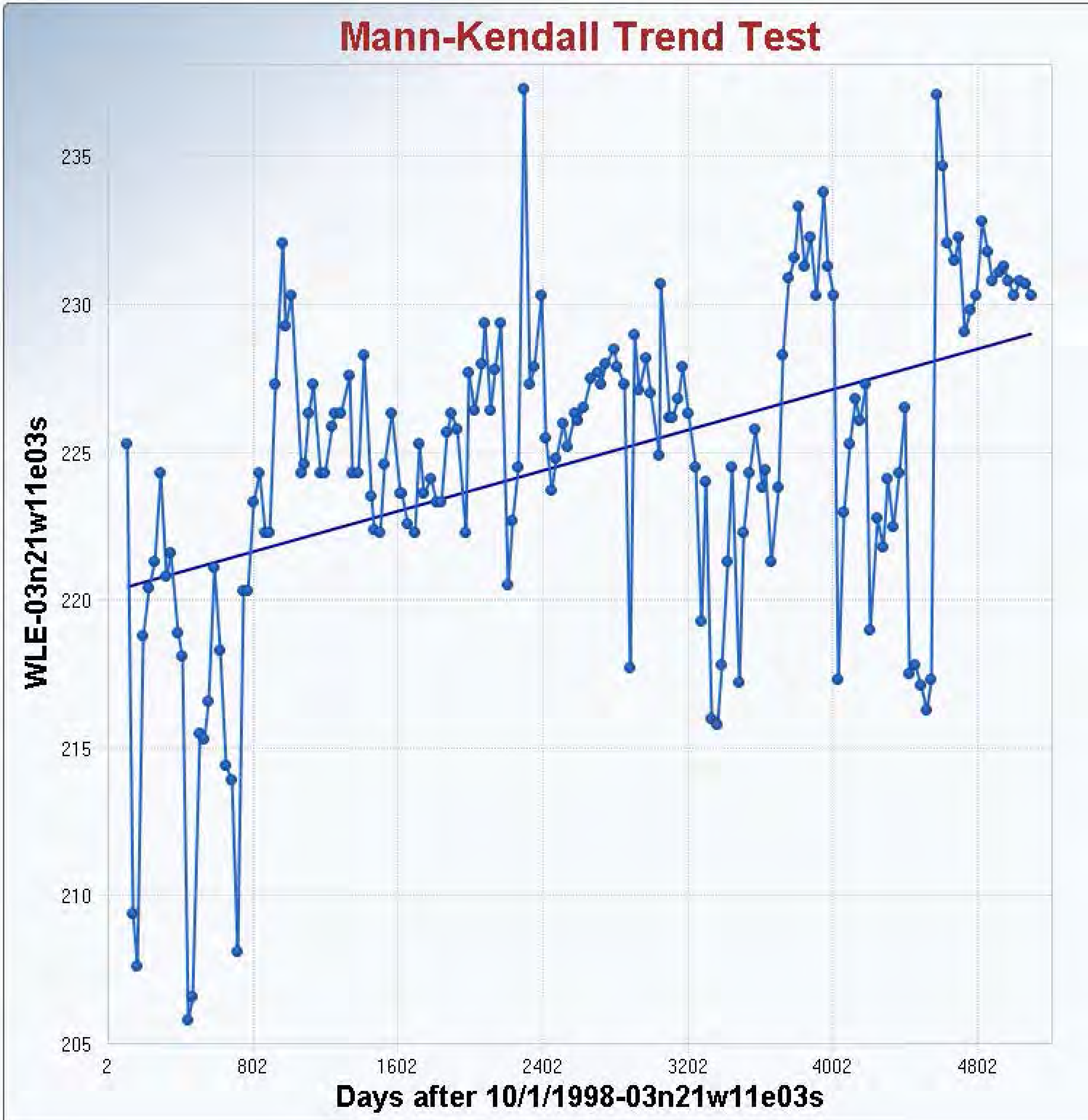
Mann-Kendall Trend Analysis

n	93
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	301.2795
Standardized Value of S	-0.6539
Test Value (S)	-198
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.2566

OLS Regression Line (Blue)

OLS Regression Slope	-0.0002
OLS Regression Intercept	247.6683

Insufficient statistical evidence of a significant trend at the specified level of significance.



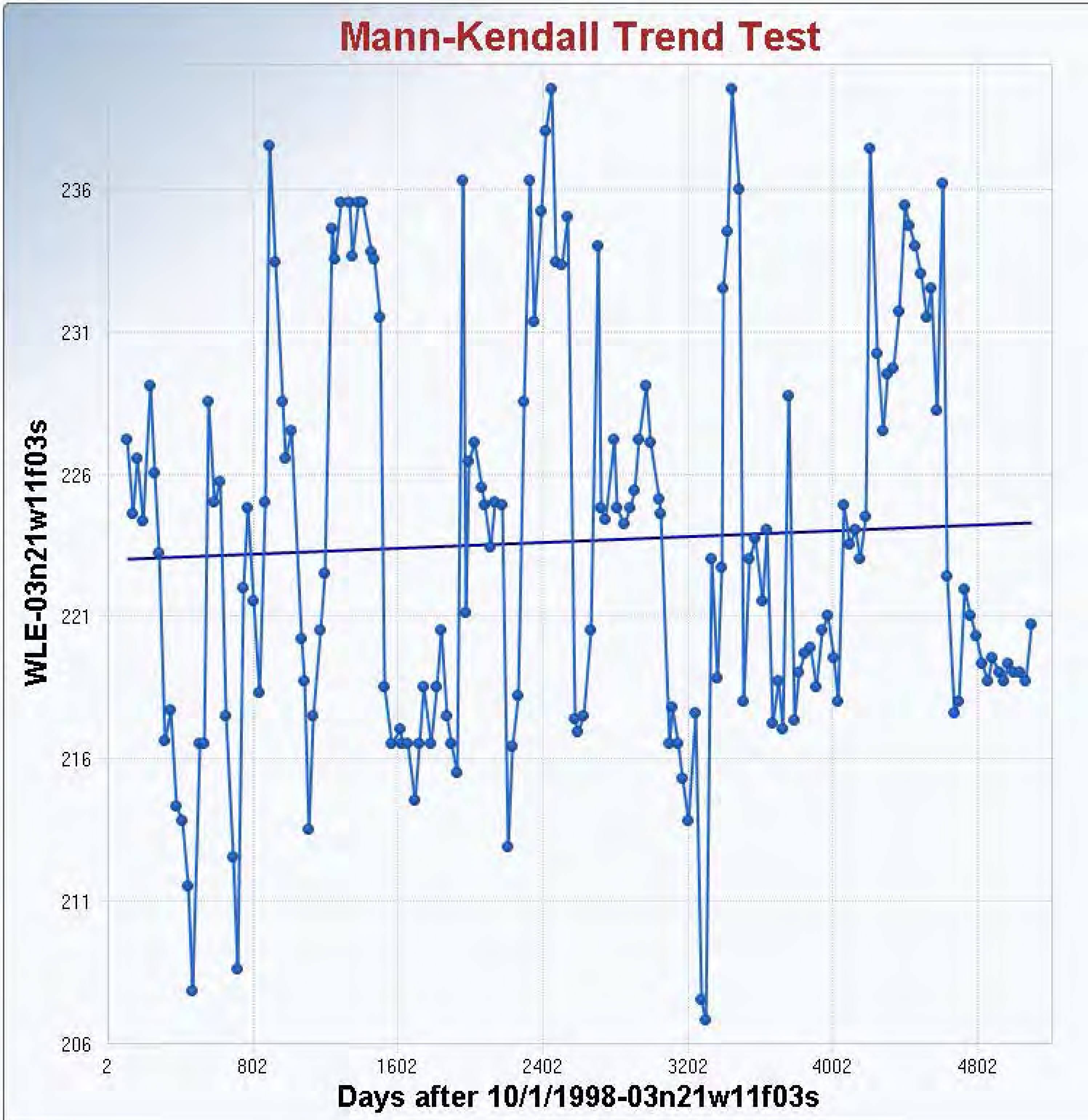
Mann-Kendall Trend Analysis

n	165
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	709.4582
Standardized Value of S	6.0187
Test Value (S)	4,271
Appx. Critical Value (0.05)	1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	0.0017
OLS Regression Intercept	220.4616

Statistically significant evidence of an increasing trend at the specified level of significance.



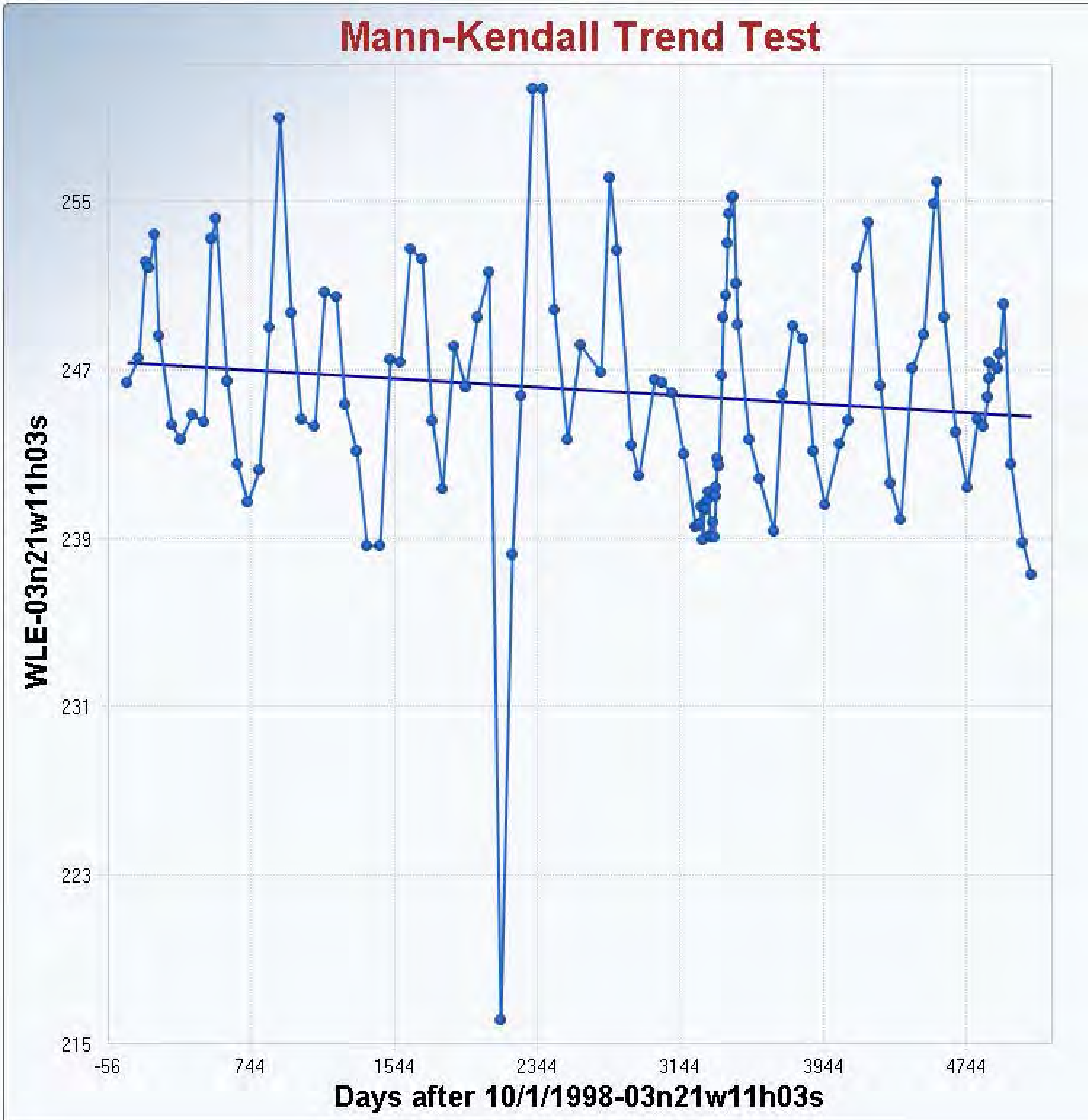
Mann-Kendall Trend Analysis

n	167
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	722.4002
Standardized Value of S	0.7627
Test Value (S)	552
Appx. Critical Value (0.05)	1.6449
Approximate p-value	0.2228

OLS Regression Line (Blue)

OLS Regression Slope	0.0003
OLS Regression Intercept	223.2067

Insufficient statistical evidence of a significant trend at the specified level of significance.



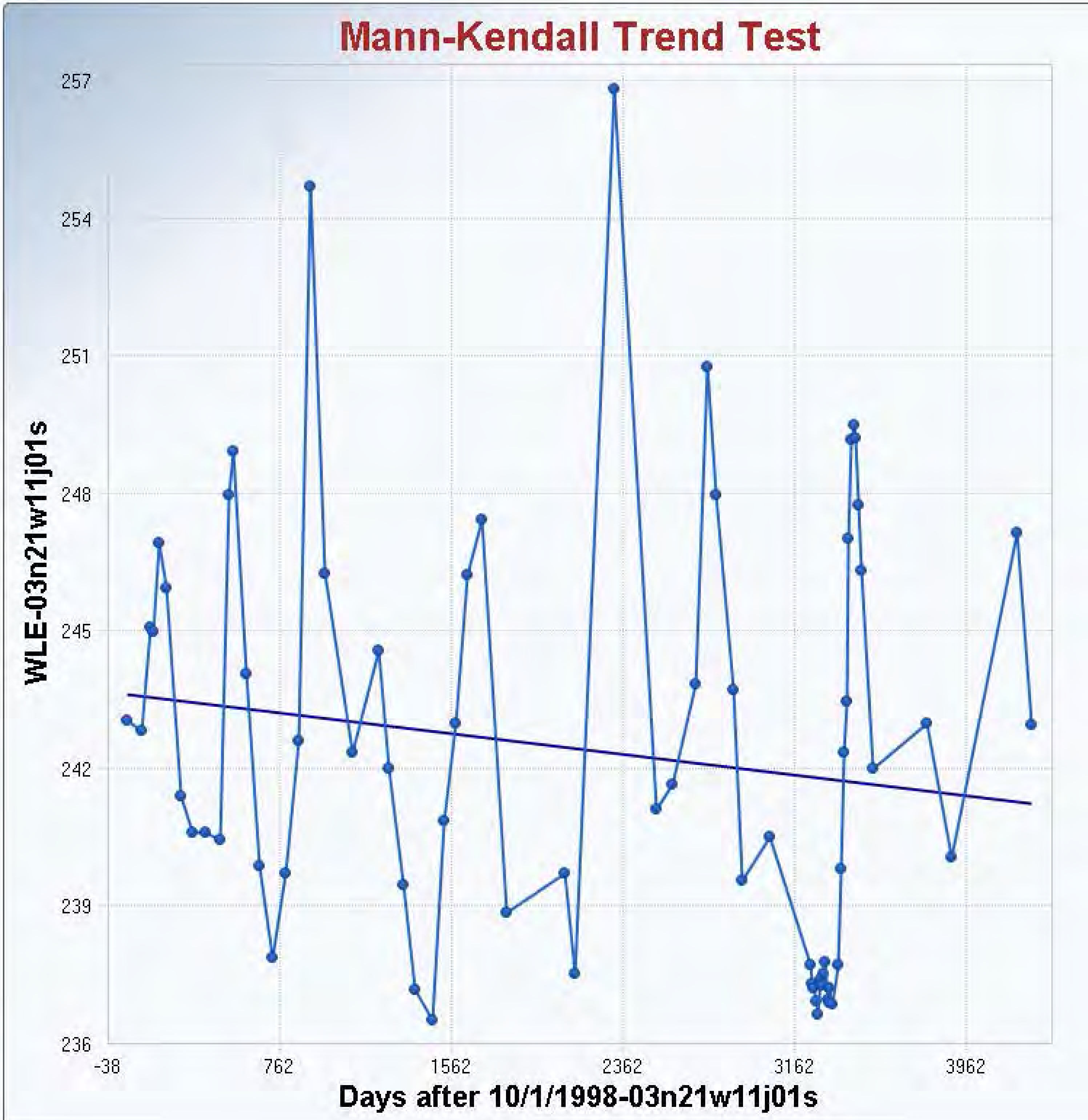
Mann-Kendall Trend Analysis

n	113
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	403.0095
Standardized Value of S	-1.1042
Test Value (S)	-446
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.1348

OLS Regression Line (Blue)

OLS Regression Slope	-0.0005
OLS Regression Intercept	247.2886

Insufficient statistical evidence of a significant trend at the specified level of significance.



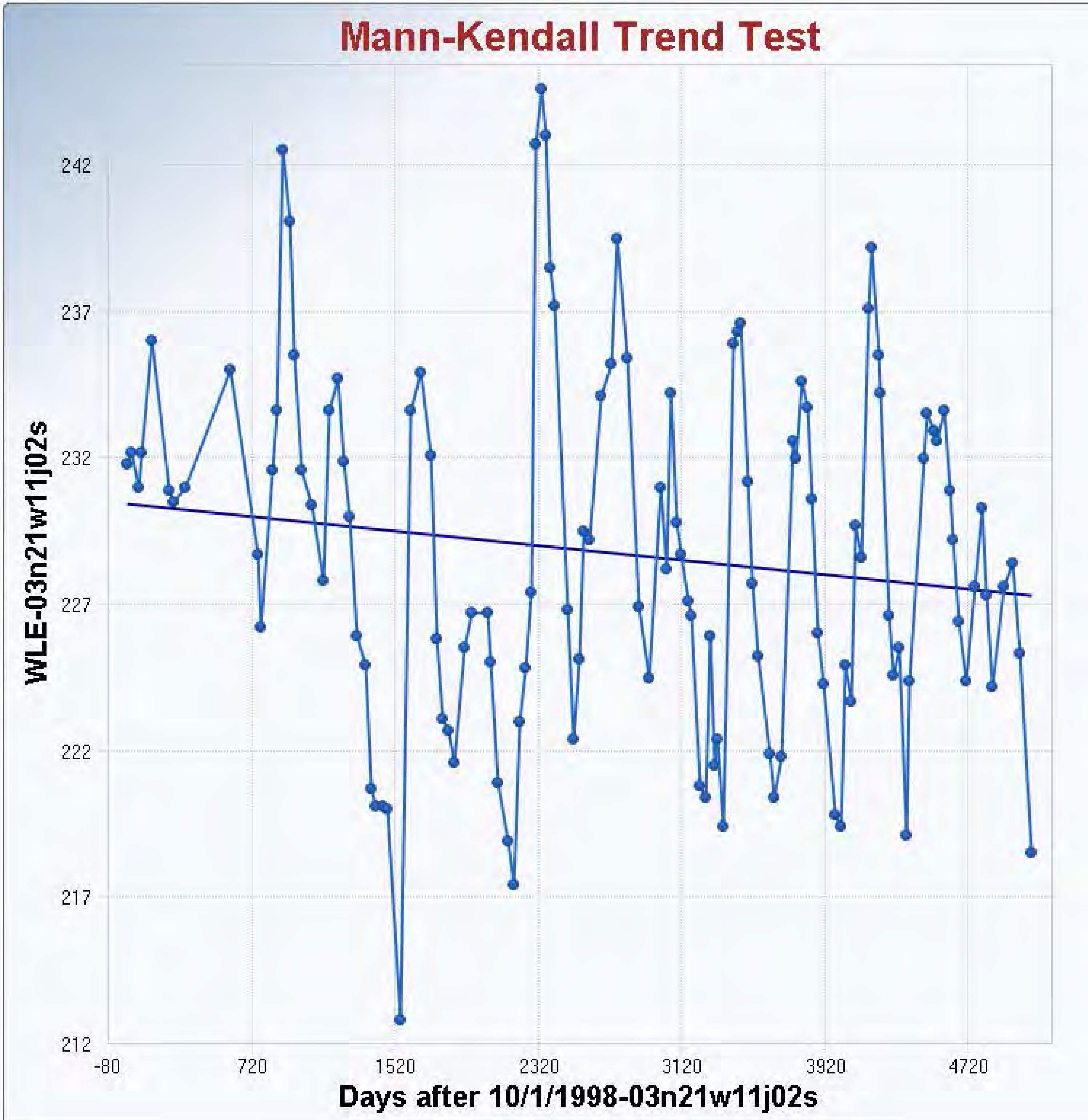
Mann-Kendall Trend Analysis

n	69
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	193.0578
Standardized Value of S	-1.1965
Test Value (S)	-232
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.1157

OLS Regression Line (Blue)

OLS Regression Slope	-0.0006
OLS Regression Intercept	243.2683

Insufficient statistical evidence of a significant trend at the specified level of significance.



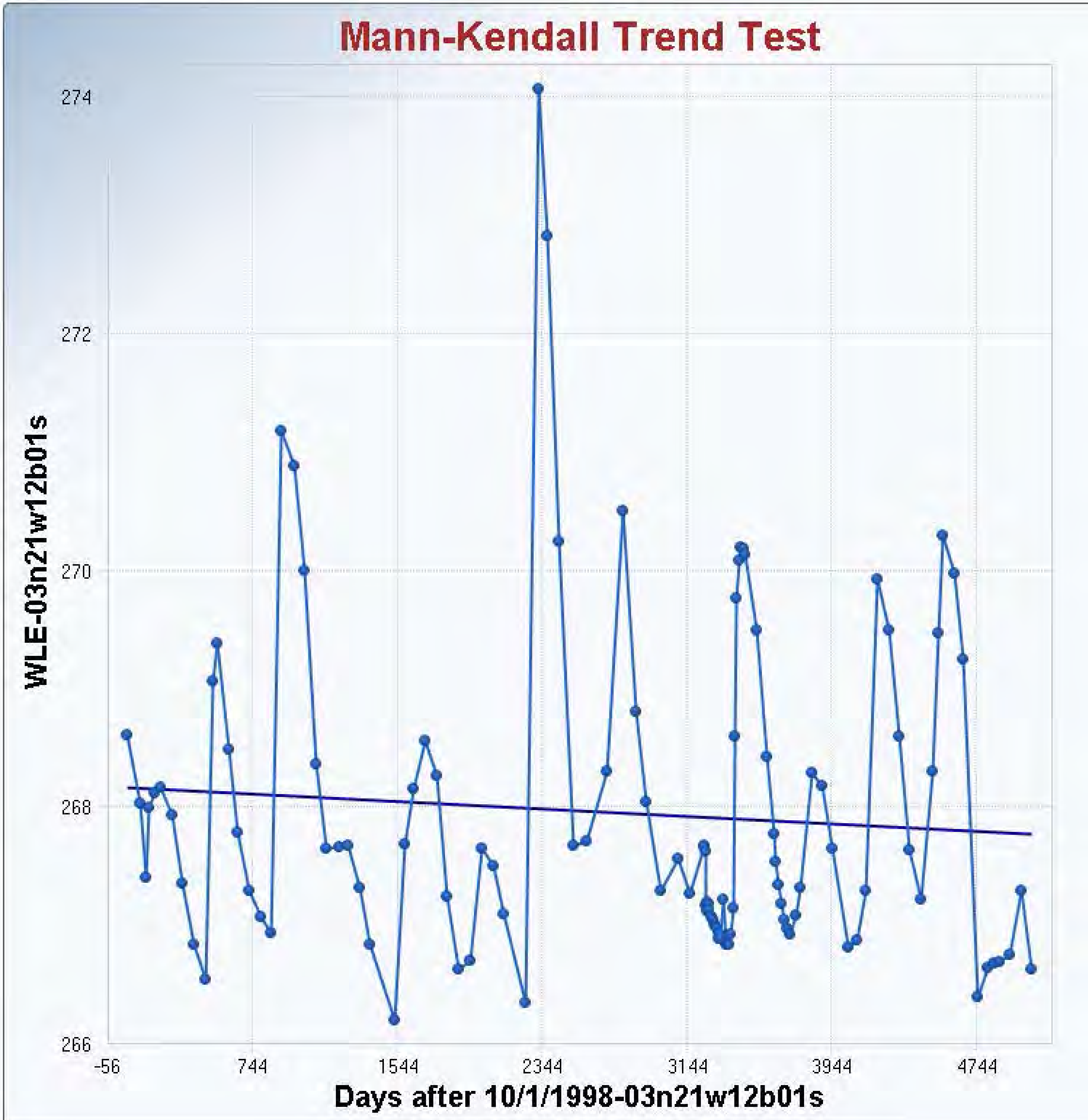
Mann-Kendall Trend Analysis

n	124
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	462.9719
Standardized Value of S	-1.6675
Test Value (S)	-773
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0477

OLS Regression Line (Blue)

OLS Regression Slope	-0.0006
OLS Regression Intercept	230.9242

Statistically significant evidence of a decreasing trend at the specified level of significance.



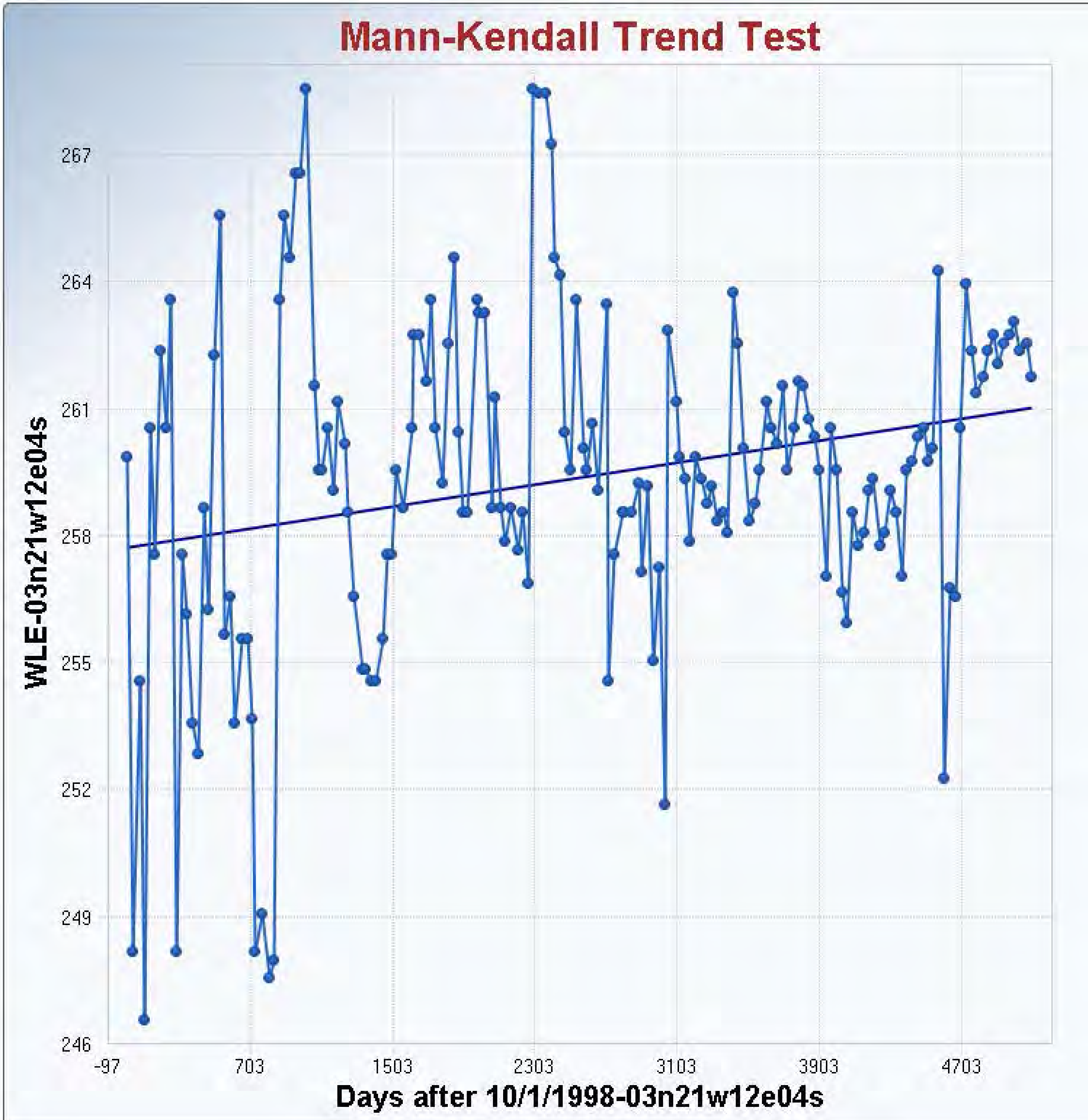
Mann-Kendall Trend Analysis

n	111
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	392.3706
Standardized Value of S	-1.9548
Test Value (S)	-768
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0253

OLS Regression Line (Blue)

OLS Regression Slope	-0.0001
OLS Regression Intercept	268.5703

Statistically significant evidence of a decreasing trend at the specified level of significance.



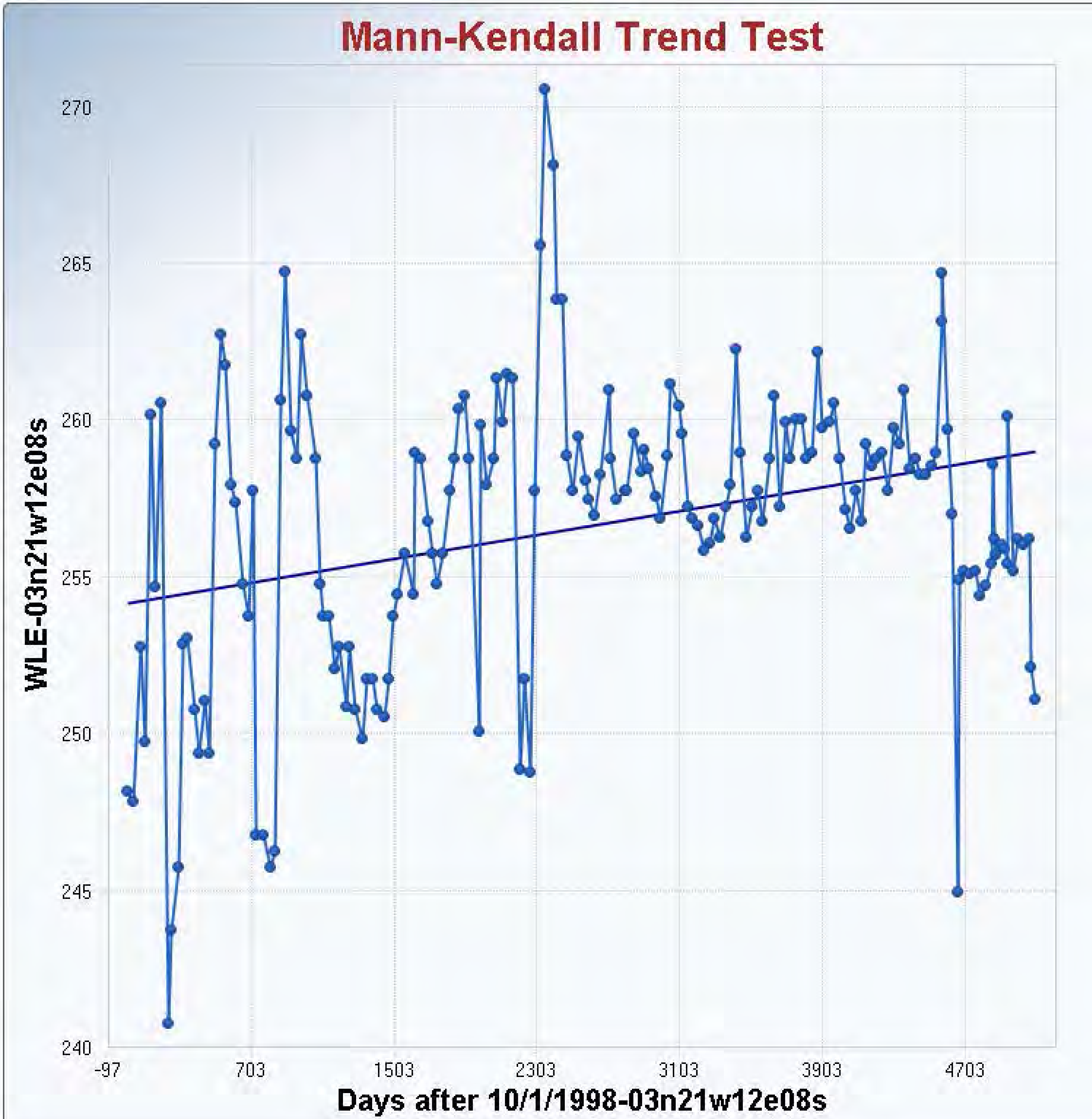
Mann-Kendall Trend Analysis

n	168
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	728.6840
Standardized Value of S	2.7968
Test Value (S)	2,039
Appx. Critical Value (0.05)	1.6449
Approximate p-value	0.0026

OLS Regression Line (Blue)

OLS Regression Slope	0.0007
OLS Regression Intercept	257.8995

Statistically significant evidence of an increasing trend at the specified level of significance.



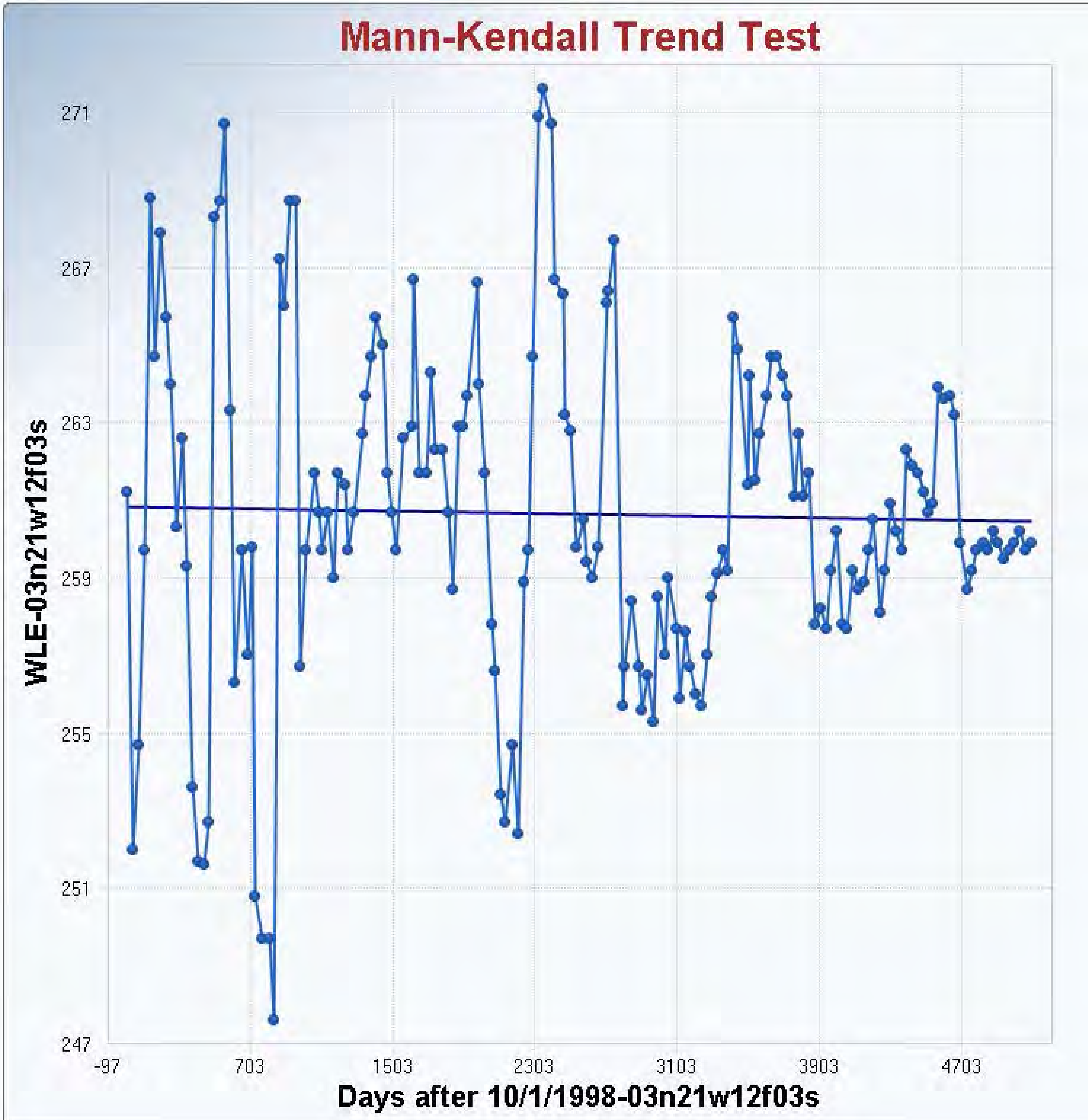
Mann-Kendall Trend Analysis

n	175
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	774.6429
Standardized Value of S	2.7703
Test Value (S)	2,147
Appx. Critical Value (0.05)	1.6449
Approximate p-value	0.0028

OLS Regression Line (Blue)

OLS Regression Slope	0.0009
OLS Regression Intercept	254.5688

Statistically significant evidence of an increasing trend at the specified level of significance.



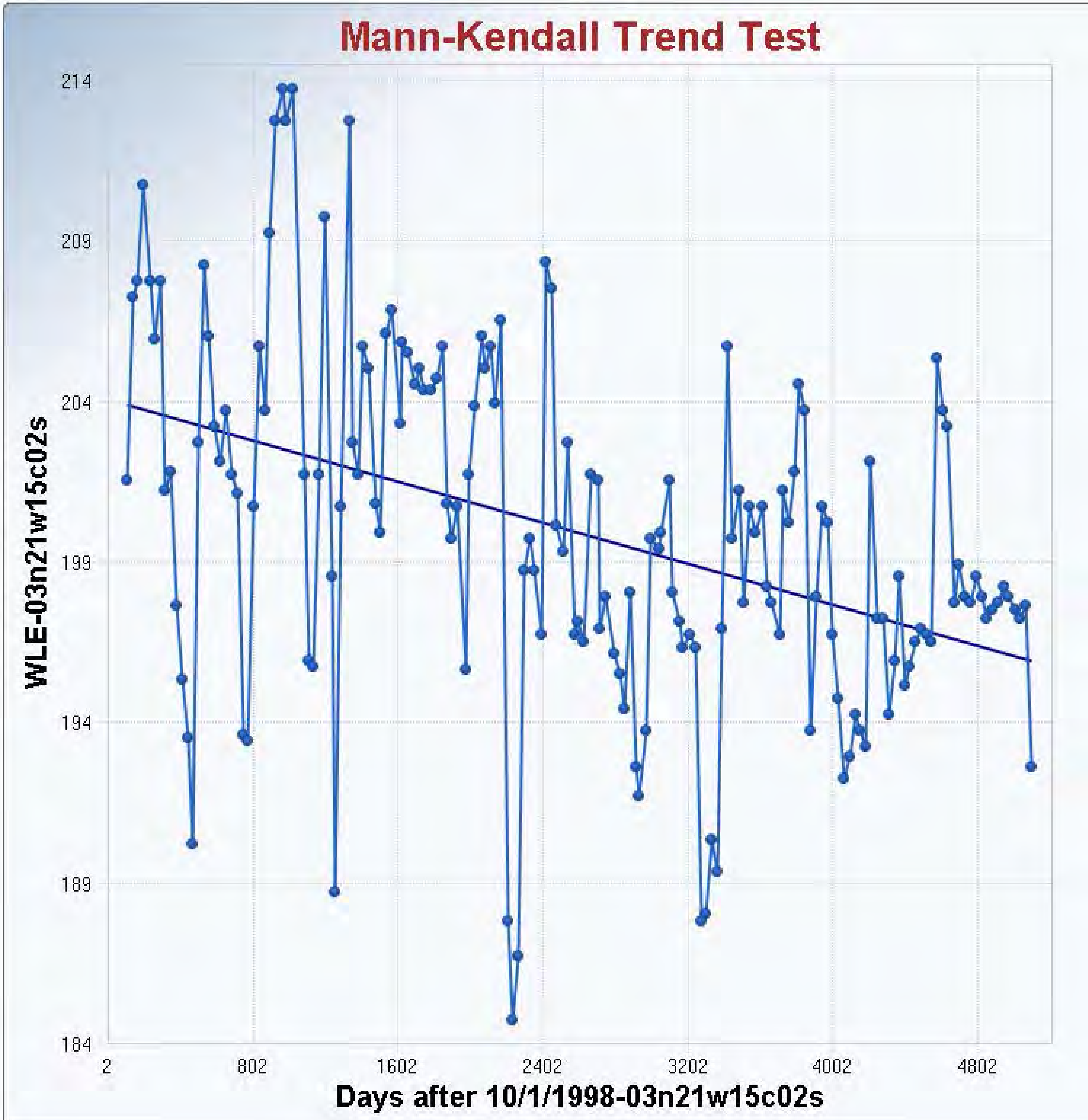
Mann-Kendall Trend Analysis

n	168
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	728.6540
Standardized Value of S	-0.8385
Test Value (S)	-612
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.2009

OLS Regression Line (Blue)

OLS Regression Slope	-0.0001
OLS Regression Intercept	260.5995

Insufficient statistical evidence of a significant trend at the specified level of significance.



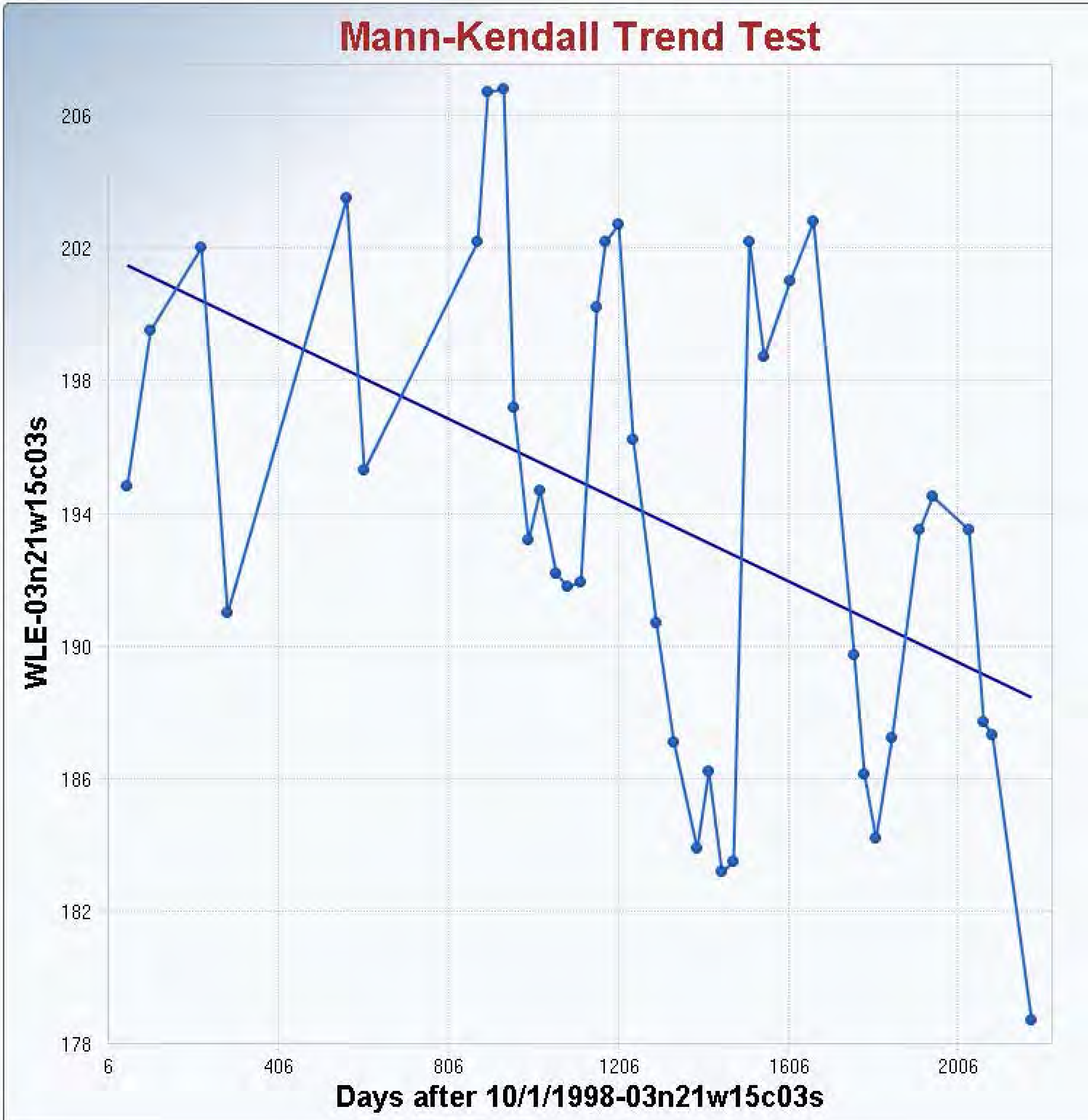
Mann-Kendall Trend Analysis

n	164
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	703.0787
Standardized Value of S	-5.8514
Test Value (S)	-4,115
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0016
OLS Regression Intercept	203.9312

Statistically significant evidence of a decreasing trend at the specified level of significance.



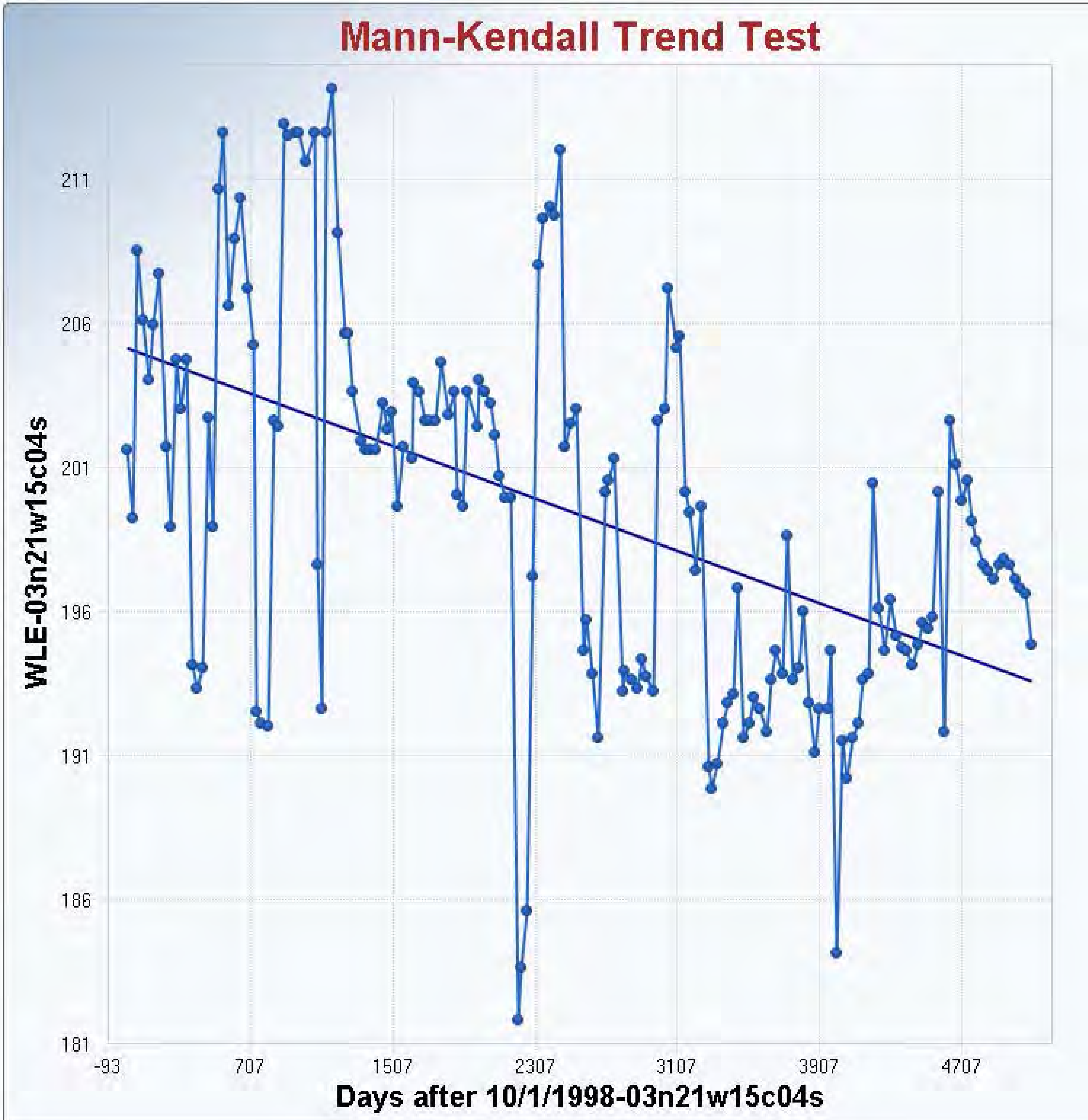
Mann-Kendall Trend Analysis

n	39
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	82.6378
Standardized Value of S	-3.0010
Test Value (S)	-249
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0013

OLS Regression Line (Blue)

OLS Regression Slope	-0.0061
OLS Regression Intercept	202.0657

Statistically significant evidence of a decreasing trend at the specified level of significance.



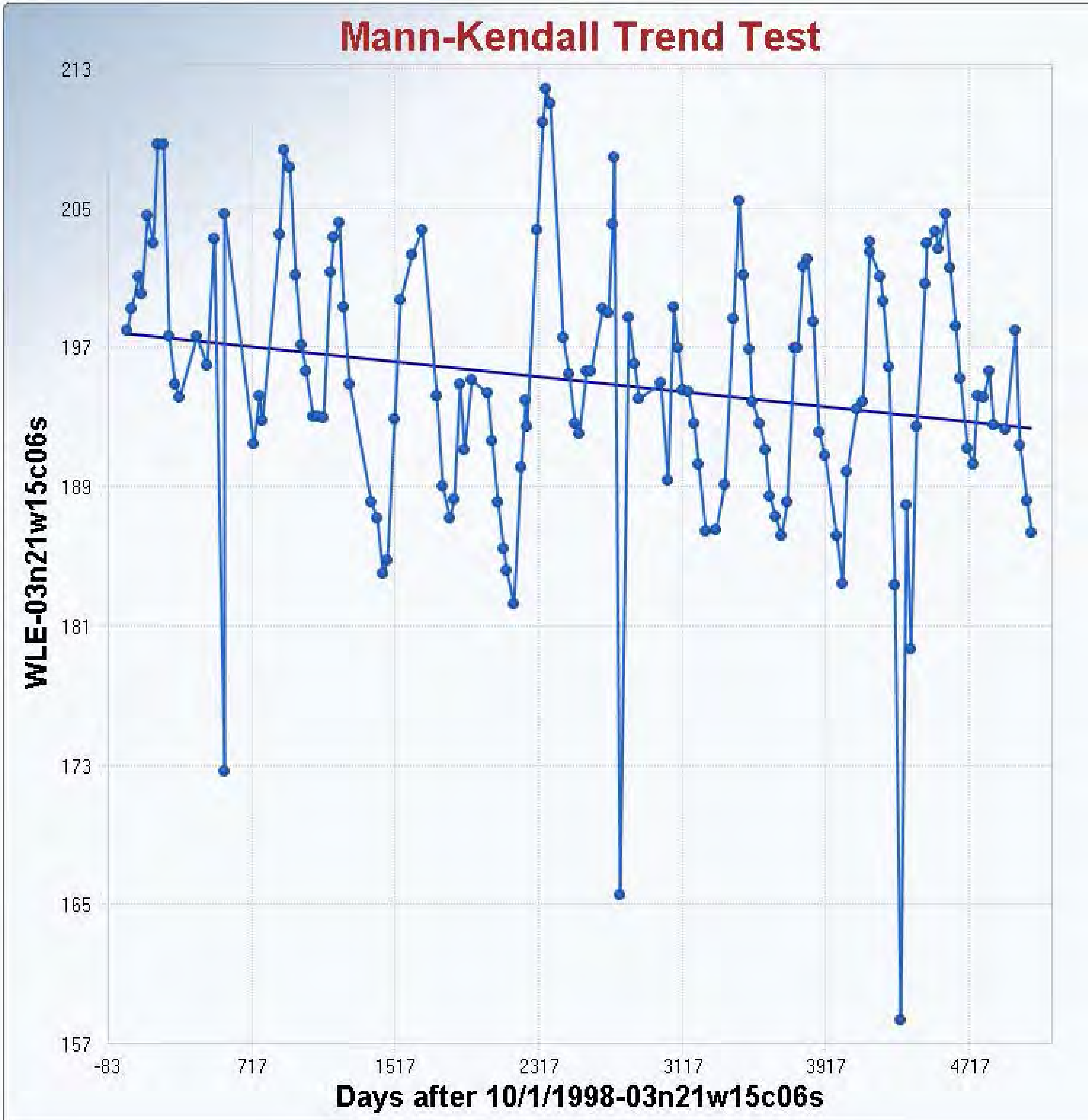
Mann-Kendall Trend Analysis

n	168
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	728.9319
Standardized Value of S	-6.6371
Test Value (S)	-4,839
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0023
OLS Regression Intercept	205.6279

Statistically significant evidence of a decreasing trend at the specified level of significance.



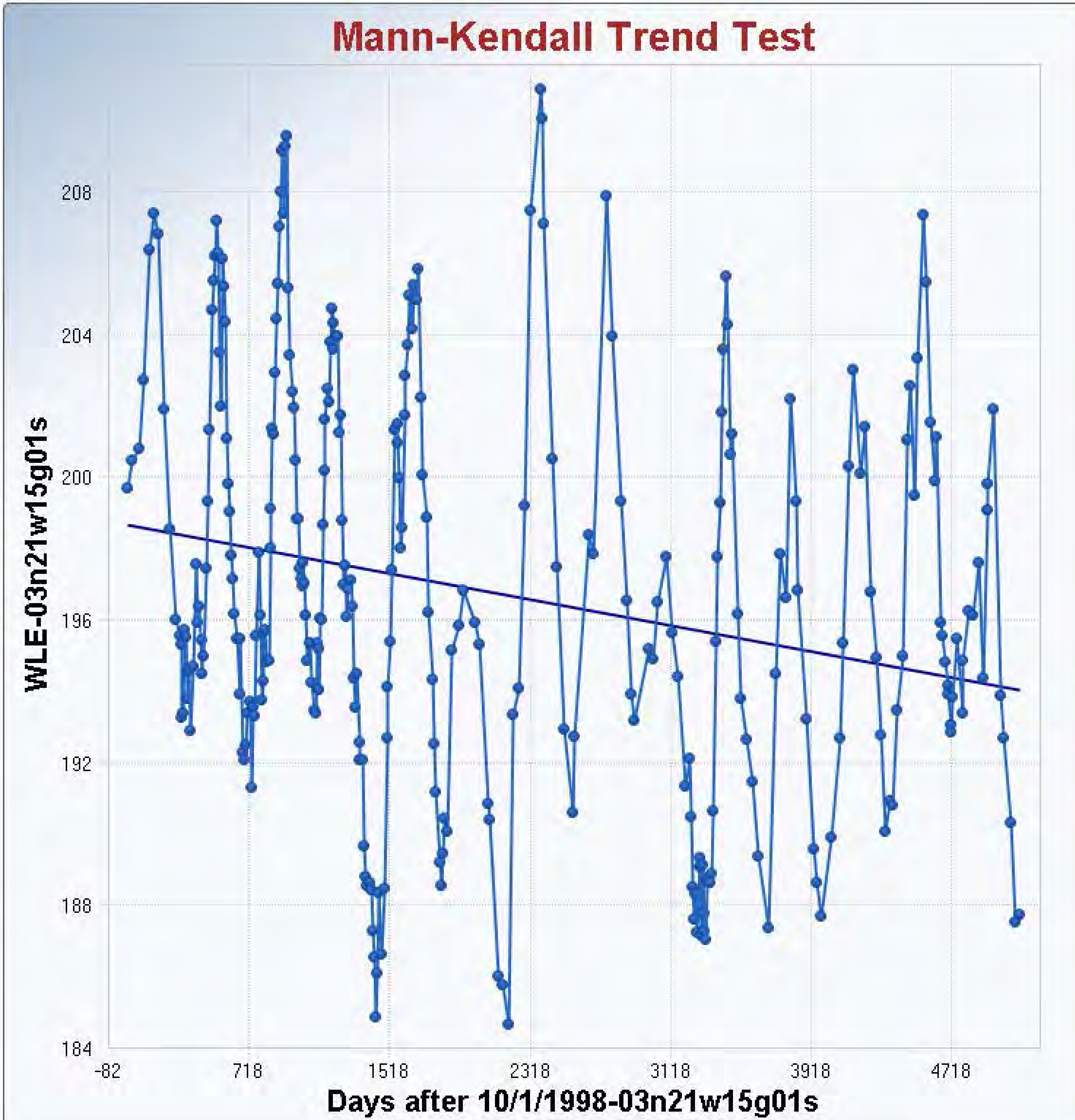
Mann-Kendall Trend Analysis

n	138
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	543.2397
Standardized Value of S	-2.4538
Test Value (S)	-1,334
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0071

OLS Regression Line (Blue)

OLS Regression Slope	-0.0011
OLS Regression Intercept	197.9864

Statistically significant evidence of a decreasing trend at the specified level of significance.



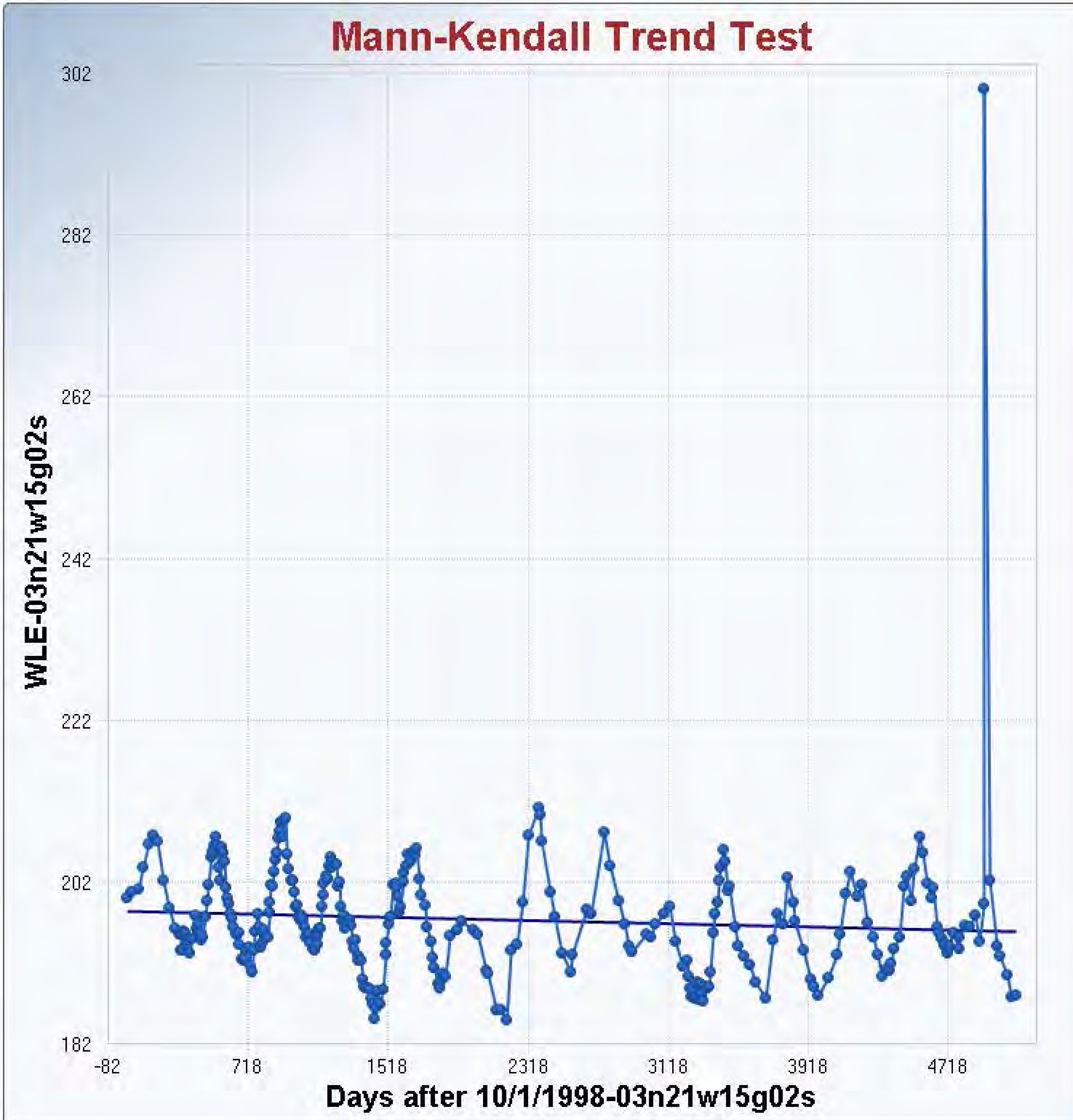
Mann-Kendall Trend Analysis

n	297
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,710.4099
Standardized Value of S	-4.2978
Test Value (S)	-7,352
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0009
OLS Regression Intercept	199.0869

Statistically significant evidence of a decreasing trend at the specified level of significance.



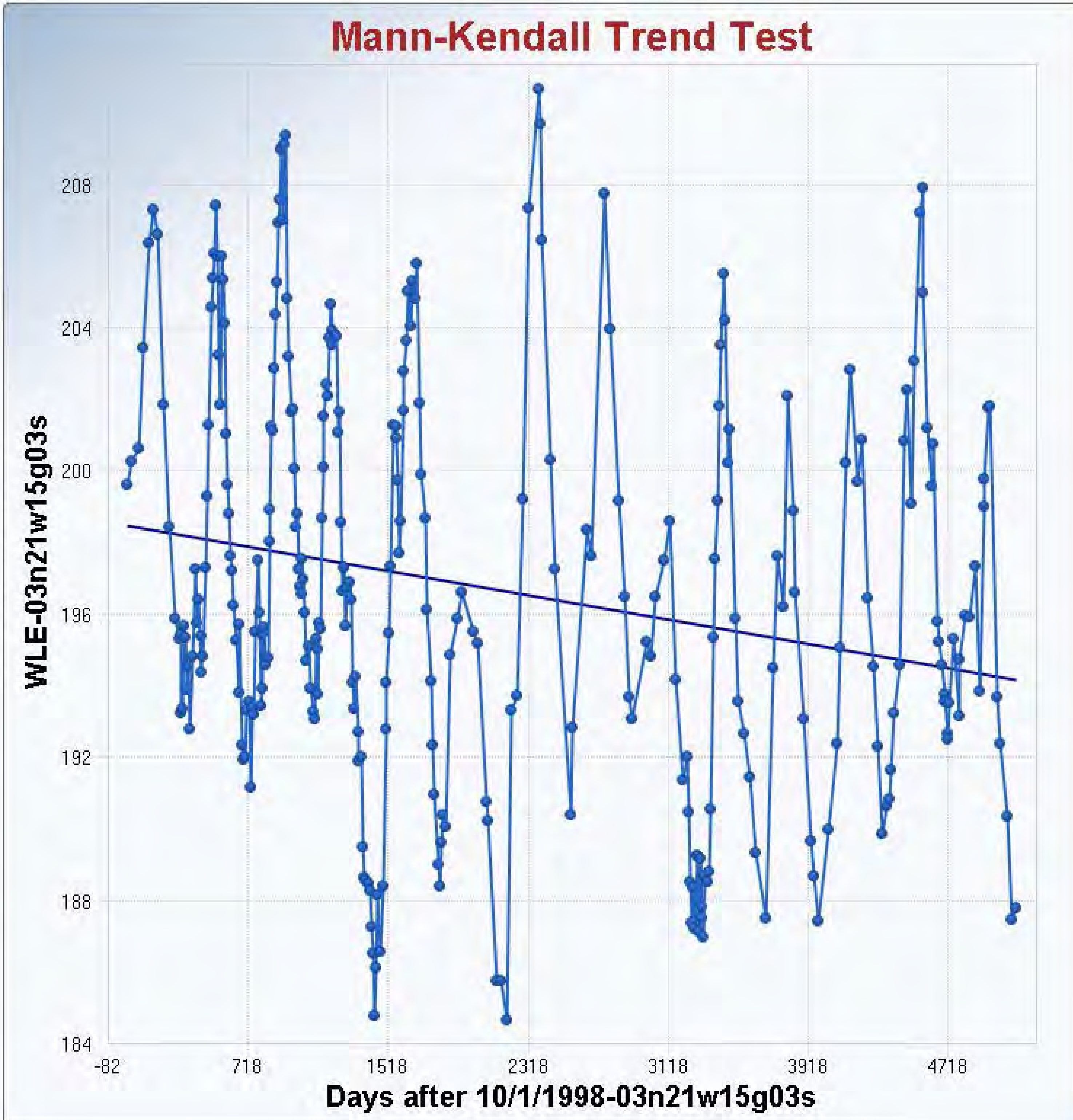
Mann-Kendall Trend Analysis

n	298
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,719.0422
Standardized Value of S	-4.1913
Test Value (S)	-7,206
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0005
OLS Regression Intercept	198.3291

Statistically significant evidence of a decreasing trend at the specified level of significance.



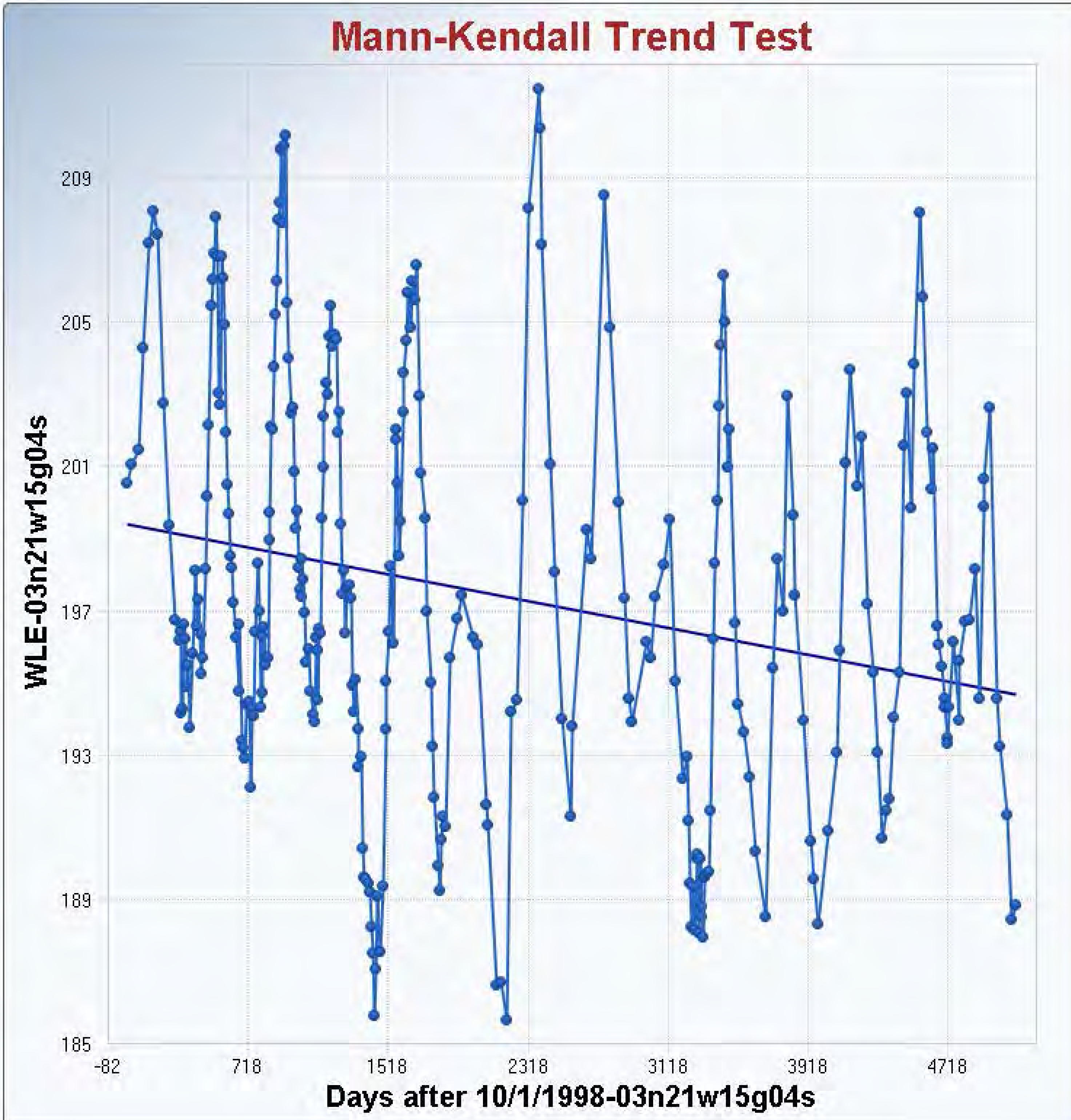
Mann-Kendall Trend Analysis

n	299
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,727.6869
Standardized Value of S	-4.1275
Test Value (S)	-7,132
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0008
OLS Regression Intercept	198.9189

Statistically significant evidence of a decreasing trend at the specified level of significance.



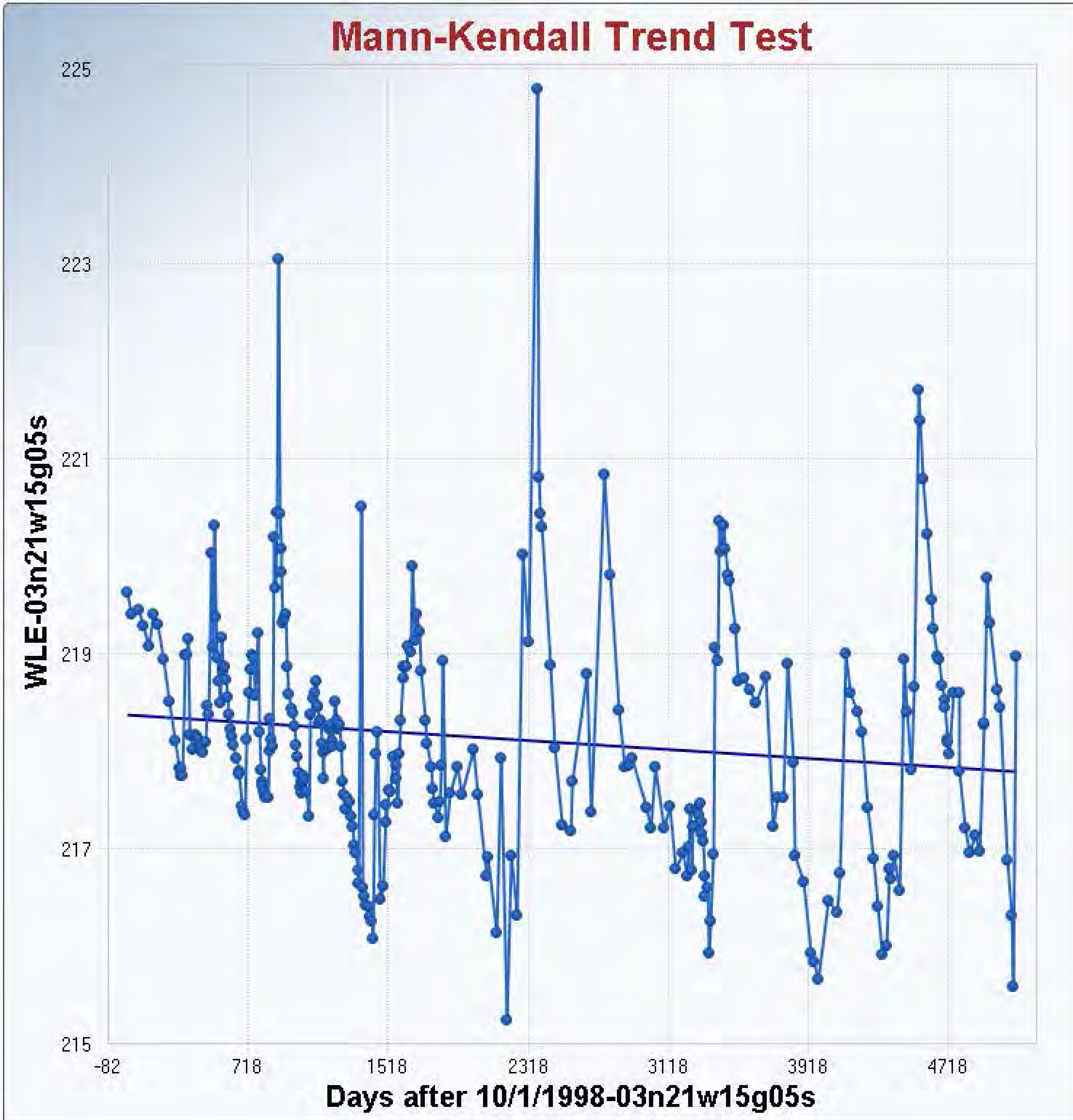
Mann-Kendall Trend Analysis

n	297
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,710.4074
Standardized Value of S	-4.4592
Test Value (S)	-7,628
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0009
OLS Regression Intercept	198.9500

Statistically significant evidence of a decreasing trend at the specified level of significance.



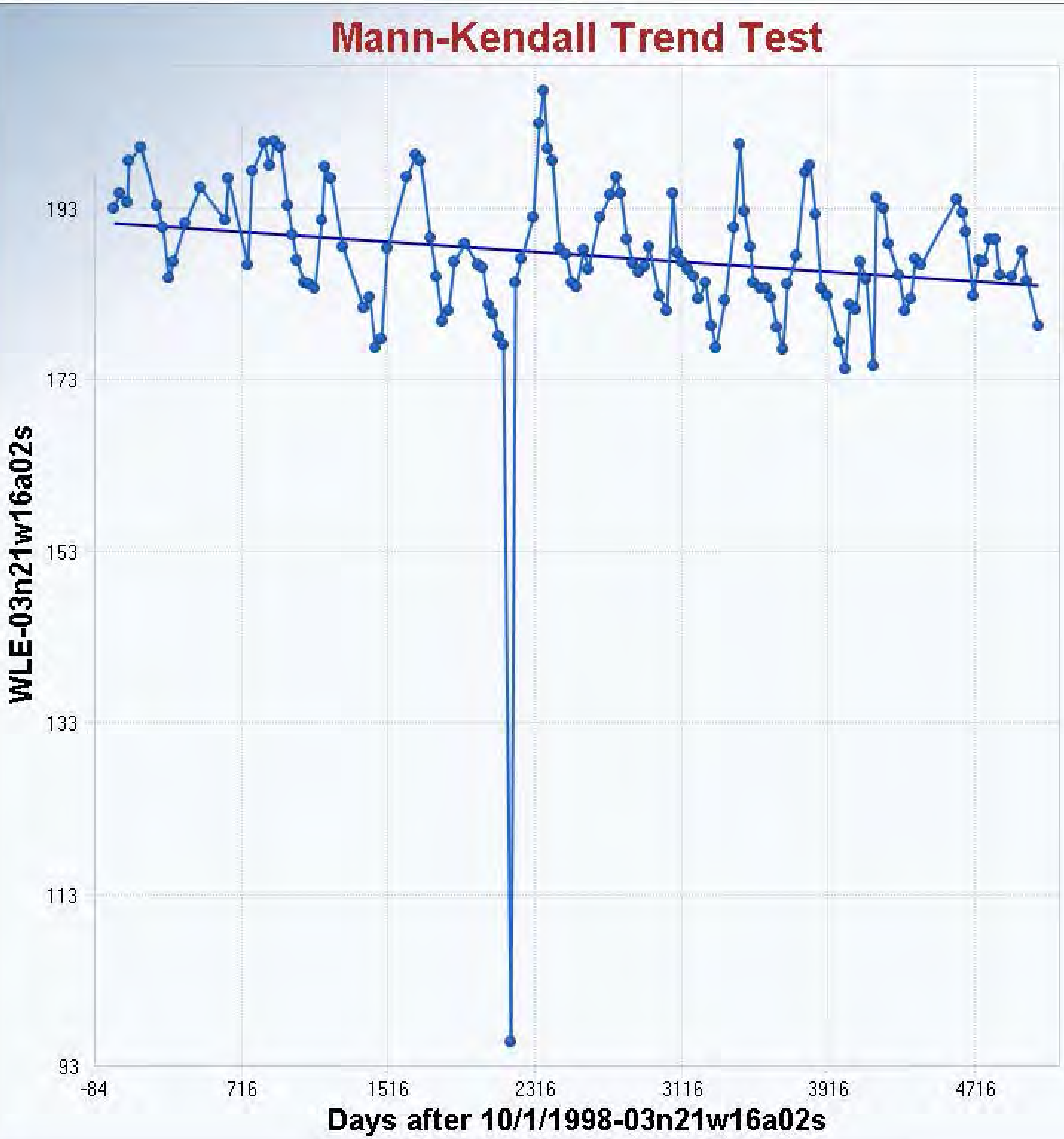
Mann-Kendall Trend Analysis

n	301
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,744.9963
Standardized Value of S	-4.5519
Test Value (S)	-7,944
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0001
OLS Regression Intercept	218.6801

Statistically significant evidence of a decreasing trend at the specified level of significance.



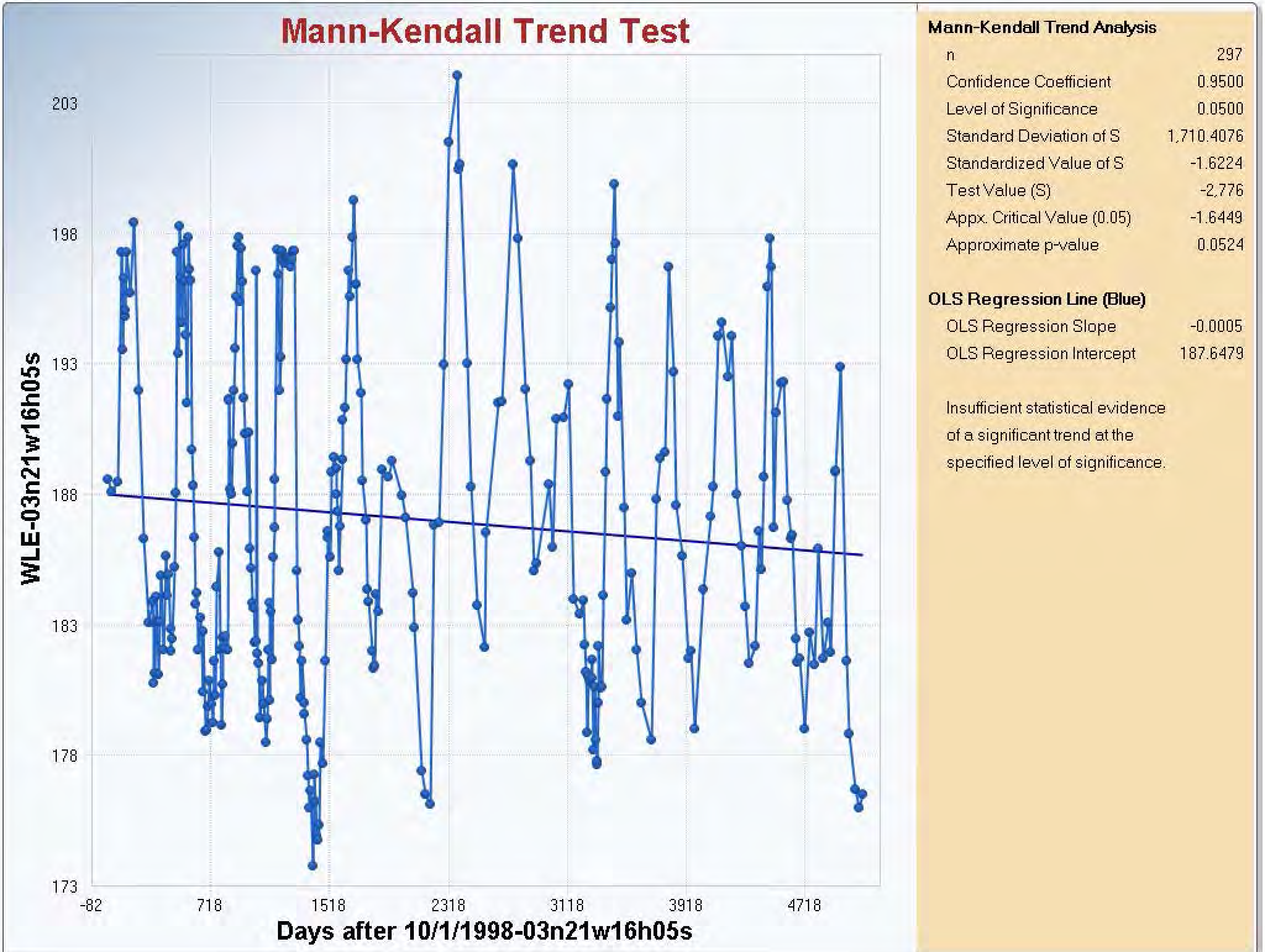
Mann-Kendall Trend Analysis

n	129
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	491.1439
Standardized Value of S	-3.5631
Test Value (S)	-1,751
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0002

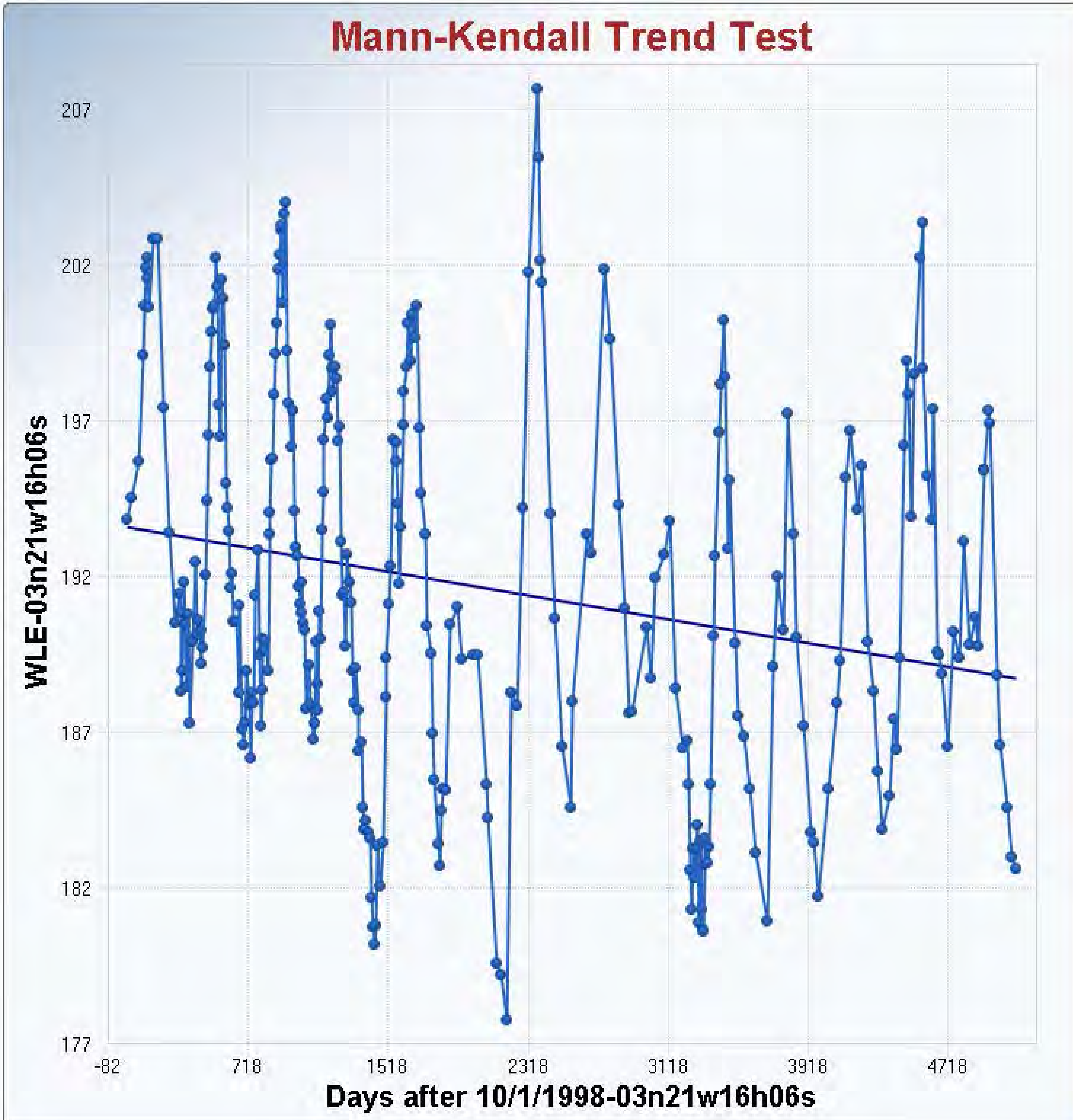
OLS Regression Line (Blue)

OLS Regression Slope	-0.0014
OLS Regression Intercept	191.5076

Statistically significant evidence of a decreasing trend at the specified level of significance.



Mann-Kendall Trend Test
WLE-03n21w16h05s
Days after 10/1/1998-03n21w16h05s
203
198
193
188
183
178
173
-82
718
1518
2318
3118
3918
4718
Mann-Kendall Trend Analysis
n 297
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 1,710.4076
Standardized Value of S -1.6224
Test Value (S) -2,776
Appx. Critical Value (0.05) -1.6449
Approximate p-value 0.0524
OLS Regression Line (Blue)
OLS Regression Slope -0.0005
OLS Regression Intercept 187.6479
Insufficient statistical evidence of a significant trend at the specified level of significance.



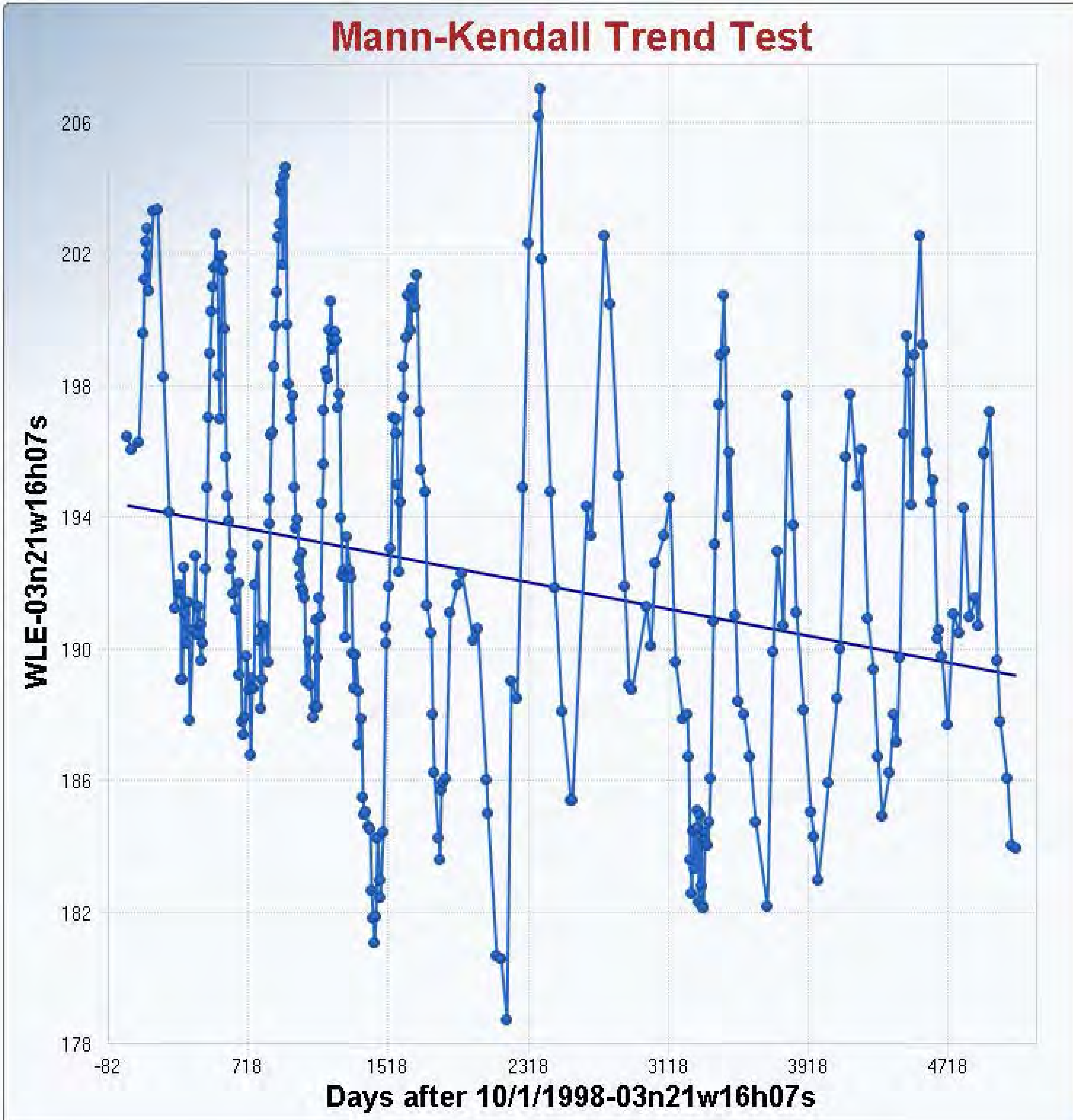
Mann-Kendall Trend Analysis

n	300
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,736.3464
Standardized Value of S	-4.7404
Test Value (S)	-8,232
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0010
OLS Regression Intercept	193.1930

Statistically significant evidence of a decreasing trend at the specified level of significance.



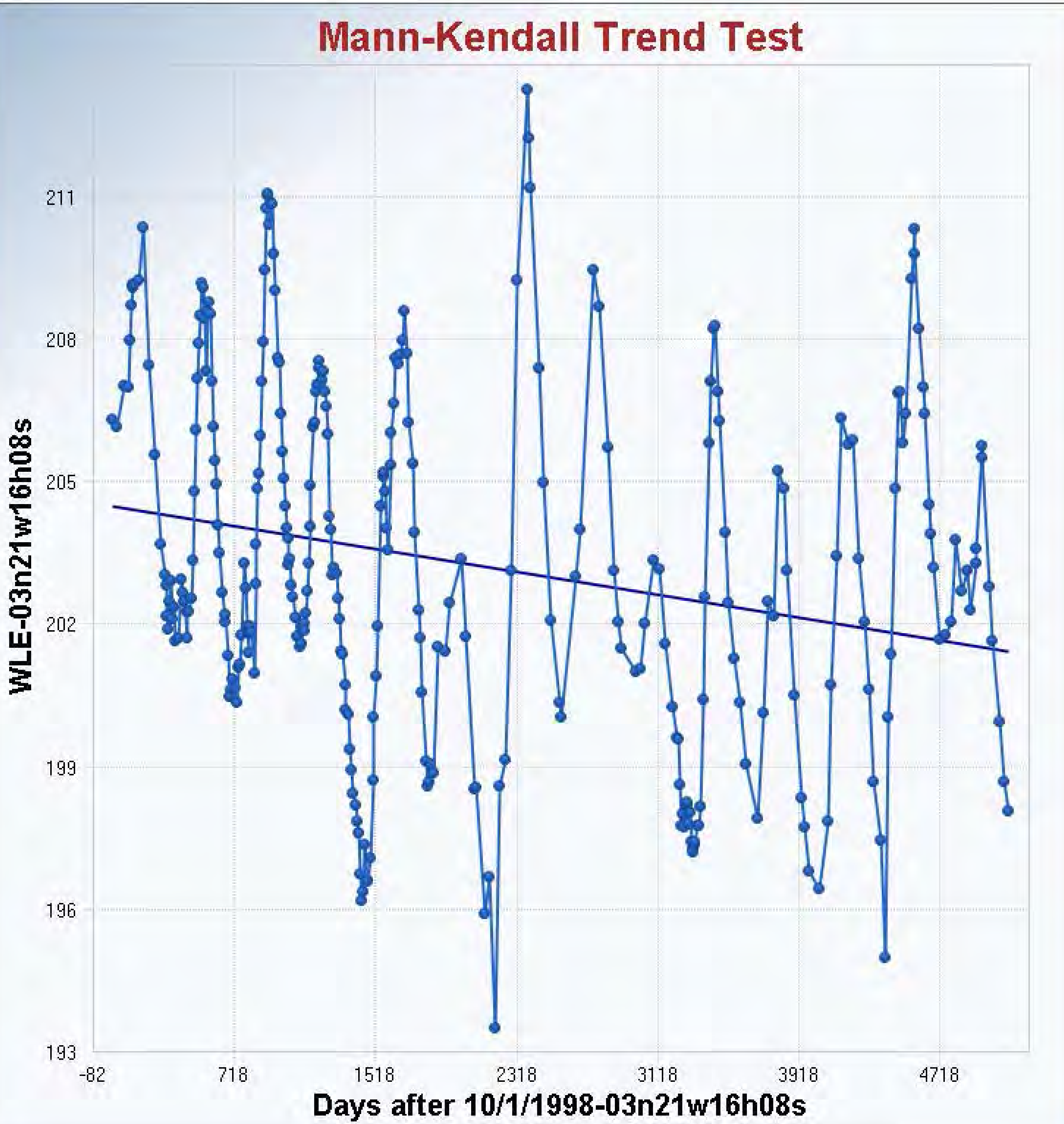
Mann-Kendall Trend Analysis

n	298
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,719.0383
Standardized Value of S	-4.9161
Test Value (S)	-8,452
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0010
OLS Regression Intercept	194.2961

Statistically significant evidence of a decreasing trend at the specified level of significance.



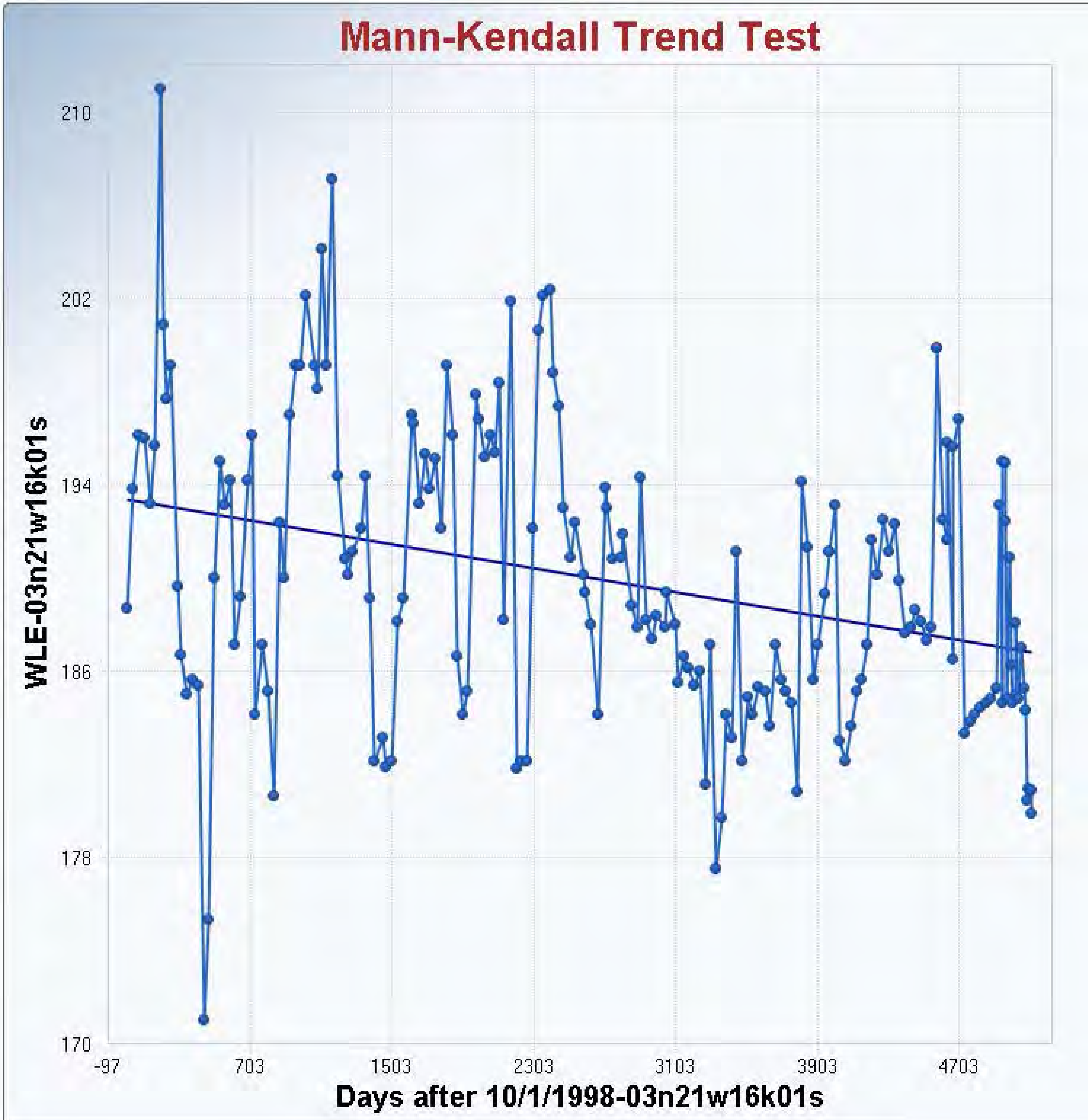
Mann-Kendall Trend Analysis

n	300
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	1,736.3403
Standardized Value of S	-4.7859
Test Value (S)	-8,311
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0006
OLS Regression Intercept	204.0449

Statistically significant evidence of a decreasing trend at the specified level of significance.



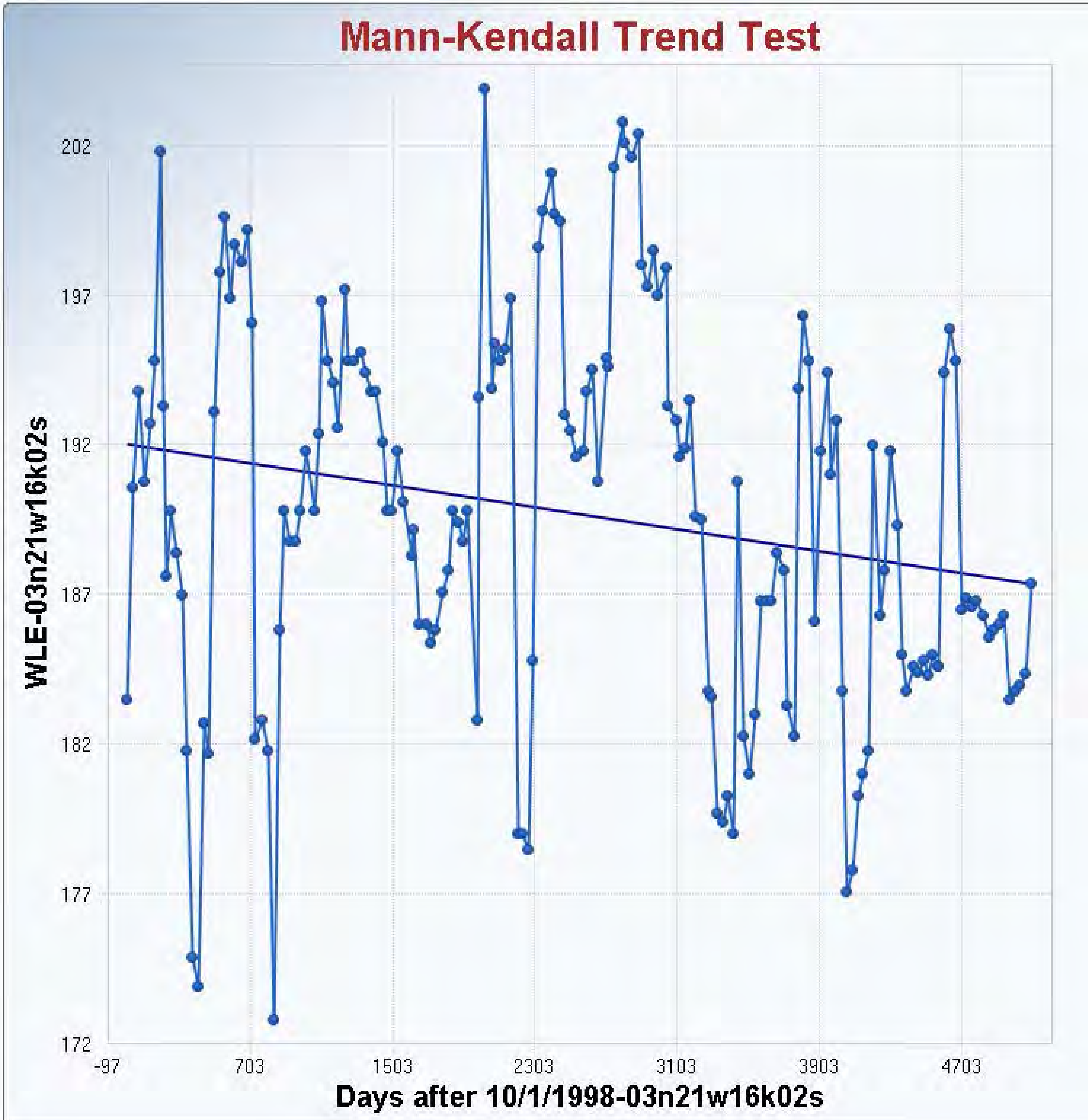
Mann-Kendall Trend Analysis

n	186
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	848.8198
Standardized Value of S	-4.8962
Test Value (S)	-4,157
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0013
OLS Regression Intercept	193.0821

Statistically significant evidence of a decreasing trend at the specified level of significance.



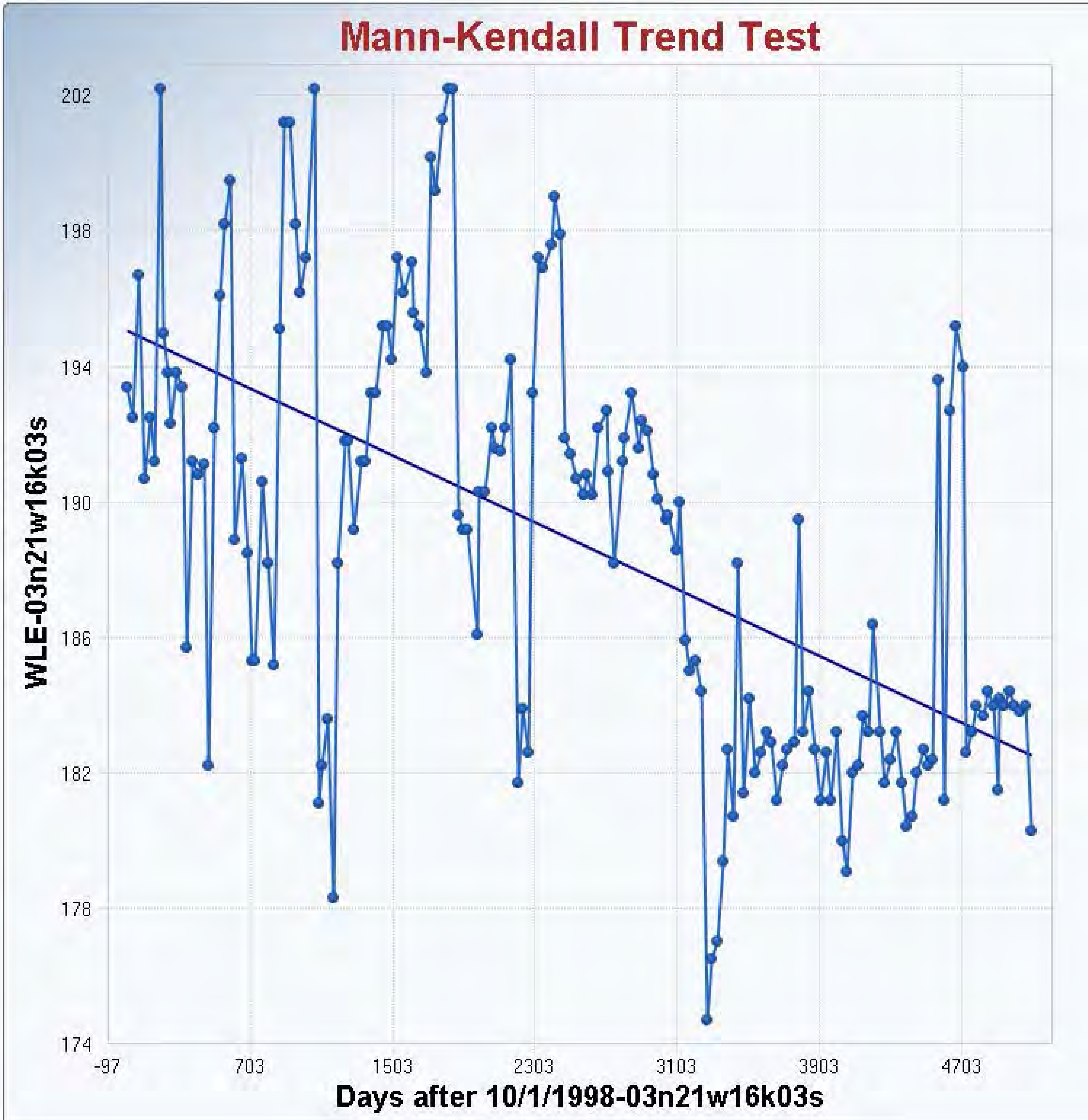
Mann-Kendall Trend Analysis

n	170
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	741.9274
Standardized Value of S	-3.1432
Test Value (S)	-2,333
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0008

OLS Regression Line (Blue)

OLS Regression Slope	-0.0009
OLS Regression Intercept	192.0686

Statistically significant evidence of a decreasing trend at the specified level of significance.



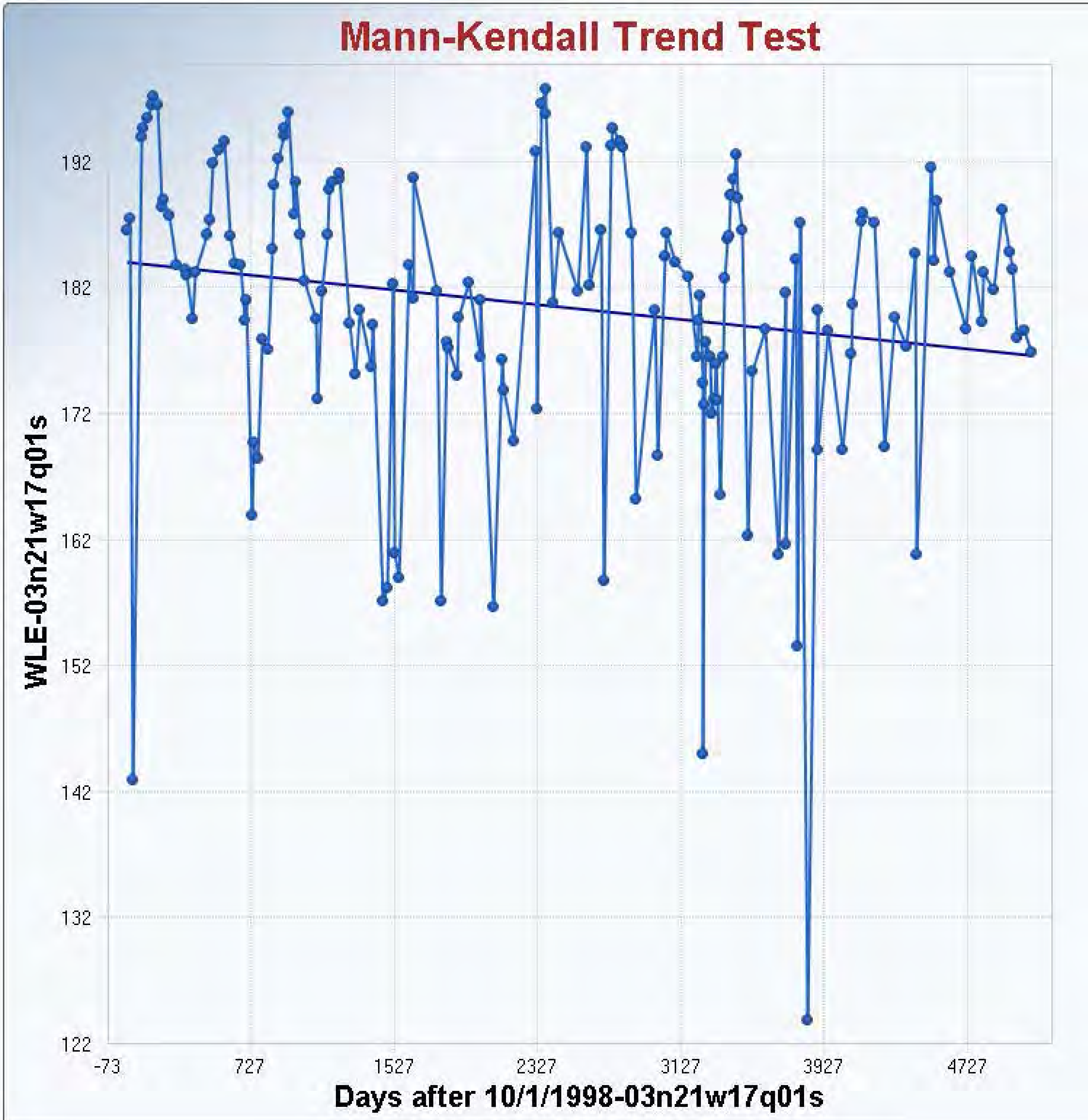
Mann-Kendall Trend Analysis

n	170
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	741.9167
Standardized Value of S	-7.6828
Test Value (S)	-5,701
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0000

OLS Regression Line (Blue)

OLS Regression Slope	-0.0025
OLS Regression Intercept	194.7921

Statistically significant evidence of a decreasing trend at the specified level of significance.



Mann-Kendall Trend Analysis

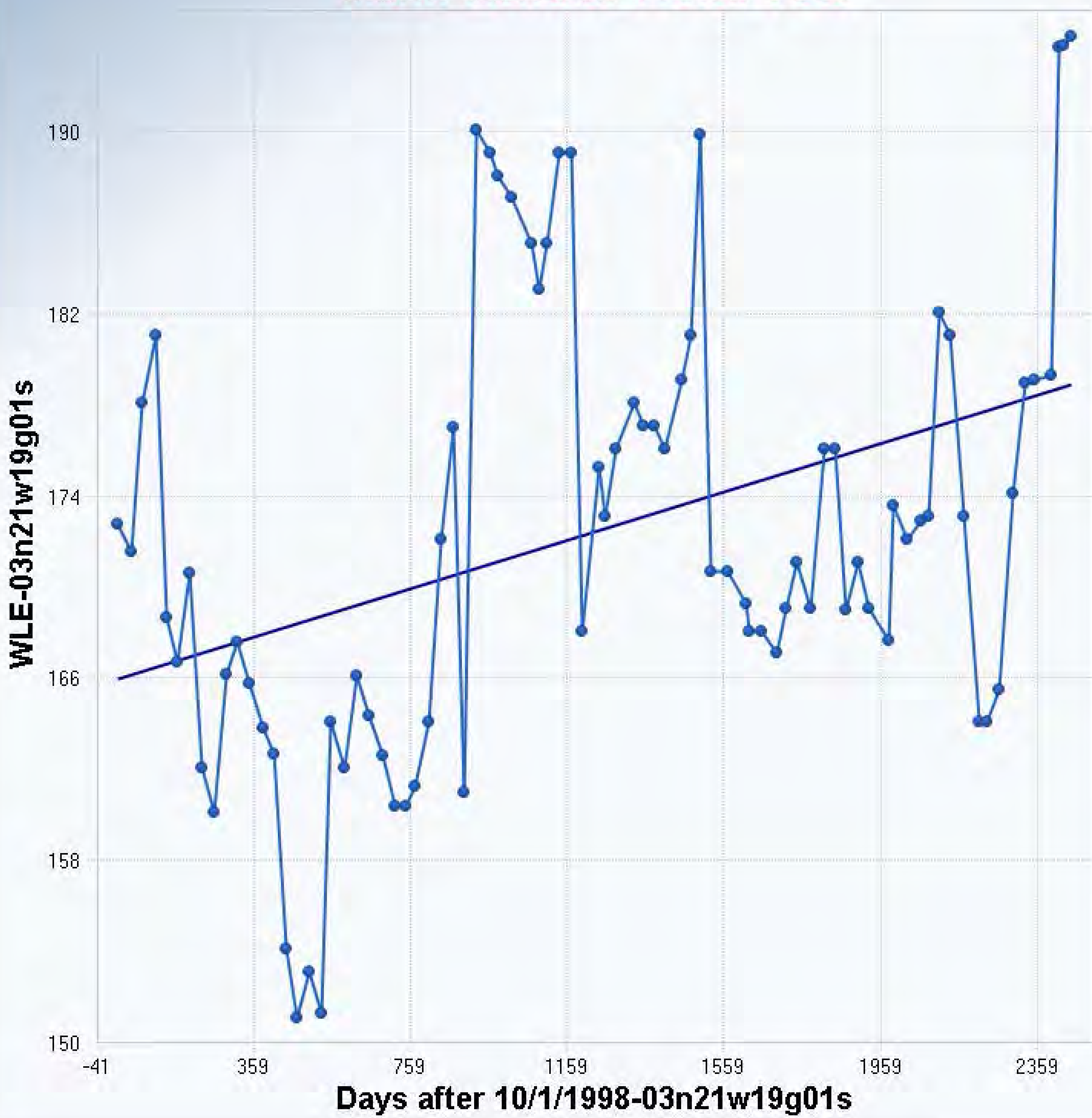
n	162
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	690.4209
Standardized Value of S	-3.1488
Test Value (S)	-2,175
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0008

OLS Regression Line (Blue)

OLS Regression Slope	-0.0014
OLS Regression Intercept	184.2129

Statistically significant evidence of a decreasing trend at the specified level of significance.

Mann-Kendall Trend Test



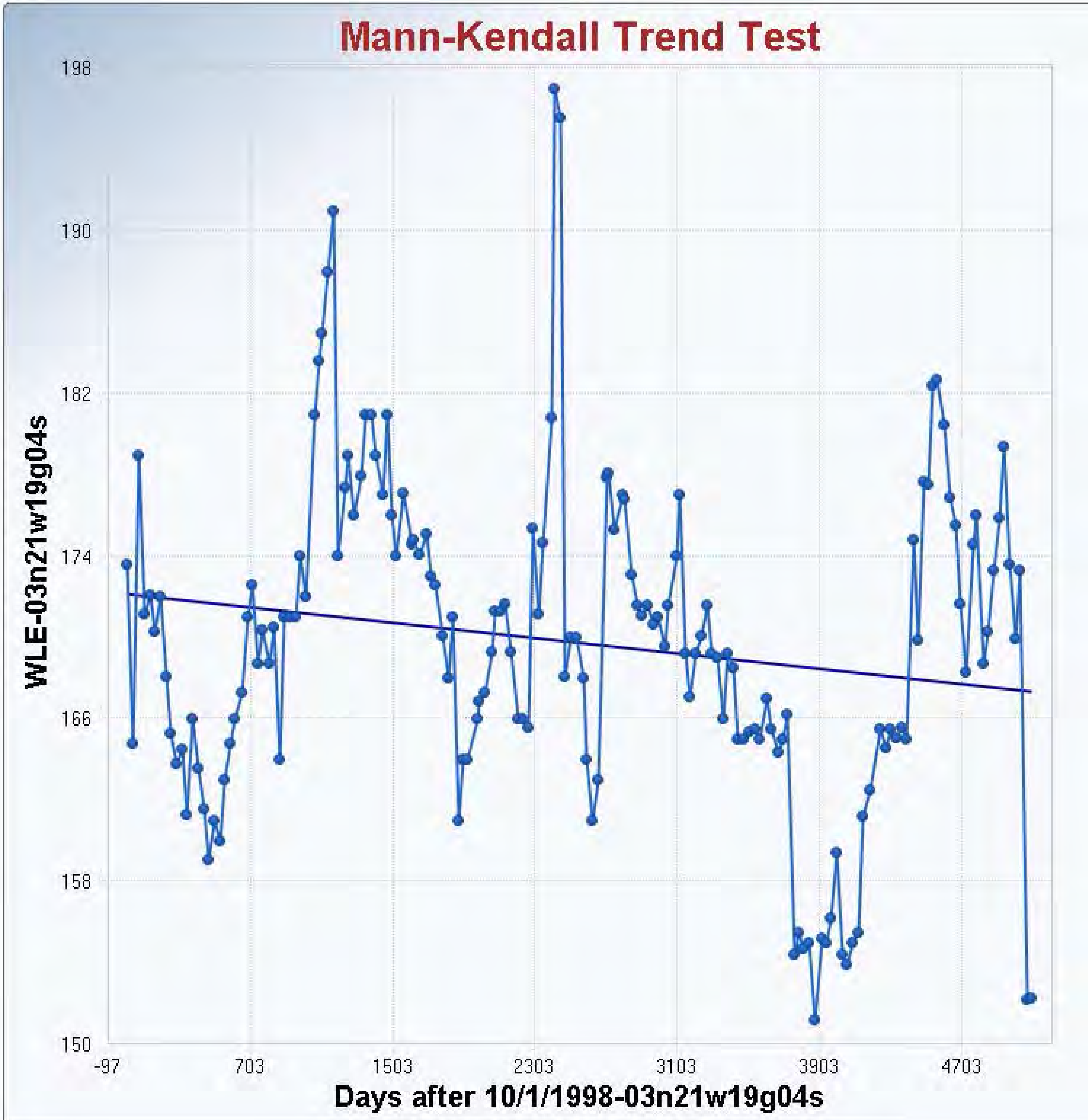
Mann-Kendall Trend Analysis

n	82
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	249.6324
Standardized Value of S	3.2688
Test Value (S)	817
Appx. Critical Value (0.05)	1.6449
Approximate p-value	0.0005

OLS Regression Line (Blue)

OLS Regression Slope	0.0053
OLS Regression Intercept	165.6338

Statistically significant evidence of an increasing trend at the specified level of significance.



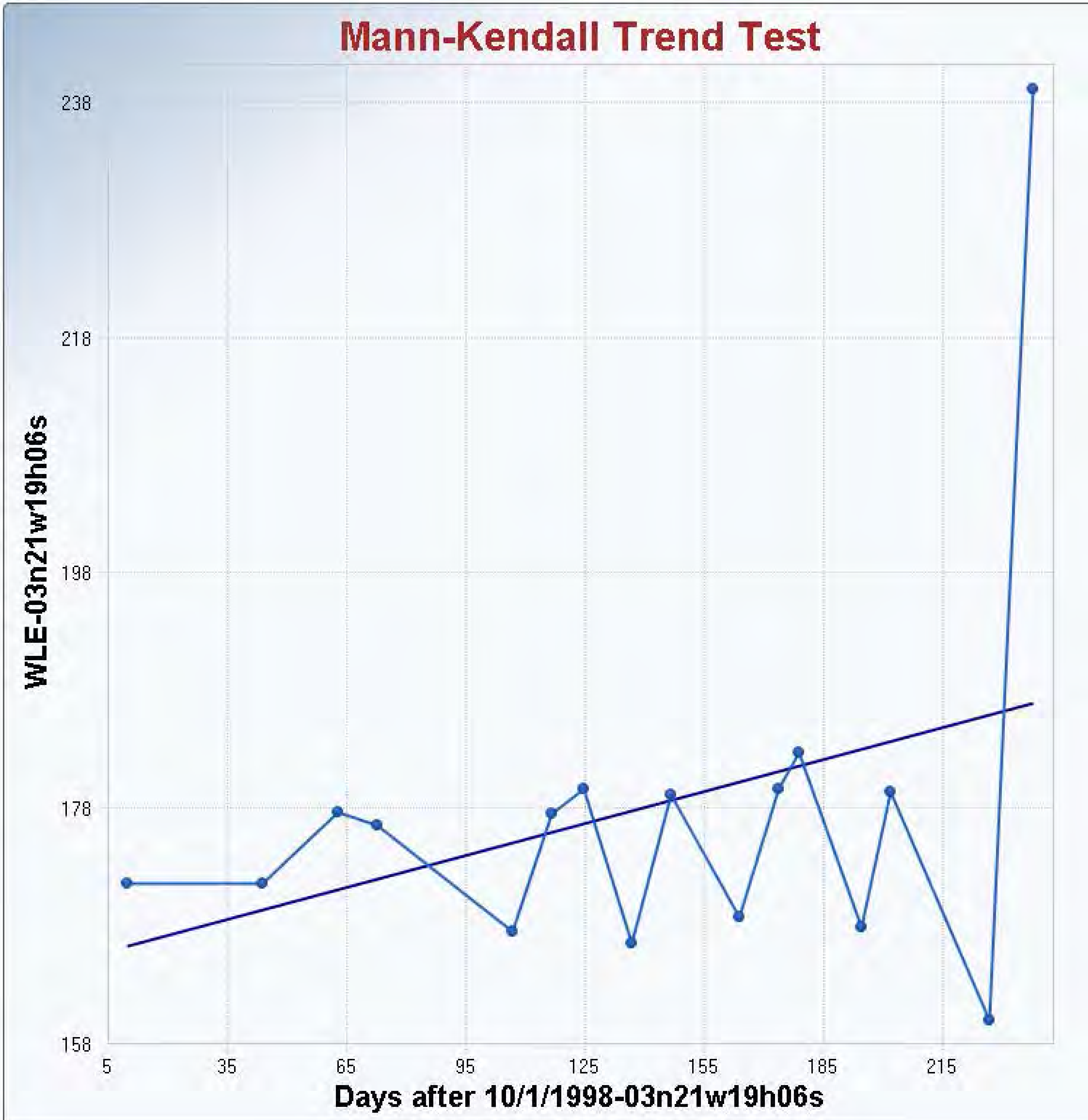
Mann-Kendall Trend Analysis

n	167
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	722.4488
Standardized Value of S	-1.9600
Test Value (S)	-1,417
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0250

OLS Regression Line (Blue)

OLS Regression Slope	-0.0009
OLS Regression Intercept	171.8014

Statistically significant evidence of a decreasing trend at the specified level of significance.



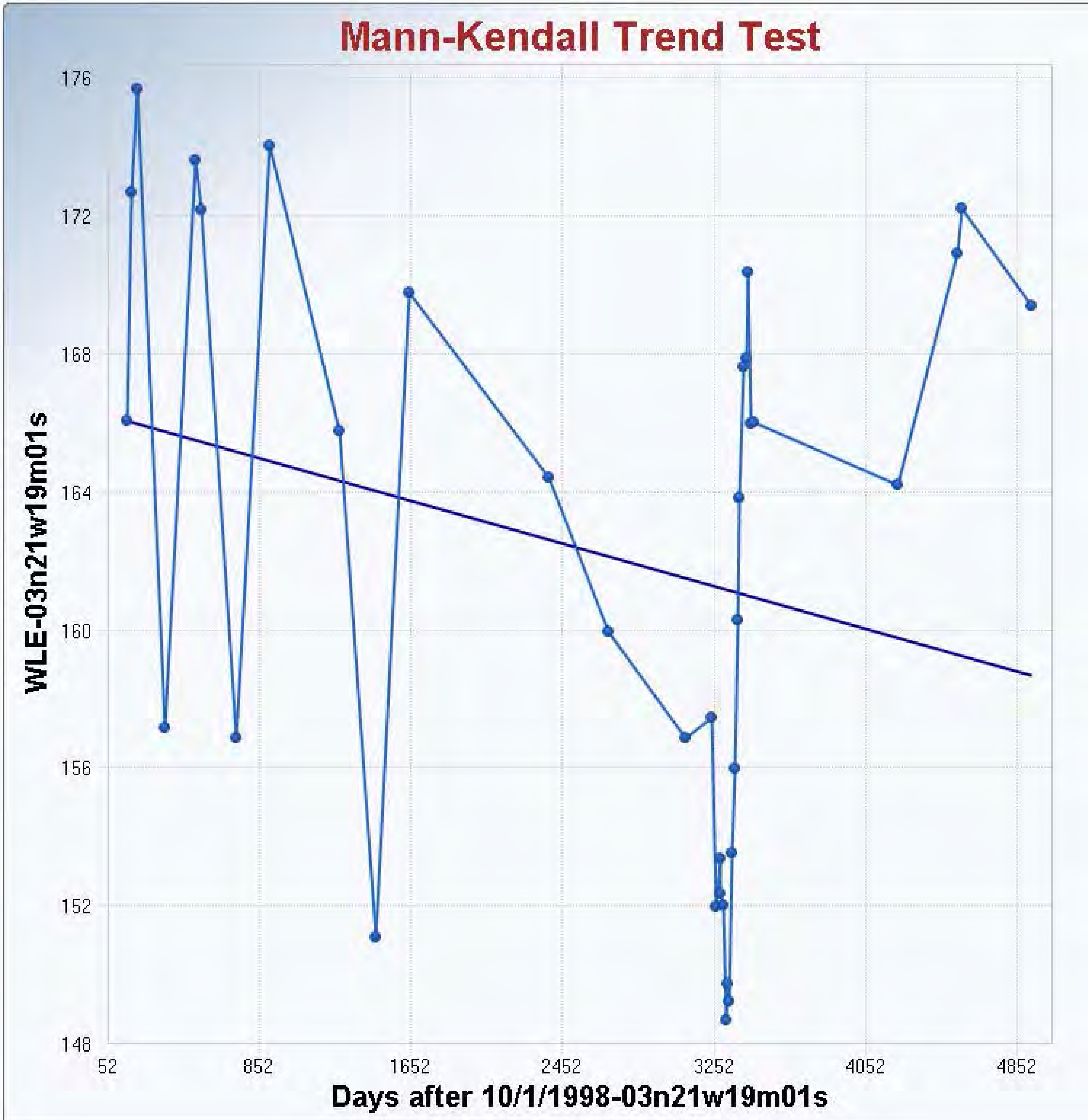
Mann-Kendall Trend Analysis

n	16
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	22.1886
Standardized Value of S	0.9915
Test Value (S)	23
Tabulated p-value	0.1750
Approximate p-value	0.1607

OLS Regression Line (Blue)

OLS Regression Slope	0.0901
OLS Regression Intercept	165.5847

Insufficient statistical evidence of a significant trend at the specified level of significance.



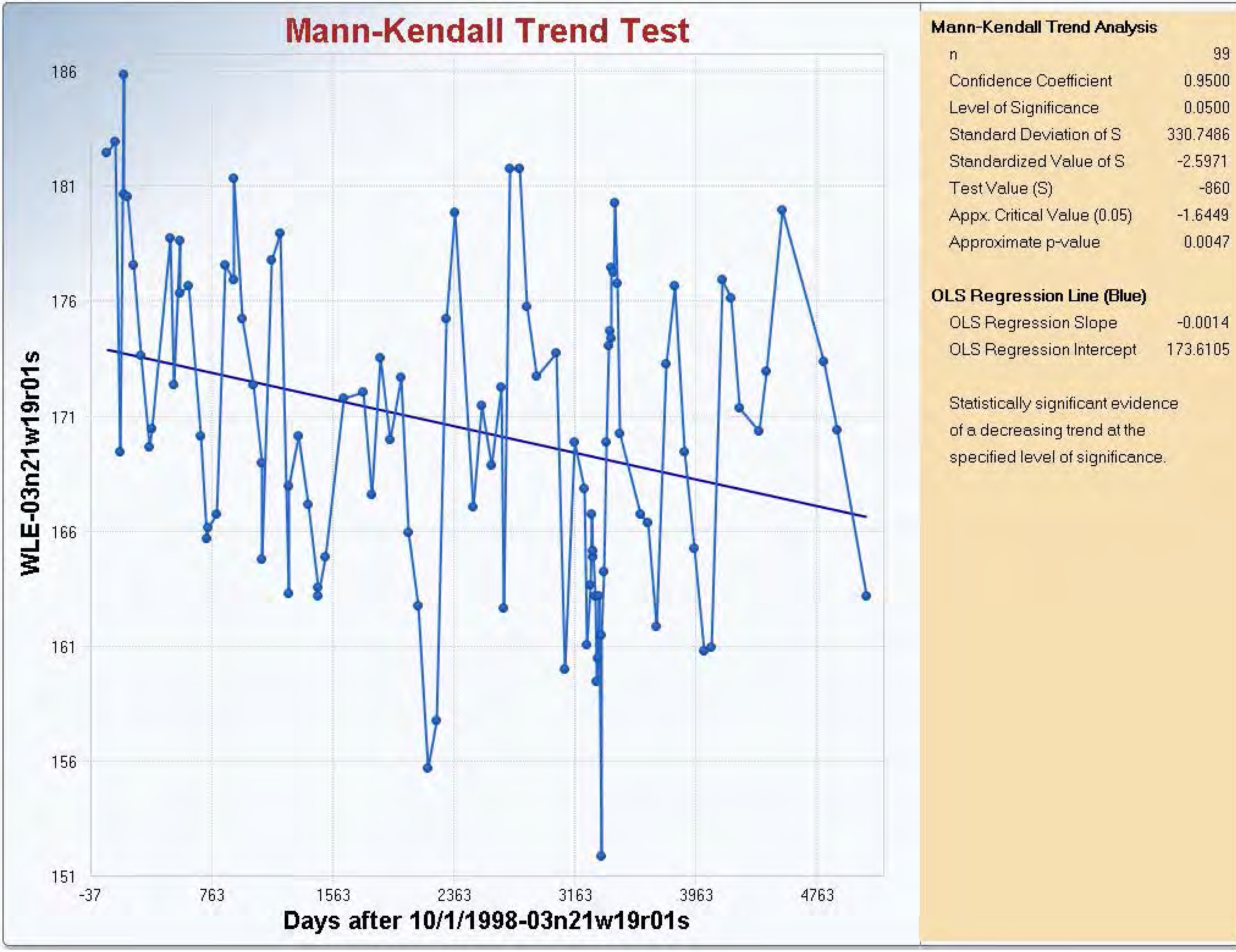
Mann-Kendall Trend Analysis

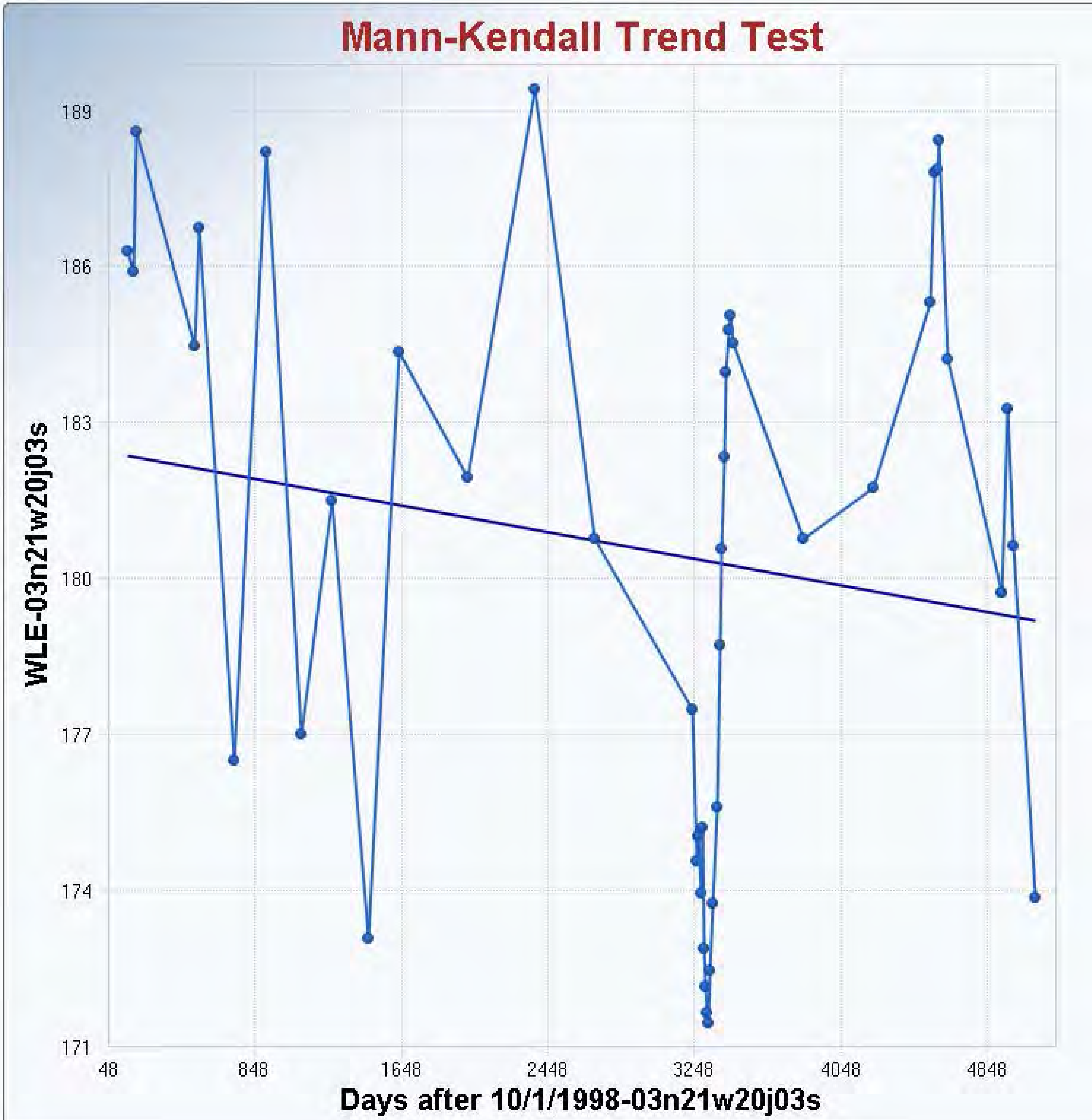
n	35
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	70.4154
Standardized Value of S	-0.1988
Test Value (S)	-15
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.4212

OLS Regression Line (Blue)

OLS Regression Slope	-0.0015
OLS Regression Intercept	165.8777

Insufficient statistical evidence of a significant trend at the specified level of significance.


Mann-Kendall Trend Test
186
181
176
171
166
161
156
151
-37
763
1563
2363
3163
3963
4763
WLE-03n21w19r01s
Days after 10/1/1998-03n21w19r01s
Mann-Kendall Trend Analysis
n 99
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 330.7486
Standardized Value of S -2.5971
Test Value (S) -860
Appx. Critical Value (0.05) -1.6449
Approximate p-value 0.0047
OLS Regression Line (Blue)
OLS Regression Slope -0.0014
OLS Regression Intercept 173.6105
Statistically significant evidence
of a decreasing trend at the
specified level of significance.



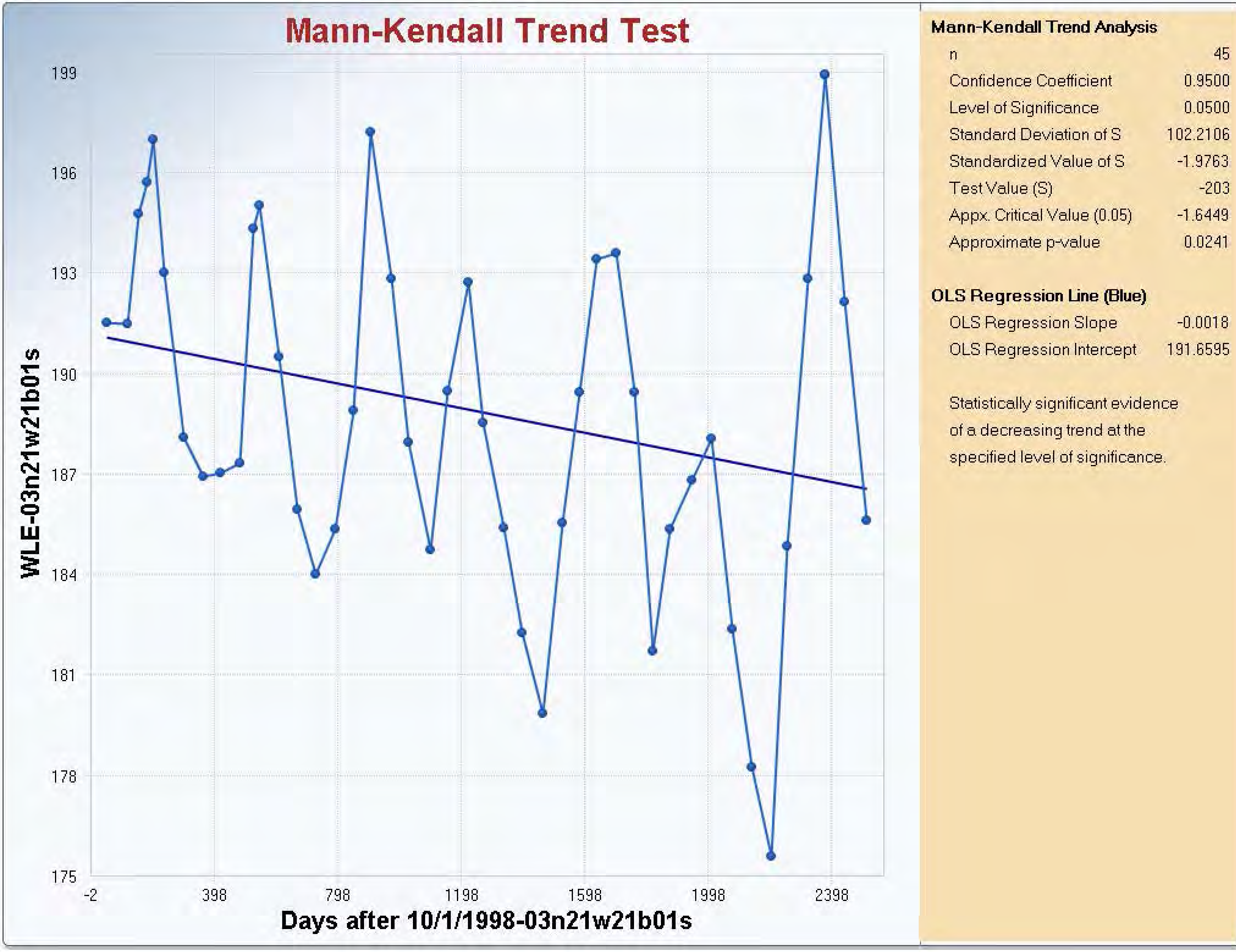
Mann-Kendall Trend Analysis

n	45
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	102.2204
Standardized Value of S	-0.0978
Test Value (S)	-11
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.4610

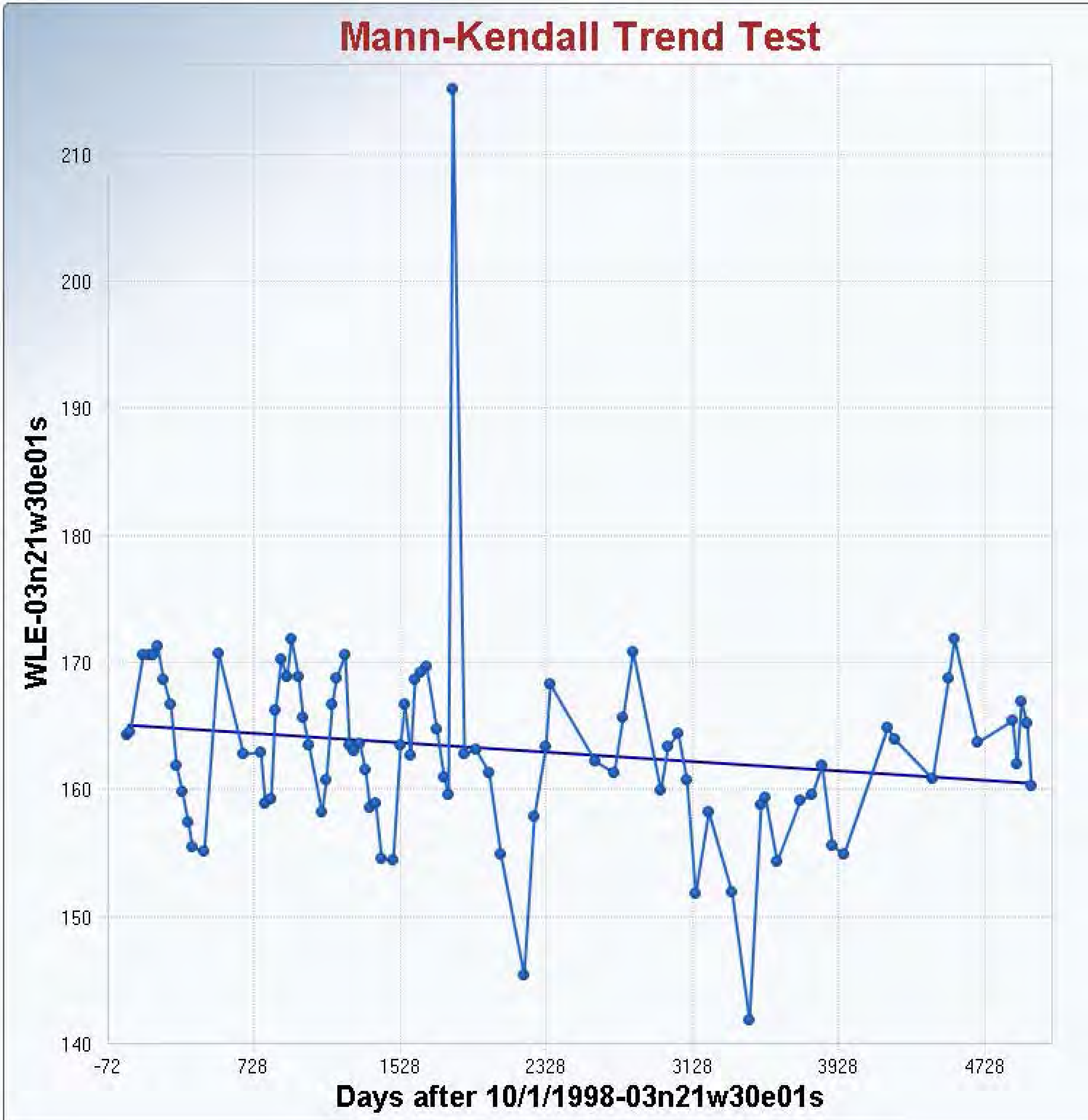
OLS Regression Line (Blue)

OLS Regression Slope	-0.0006
OLS Regression Intercept	182.6696

Insufficient statistical evidence of a significant trend at the specified level of significance.



Mann-Kendall Trend Test
199
196
193
190
187
184
181
178
175
-2
398
798
1198
1598
1998
2398
WLE-03n21w21b01s
Days after 10/1/1998-03n21w21b01s
Mann-Kendall Trend Analysis
n 45
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 102.2106
Standardized Value of S -1.9763
Test Value (S) -203
Appx. Critical Value (0.05) -1.6449
Approximate p-value 0.0241
OLS Regression Line (Blue)
OLS Regression Slope -0.0018
OLS Regression Intercept 191.6595
Statistically significant evidence
of a decreasing trend at the
specified level of significance.



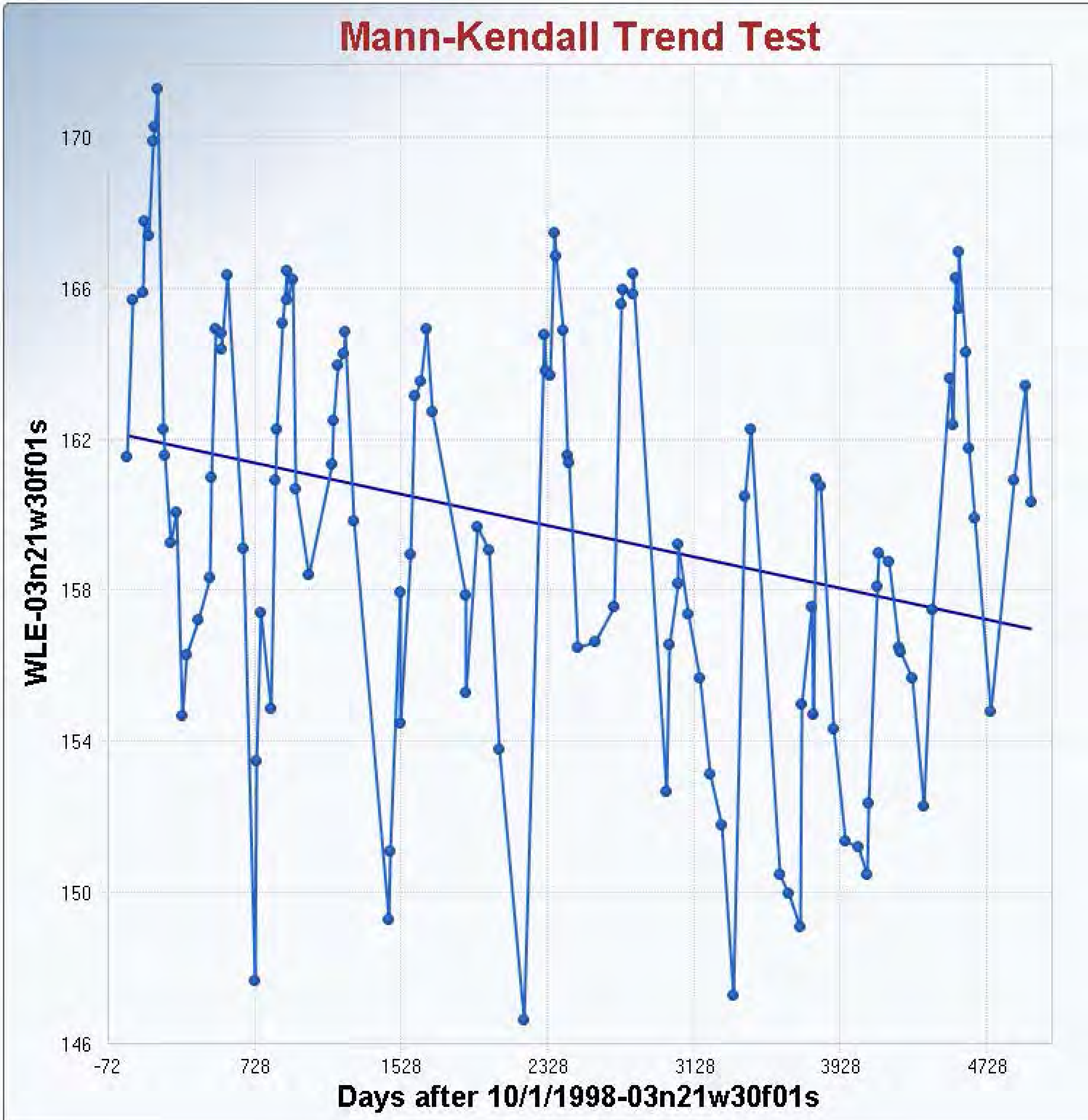
Mann-Kendall Trend Analysis

n	87
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	272.7587
Standardized Value of S	-2.2107
Test Value (S)	-604
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0135

OLS Regression Line (Blue)

OLS Regression Slope	-0.0009
OLS Regression Intercept	164.7761

Statistically significant evidence of a decreasing trend at the specified level of significance.



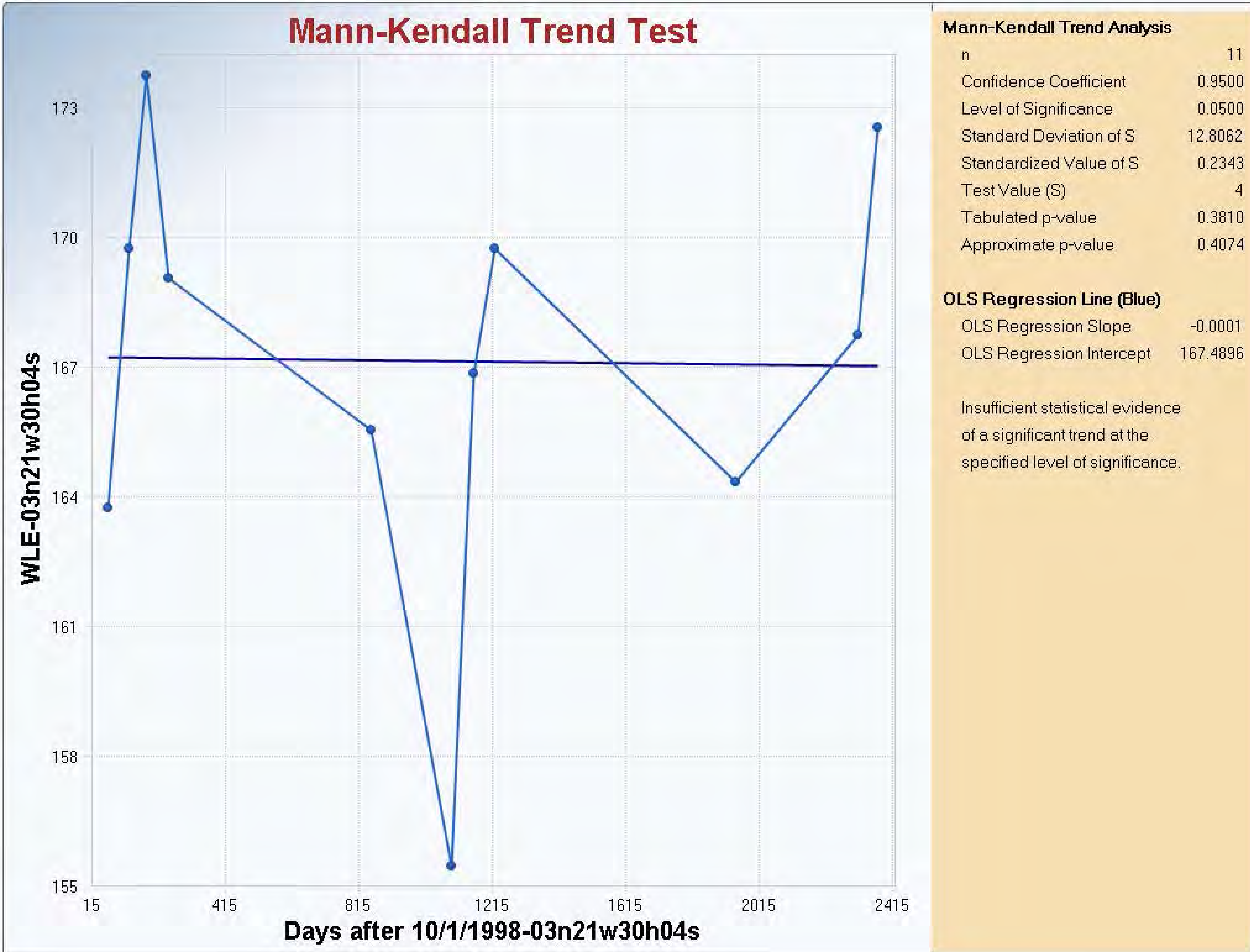
Mann-Kendall Trend Analysis

n	114
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	408.3422
Standardized Value of S	-3.0342
Test Value (S)	-1,240
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0012

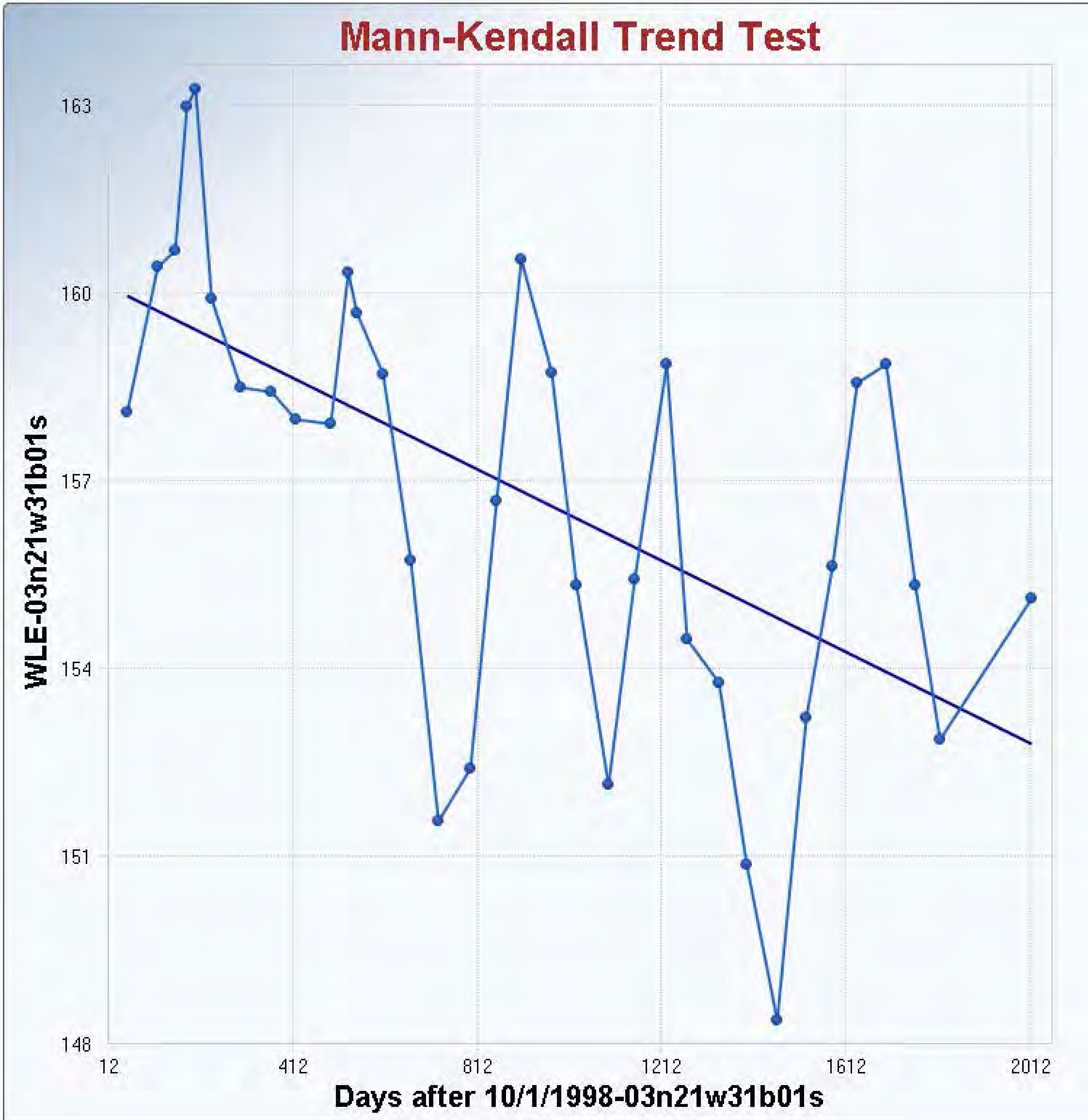
OLS Regression Line (Blue)

OLS Regression Slope	-0.0010
OLS Regression Intercept	161.8778

Statistically significant evidence of a decreasing trend at the specified level of significance.



Mann-Kendall Trend Test
173
170
167
164
161
158
155
15
415
815
1215
1615
2015
2415
WLE-03n21w30h04s
Days after 10/1/1998-03n21w30h04s
Mann-Kendall Trend Analysis
n 11
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 12.8062
Standardized Value of S 0.2343
Test Value (S) 4
Tabulated p-value 0.3810
Approximate p-value 0.4074
OLS Regression Line (Blue)
OLS Regression Slope -0.0001
OLS Regression Intercept 167.4896
Insufficient statistical evidence
of a significant trend at the
specified level of significance.



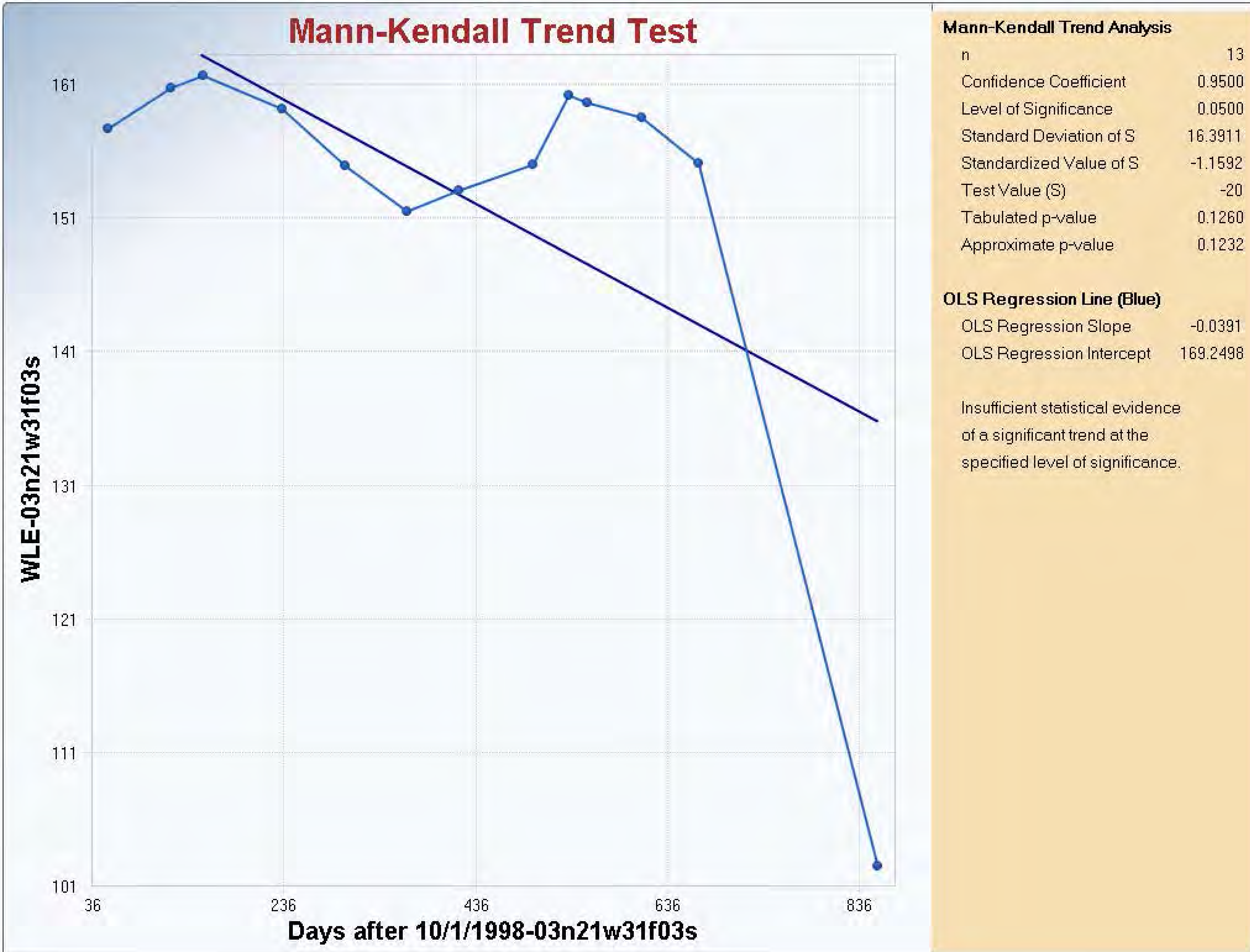
Mann-Kendall Trend Analysis

n	34
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	67.4487
Standardized Value of S	-3.5434
Test Value (S)	-240
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0002

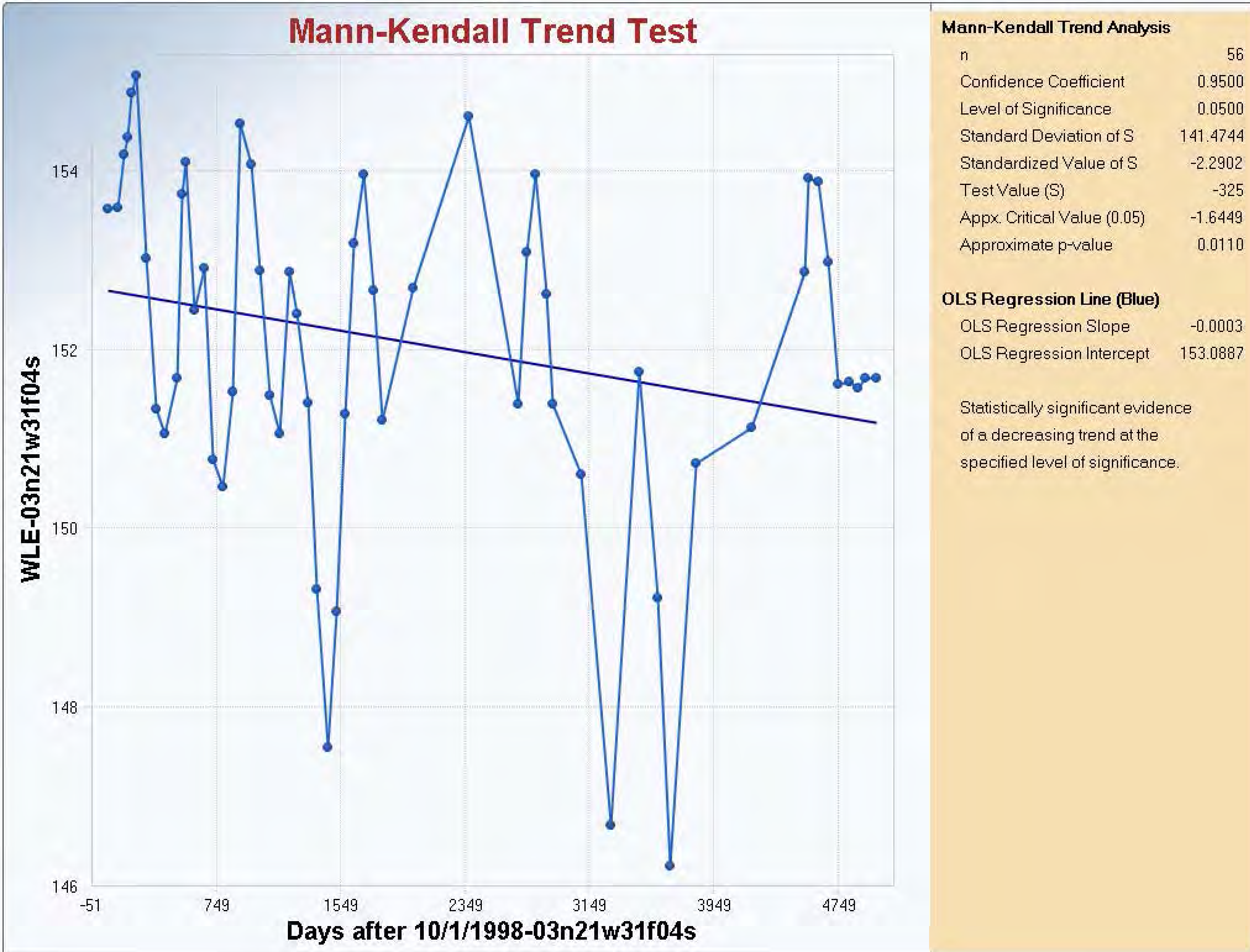
OLS Regression Line (Blue)

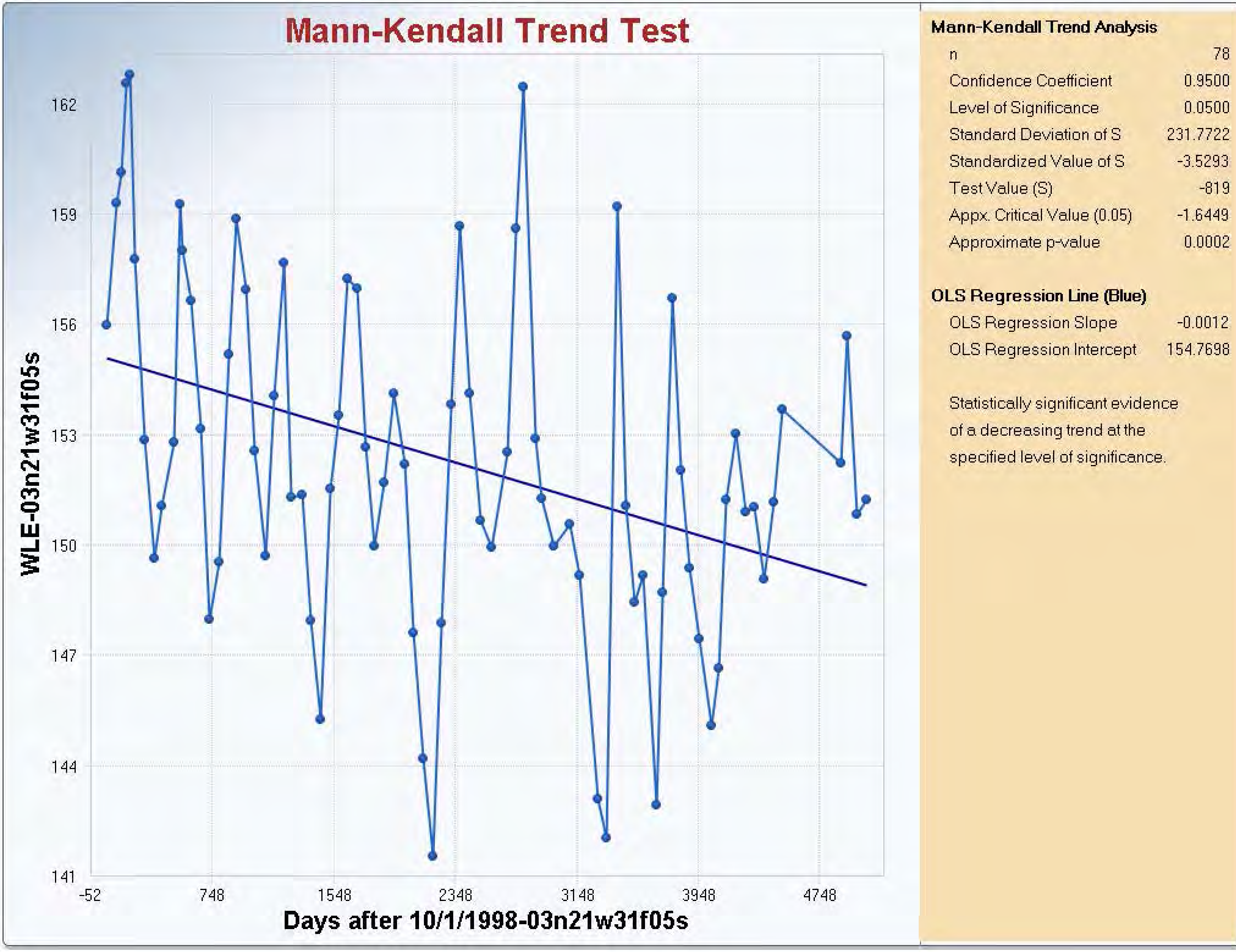
OLS Regression Slope	-0.0036
OLS Regression Intercept	160.1686

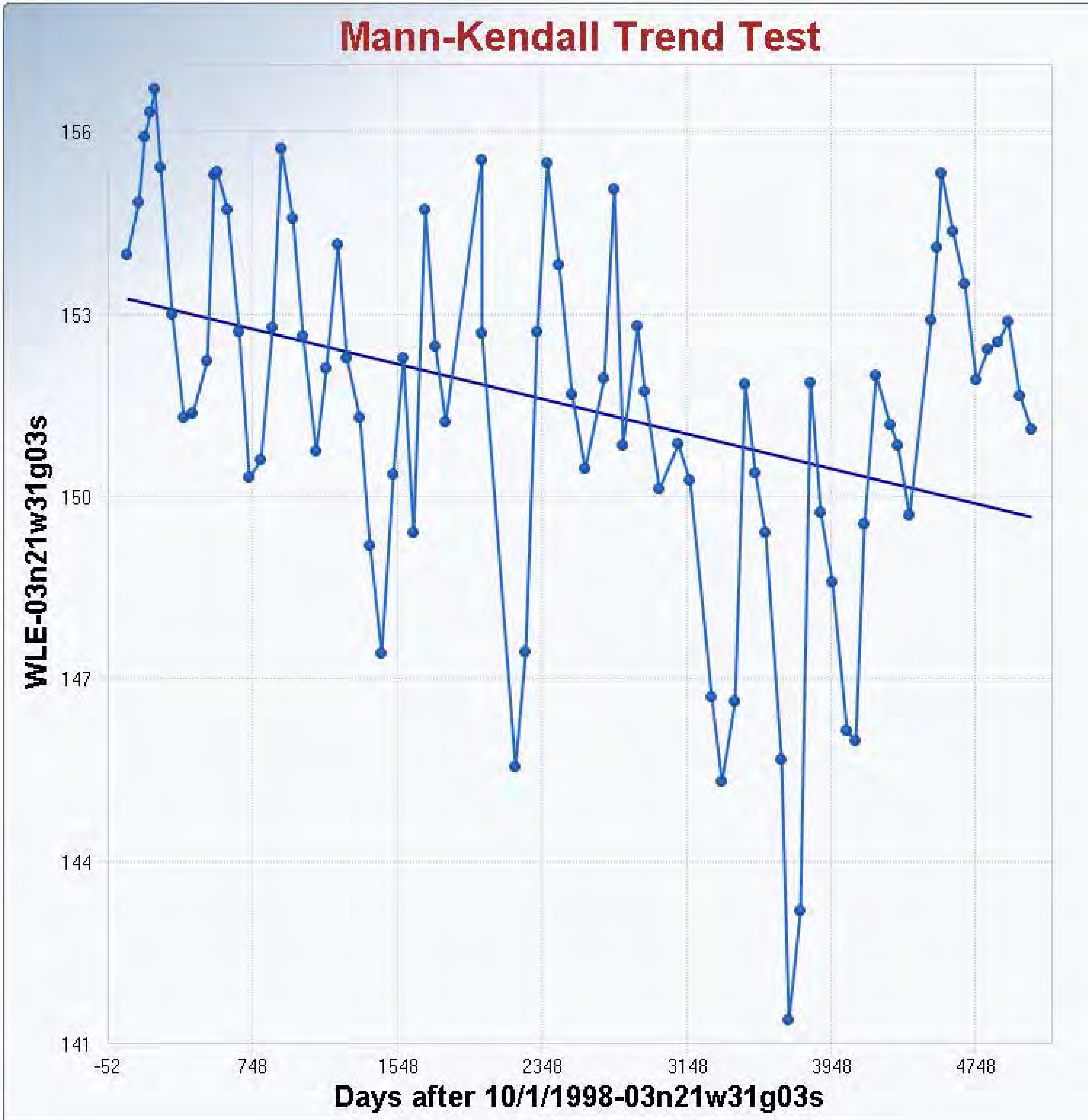
Statistically significant evidence of a decreasing trend at the specified level of significance.



Mann-Kendall Trend Test
WLE-03n21w31f03s
Days after 10/1/1998-03n21w31f03s
161
151
141
131
121
111
101
36
236
436
636
836
Mann-Kendall Trend Analysis
n 13
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 16.3911
Standardized Value of S -1.1592
Test Value (S) -20
Tabulated p-value 0.1260
Approximate p-value 0.1232
OLS Regression Line (Blue)
OLS Regression Slope -0.0391
OLS Regression Intercept 169.2498
Insufficient statistical evidence
of a significant trend at the
specified level of significance.


Mann-Kendall Trend Test
WLE-03n21w31f04s
154
152
150
148
146
-51
749
1549
2349
3149
3949
4749
Days after 10/1/1998-03n21w31f04s
Mann-Kendall Trend Analysis
n 56
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 141.4744
Standardized Value of S -2.2902
Test Value (S) -325
Appx. Critical Value (0.05) -1.6449
Approximate p-value 0.0110
OLS Regression Line (Blue)
OLS Regression Slope -0.0003
OLS Regression Intercept 153.0887
Statistically significant evidence
of a decreasing trend at the
specified level of significance.


Mann-Kendall Trend Test
WLE-03n21w31f05s
162
159
156
153
150
147
144
141
-52
748
1548
2348
3148
3948
4748
Days after 10/1/1998-03n21w31f05s
Mann-Kendall Trend Analysis
n 78
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 231.7722
Standardized Value of S -3.5293
Test Value (S) -819
Appx. Critical Value (0.05) -1.6449
Approximate p-value 0.0002
OLS Regression Line (Blue)
OLS Regression Slope -0.0012
OLS Regression Intercept 154.7698
Statistically significant evidence of a decreasing trend at the specified level of significance.



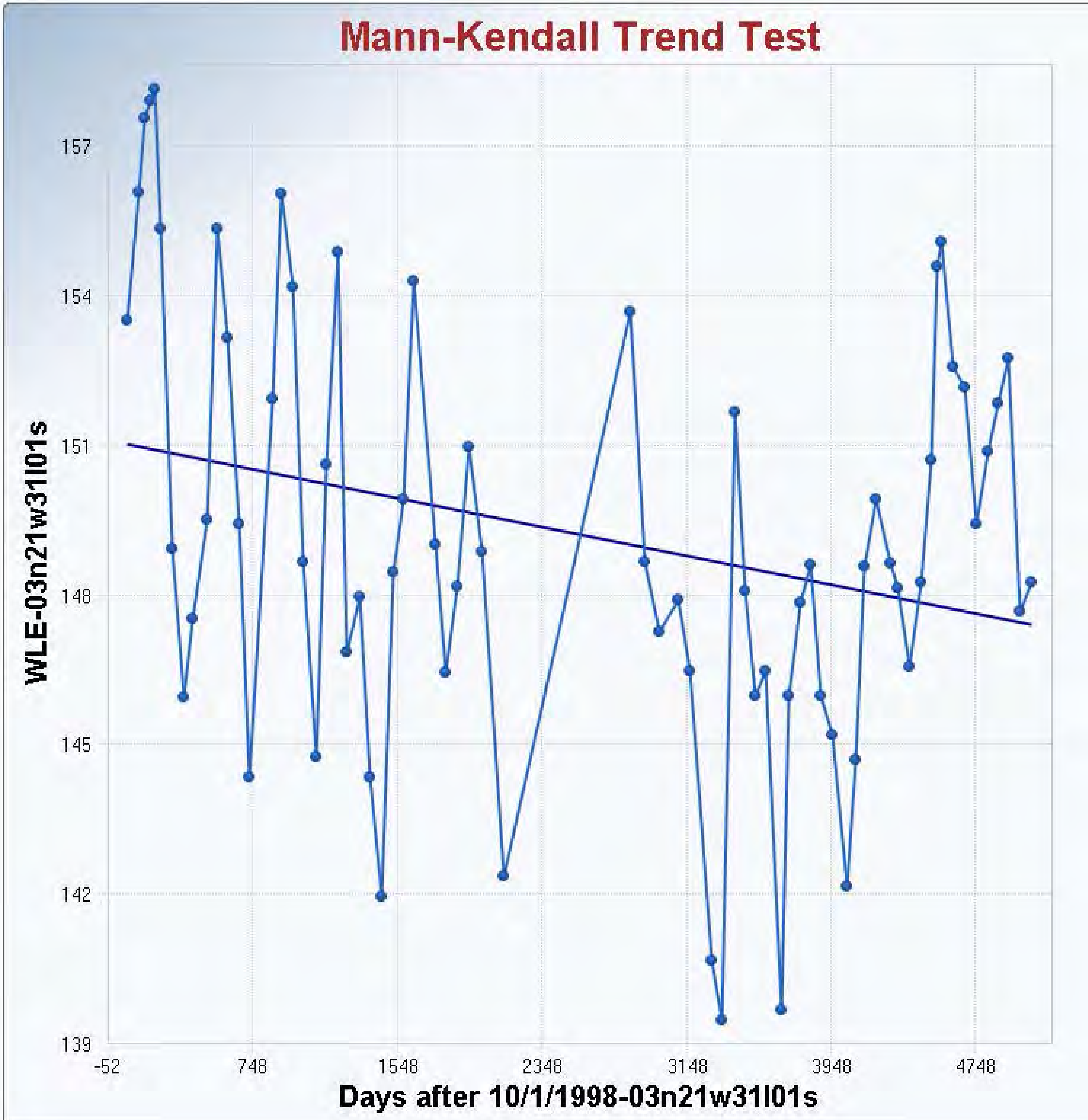
Mann-Kendall Trend Analysis

n	80
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	240.6872
Standardized Value of S	-3.2823
Test Value (S)	-791
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0005

OLS Regression Line (Blue)

OLS Regression Slope	-0.0007
OLS Regression Intercept	153.7790

Statistically significant evidence of a decreasing trend at the specified level of significance.



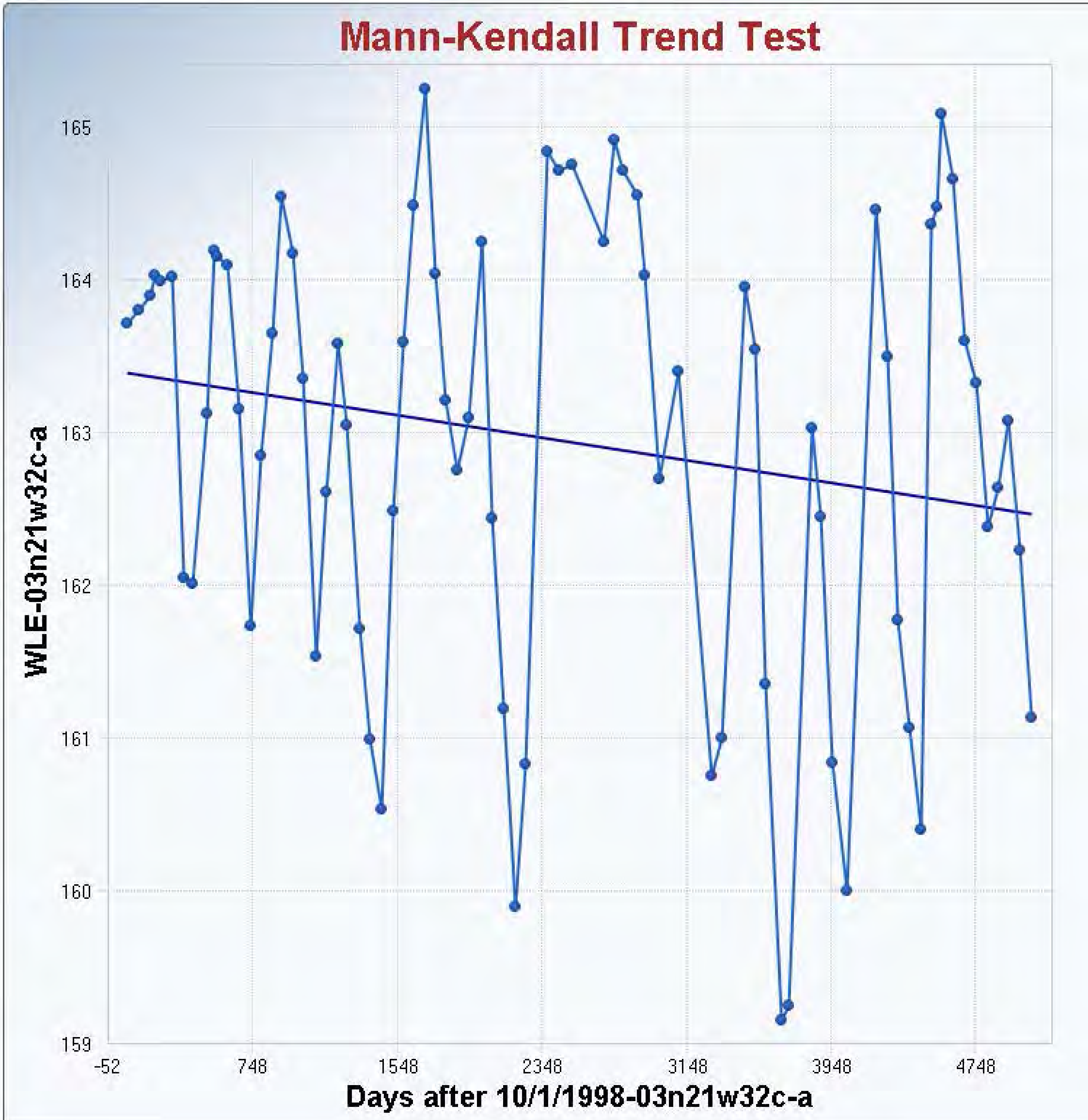
Mann-Kendall Trend Analysis

n	70
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	197.2376
Standardized Value of S	-1.8100
Test Value (S)	-358
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0351

OLS Regression Line (Blue)

OLS Regression Slope	-0.0007
OLS Regression Intercept	151.0504

Statistically significant evidence of a decreasing trend at the specified level of significance.



Mann-Kendall Trend Analysis

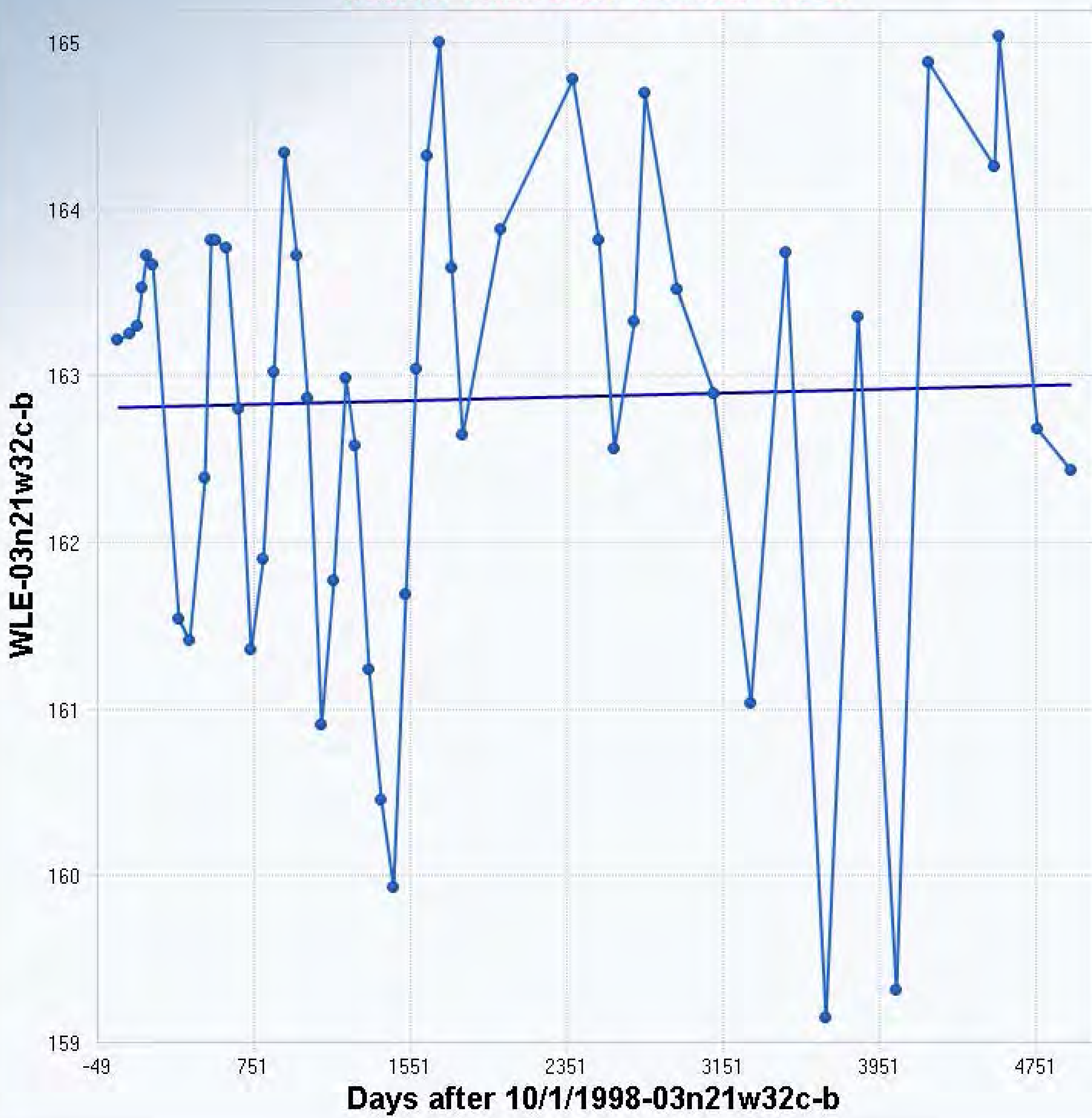
n	76
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	222.9656
Standardized Value of S	-1.3724
Test Value (S)	-307
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0850

OLS Regression Line (Blue)

OLS Regression Slope	-0.0002
OLS Regression Intercept	162.9625

Insufficient statistical evidence of a significant trend at the specified level of significance.

Mann-Kendall Trend Test



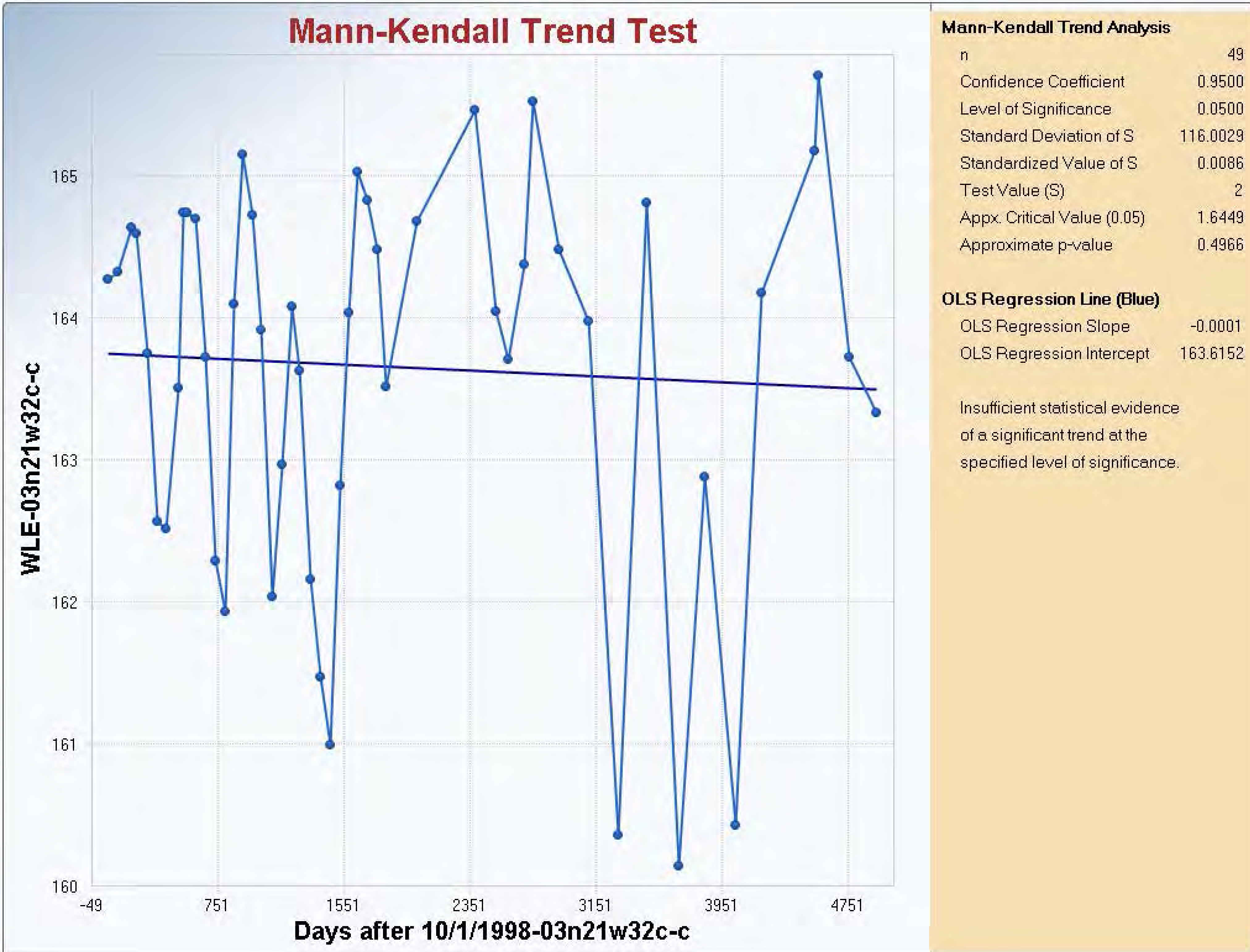
Mann-Kendall Trend Analysis

n	50
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	119.5282
Standardized Value of S	0.4852
Test Value (S)	59
Appx. Critical Value (0.05)	1.6449
Approximate p-value	0.3138

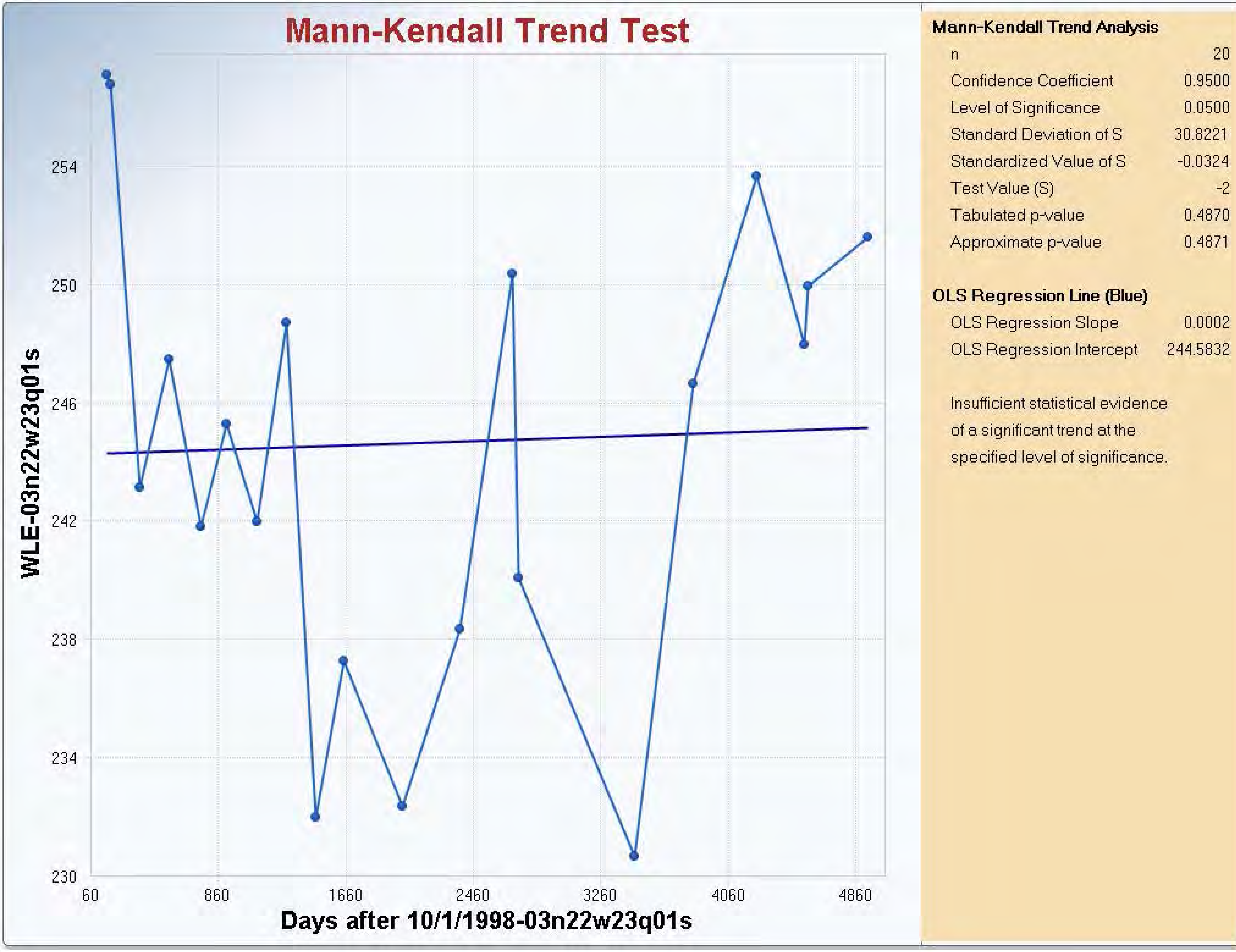
OLS Regression Line (Blue)

OLS Regression Slope	0.0000
OLS Regression Intercept	162.8785

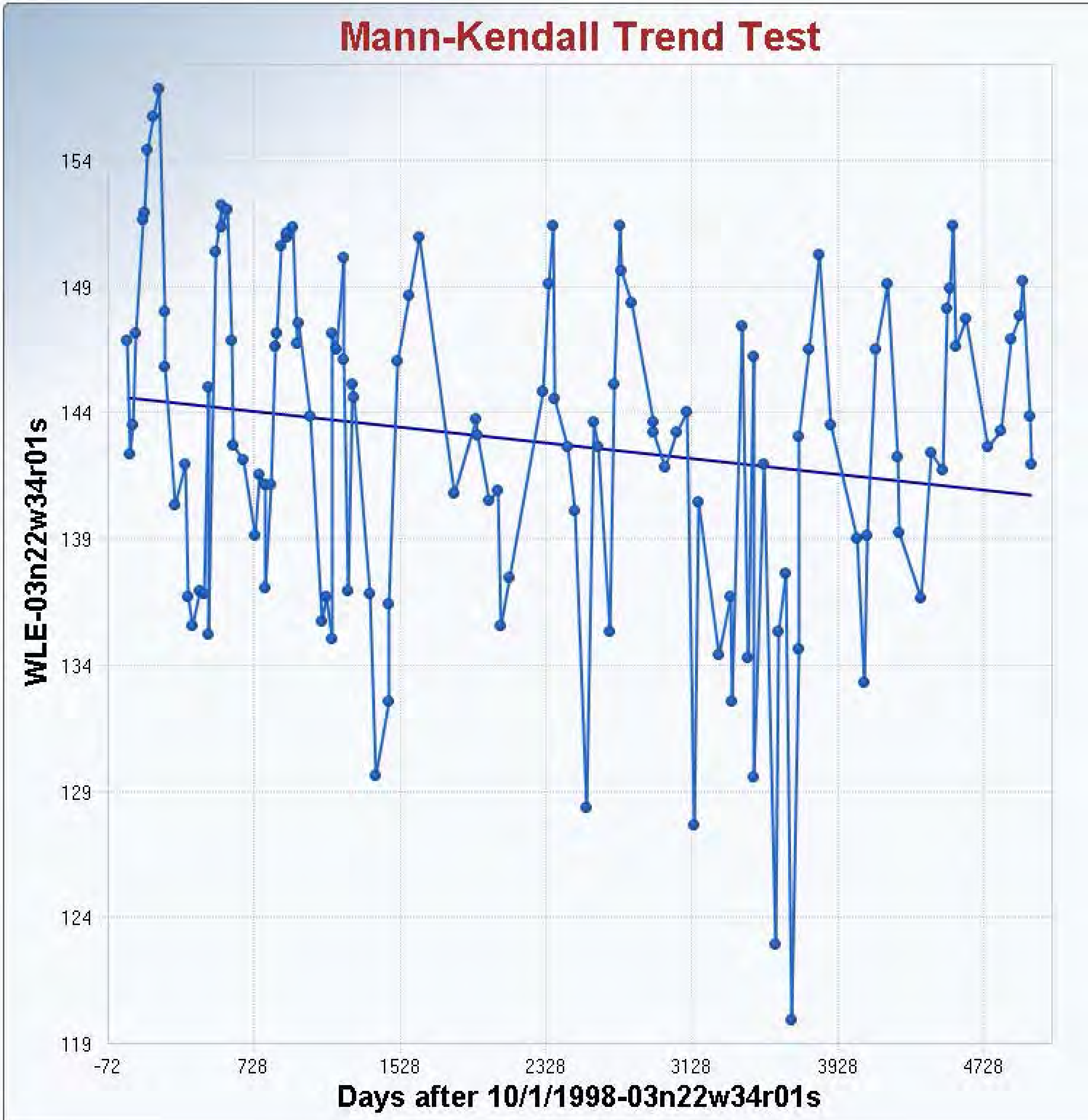
Insufficient statistical evidence of a significant trend at the specified level of significance.



Mann-Kendall Trend Test
WLE-03n21w32c-c
Days after 10/1/1998-03n21w32c-c
165
164
163
162
161
160
-49
751
1551
2351
3151
3951
4751
Mann-Kendall Trend Analysis
n 49
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 116.0029
Standardized Value of S 0.0086
Test Value (S) 2
Appx. Critical Value (0.05) 1.6449
Approximate p-value 0.4966
OLS Regression Line (Blue)
OLS Regression Slope -0.0001
OLS Regression Intercept 163.6152
Insufficient statistical evidence of a significant trend at the specified level of significance.



Mann-Kendall Trend Test
WLE-03n22w23q01s
254
250
246
242
238
234
230
60
860
1660
2460
3260
4060
4860
Days after 10/1/1998-03n22w23q01s
Mann-Kendall Trend Analysis
n 20
Confidence Coefficient 0.9500
Level of Significance 0.0500
Standard Deviation of S 30.8221
Standardized Value of S -0.0324
Test Value (S) -2
Tabulated p-value 0.4870
Approximate p-value 0.4871
OLS Regression Line (Blue)
OLS Regression Slope 0.0002
OLS Regression Intercept 244.5832
Insufficient statistical evidence of a significant trend at the specified level of significance.



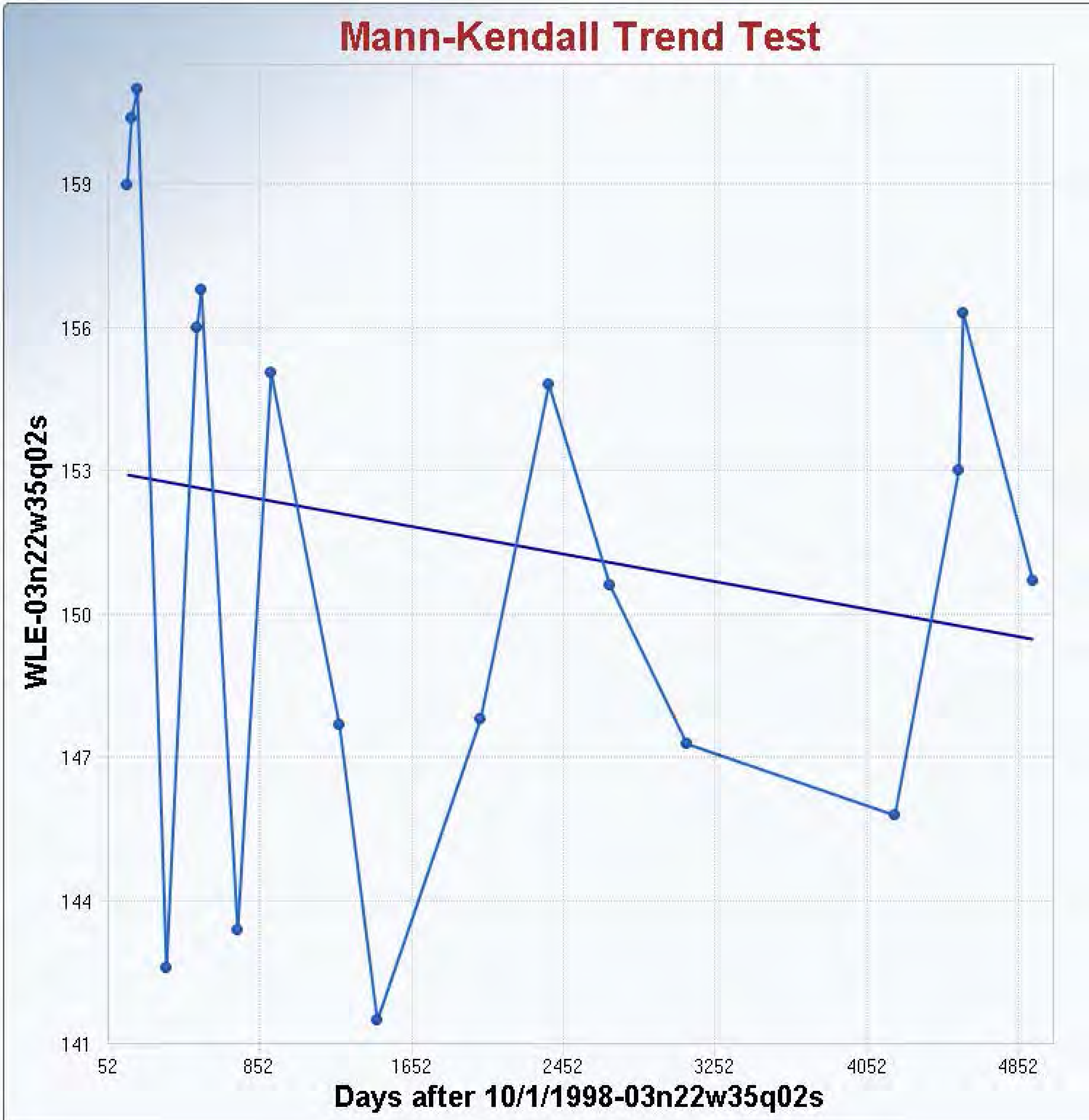
Mann-Kendall Trend Analysis

n	124
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	462.9669
Standardized Value of S	-1.9526
Test Value (S)	-905
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0254

OLS Regression Line (Blue)

OLS Regression Slope	-0.0008
OLS Regression Intercept	145.0942

Statistically significant evidence of a decreasing trend at the specified level of significance.



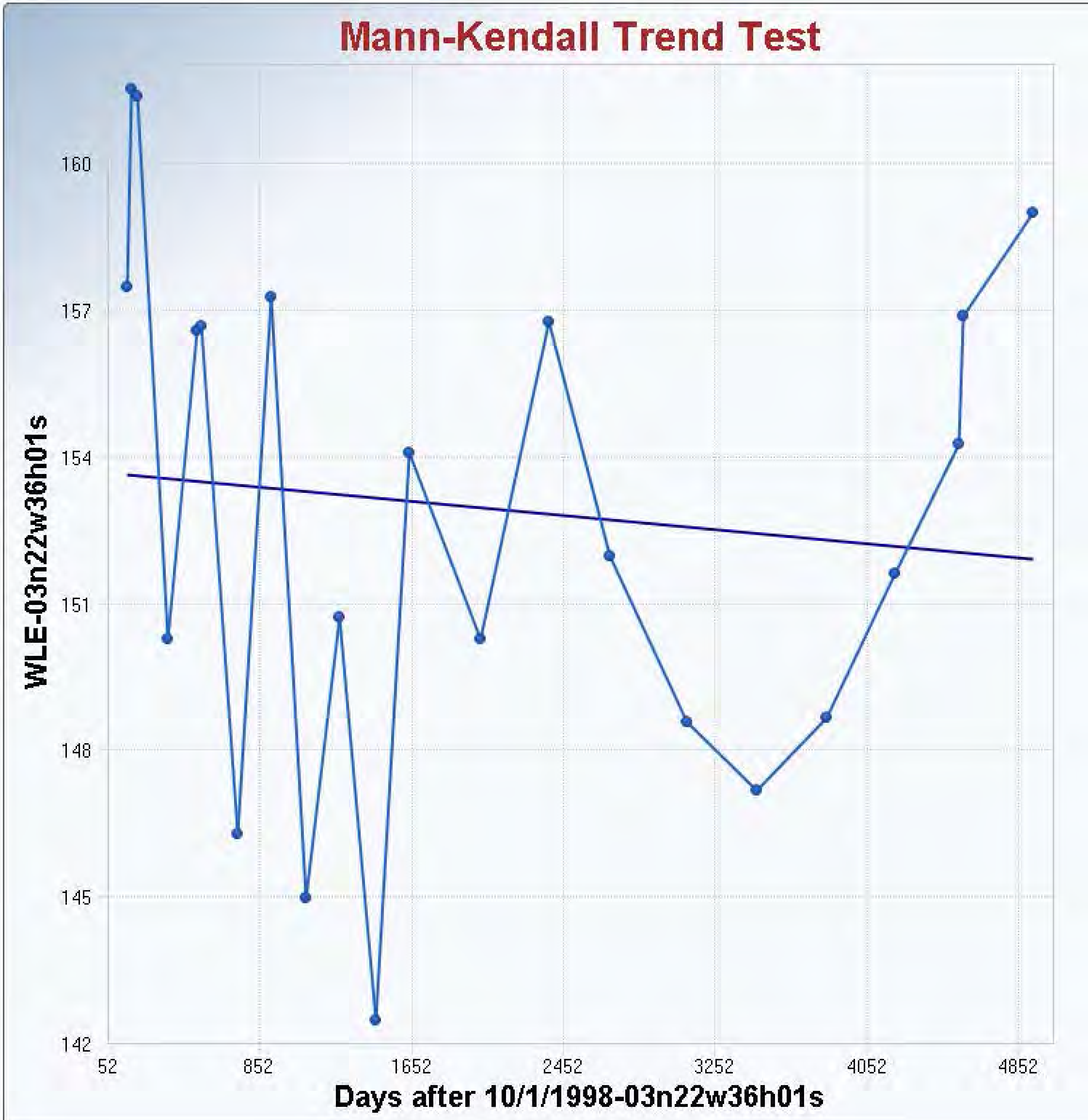
Mann-Kendall Trend Analysis

n	18
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	26.4008
Standardized Value of S	-1.2878
Test Value (S)	-35
Tabulated p-value	0.1000
Approximate p-value	0.0989

OLS Regression Line (Blue)

OLS Regression Slope	-0.0007
OLS Regression Intercept	153.3257

Insufficient statistical evidence of a significant trend at the specified level of significance.



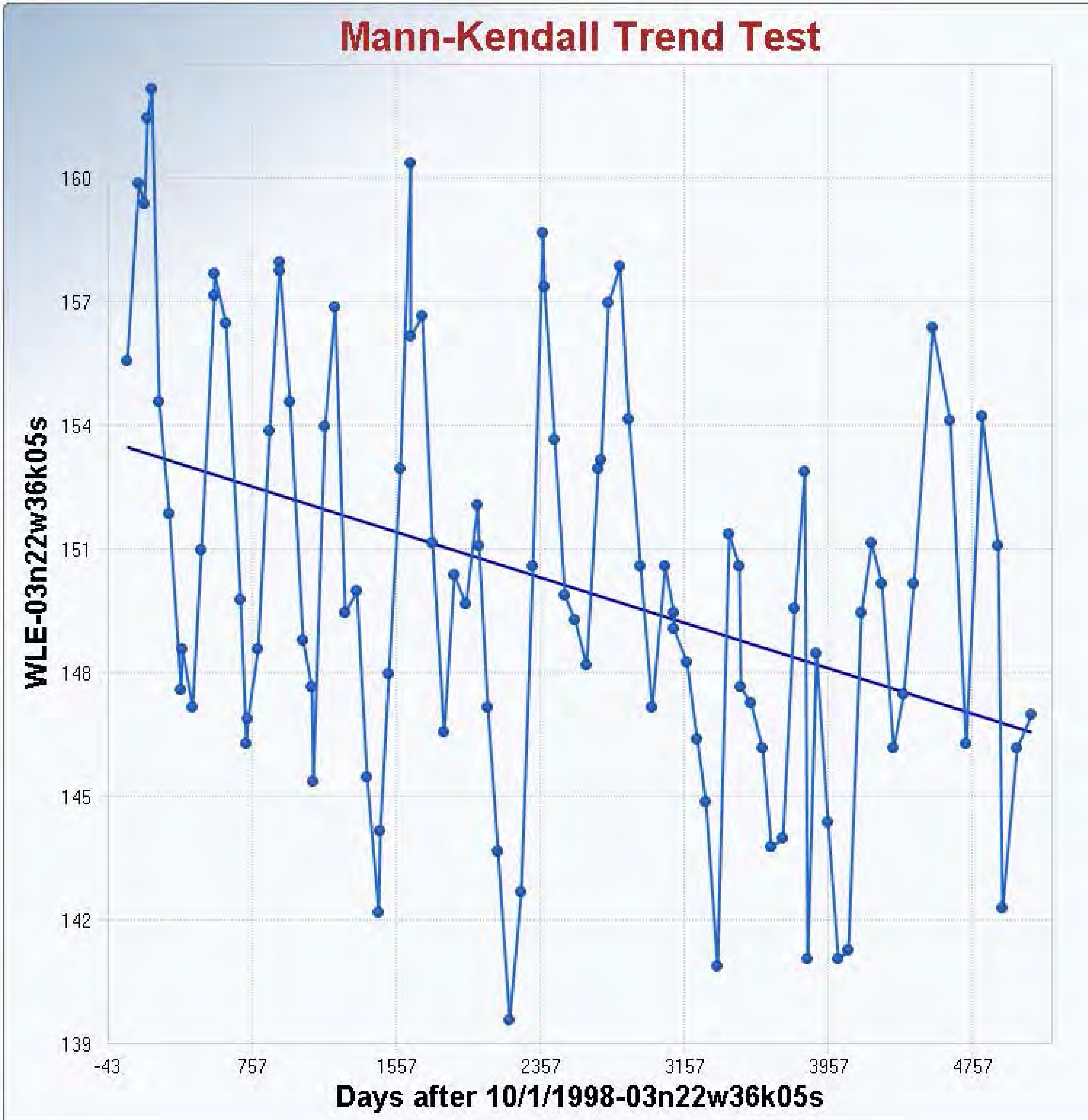
Mann-Kendall Trend Analysis

n	22
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	35.4495
Standardized Value of S	-0.7052
Test Value (S)	-26
Tabulated p-value	0.2340
Approximate p-value	0.2403

OLS Regression Line (Blue)

OLS Regression Slope	-0.0004
OLS Regression Intercept	154.0048

Insufficient statistical evidence of a significant trend at the specified level of significance.



Mann-Kendall Trend Analysis

n	96
Confidence Coefficient	0.9500
Level of Significance	0.0500
Standard Deviation of S	315.8887
Standardized Value of S	-3.6595
Test Value (S)	-1,157
Appx. Critical Value (0.05)	-1.6449
Approximate p-value	0.0001

OLS Regression Line (Blue)

OLS Regression Slope	-0.0014
OLS Regression Intercept	153.2891

Statistically significant evidence of a decreasing trend at the specified level of significance.

Appendix I

Response-to-Comments

Response to Comments on *Draft Santa Paula Basin Hydrogeologic Characterization and Safe Yield Study Ventura County, California*, dated October 19, 2016

Comments provided by Santa Paula Basin Pumpers Association (SPBPA), Inc., November 23, 2016

***General Comment #1**: The revised draft has tightened some of the language that we commented on previously (June 14, 2016). However, we still feel that the revised draft does not clearly articulate the approach which was ultimately relied upon to develop the estimate of safe yield. In particular, the estimate relied upon reported pumpage and the estimated change in storage, and this should be made clear. While the subject draft reflects a change to the Executive Summary in this regard, the change did not make it clear, so it remains misleading. Further, as noted in the SPBPA's previous comments, this should be made clear, not only in the Executive Summary, but also wherever it appears in the main body of the report, including tables.*

Response: The following text was previously added to the Executive Summary: "Therefore, safe yield of the Basin was estimated based on the sum of groundwater inflows minus natural groundwater outflow, which is also assumed equal to the sum of historical groundwater extraction and change in groundwater storage." Equation 5-2 in the body of the report clearly shows how the safe-yield calculation is related to extraction and change-in-storage, and this is further discussed in Section 5.3. Therefore, no further changes will be made based on this comment.

***General Comment #2:** We also believe that the range in the safe yield is not correctly presented. The range of storativity values used in the storage calculation is 0.01 to 0.2 (the latter implying the entire basin is unconfined) – both numbers represent values that are higher than many of those referenced in the report. A more-defensible range would include the lower numbers reported (perhaps as low as 10^{-3}) and a higher number that was short of a completely unconfined basin (e.g., something between 0.01 and 0.1).*

Response: As stated in our July 21, 2016 response to the SPBPA comment's on our earlier draft: "As discussed in Sections 4.5 and 5.3, and displayed in Figure 16, a sensitivity analysis of groundwater-elevation rate of change (0.18 to 0.32 ft/yr) and storativity (0.01 to 0.2) indicates a narrow range of safe yield (24,000 to 25,500 ac-ft/yr). Considering an even smaller Basin-wide average storativity value of 0.001 would make essentially no difference in the final calculated range, with the maximum safe yield value still equaling 25,500 ac-ft/yr after adjusting results to three significant digits (see Figure 16). Based on this sensitivity analysis, it was determined that further effort to characterize storativity in a more detailed matter would not materially change the conclusions of the safe yield study. Furthermore, available storativity data for the Basin has been compiled in the report (see Appendix D). As noted in Section 3.6.2, the storativity data that do exist also include inherent error due to the length of the aquifer testing (an insufficiently-long aquifer test may yield a storativity value that suggests confined conditions, whereas extending the test may have revealed unconfined conditions)."

In response to this comment, the following sentence will be added to the end of Section 5.3: "Considering an even smaller Basin-wide average storativity value of 0.001 would make essentially no difference in the final calculated range, with the maximum safe yield value still equaling approximately 25,500 ac-ft/yr."

***General Comment #3:** We recommend calculating the actual storage change for only the unconfined part of the groundwater basin. This can be done using the Confining Bed Evaluation performed as part of the overall yield analysis. Water level data can then be used in calculating storage change in only the groundwater that is unconfined.*

Response: As shown on Figure 16 and discussed in Sections 4.5 and 5.3, considering a range of change in water levels and storativity has a minor impact on the overall analysis. Furthermore, there remains uncertainty regarding portions of the Basin that are confined or unconfined. For example, as stated in Section 3.3 of our report: “The general extent of confining materials observed on E-logs is generally in agreement with the KDSA (2015) findings, although the lateral continuity of the confining layers as illustrated in the KDSA (2015) report is subject to some uncertainty as it is based primarily on subjective interpretations in drillers’ logs. No changes will be made based on this comment.

***General Comment #4:** It is important that the change in storage could be as low as near-zero, resulting in current pumping being within safe yield. It is then up to the TAC to decide whether to manage the basin to the lower or higher of the yield calculations.*

Response: Comment noted; no changes will be made based on this comment.

***General Comment #5:** There continues to be a problem with significant figures and not correctly rounding off. For example, the hydraulic conductivity values on page ES-4 were presented to the nearest 1 foot per day. Another example on page ES-5 is water budget values to the nearest 10 acre-feet by year. These are highly misleading in terms of the accuracy of the estimates. In this regard, Ventura’s November 18, 2016 comments include the suggestion that a qualifying statement or disclaimer be added to the Executive Summary. This would be acceptable if use of the disclaimer is extended to the narrative and tables that follow in the main body of the report.*

Response: The report will be edited as suggested.

***General Comment #6:** Wherever "standard methods" are referred to in the report, the source should be identified.*

Response: The report will be edited to add references as suggested (e.g., Fetter, 2001).

***Specific Comment #1:** Section 2.6, Santa Paula Basin Groundwater Elevation Trend Assessment (page 9). The UWCD 2013 evaluation was discussed, but other factors besides pumpage, such as reservoir releases (from the Curtis Hopkins report) that could cause water level declines weren't mentioned. Other factors should be acknowledged.*

Response: This section is intended as brief summary of the earlier UWCD (2013) report; the reader can refer to the earlier study for additional detail. No changes will be made based on this comment.

***Specific Comment #2:** Section 2.9, Ventura County Watershed Protection District Groundwater Section Annual Reports, 2008 to 2013 (page 11). The number of wells sampled by VCWPD in the basin should be provided, along with the specific constituents that were determined. This would help the reader put the results in perspective.*

Response: This section is intended as brief summary of the earlier VCWPD reports; the reader can refer to the earlier reports for additional detail. No changes will be made based on this comment.

Specific Comment #3: *Section 3.1, Electric Log Correlations (page 14). It is suggested that the locations and the cross sections themselves be presented in the text of the report, not just in an appendix.*

Response: As stated in our July 21, 2016 response-to-comments, we consider materials in the Appendices to be readily available to the reader. No changes will be made based on this comment.

Specific Comment #4: *Section 3.3, Low-Permeability Units (page 18). The depths to the top of the electric logs should be provided. For example, many logs from the DOG&GR start hundreds of feet deep or deeper. Also, calling a low-permeability layer a "lens" is not technically correct, as this infers that they are not laterally continuous.*

Response: The range of top depth of the e-logs will be added, as requested. The term “lens” in this sentence will be replaced with “layer.”

Specific Comment #5: *Section 3.6, Aquifer Transmissivity, Hydraulic Conductivity, and Storativity (page 24). Specific yields should be determined only for the unconfined groundwater based on textural descriptions. This should provide a more correct estimate of storage change.*

Response: All available storativity values obtained from Basin aquifer tests and other sources are of general interest. However, as shown on Figure 16 and discussed in Sections 4.5 and 5.3, considering a range of change storativity has a minor impact on the overall analysis. No changes will be made based on this comment.

Specific Comment #6a: *Section 3.6.2, Supply Well Aquifer Test Reports (pages 27-30). Transmissivities were discussed based on results of pump tests for a number of wells. At the end of the discussion, the conversion factors between specific capacity and transmissivity should be discussed. For example, factors for Santa Paula Wells No. 13 and 14 are within the expected range of 1,500 and 2,000. However, the factors for Saticoy Wells No. 2 and 3 are much greater than expected (by 2 to 3 times). The purpose of the exercise was to compare the conversion factors determined from pump tests in the basin to more general values developed elsewhere. Then, a more applicable range in conversion factors could be used (for example in the Saticoy area).*

Response: We reiterate our response to the same SPBPA comment on an earlier draft of the report stated in our July 21, 2016 response-to-comments: “Conversion factors used in this study are based on standard hydrogeologic practices used in the industry and reported in industry-standard reference materials [for example see Driscoll, 1986]. Calculation of Basin-specific conversion factors would add uncertainty to the study because of the relative scarcity of aquifer-test results. Basin specific factors, if calculated, could rely only on aquifer tests for five of the tests shown on Table D-1 in which the transmissivity values were calculated from water level data and curve-fitting solutions; as stated in the text and on Table D-1, some of the transmissivity values reported for the aquifer tests were also derived using the standard conversion factors.” No changes will be made based on this comment.

Specific Comment #6b: *On page 28, the very high transmissivity values which result from the use of “late time” drawdown data are not considered meaningful because a positive boundary was encountered.*

Response: We note that there is some uncertainty regarding if a positive boundary was encountered during this aquifer test. However, to be conservative the late-time data from this well test was not used in calculations of hydraulic conductivity used in inflow estimate (see Appendix D Table D-2). No changes will be made based on this comment.

Specific Comment #6c: *For the FICO Well No. 12 test, specific capacities were not provided.*

Response: Specific capacities were not provided in all cases; for FICO Well No. 12 the aquifer-test derived transmissivity values calculated by others were used as they were available for this well. No changes will be made based on this comment.

Specific Comment #7: *The cited maps (particularly 1, 2, and 3) should be provided in the text, not just in an appendix.*

Response: As stated in our July 21, 2016 response-to-comments, we consider materials in the Appendices to be readily available to the reader. No changes will be made based on this comment.

Specific Comment #8: *Section 3.9, Vertical Gradient Evaluation (page 36). The method of determining vertical gradients should be provided. For example, was the water-level difference divided by the thickness of the confining bed? Conventional USGS units for expressing vertical gradients are "feet per 100 feet".*

Response: Methods used for vertical gradient calculations are clearly shown in Appendix D, Table D-8a and Table D-8b. We use the standard units for hydraulic gradient of ft/ft (or unitless). A quick search of several USGS reports reveals various units are used for vertical hydraulic gradient. No changes will be made based on this comment.

Specific Comment #9: *Section 4, Groundwater Balance (page 38+). The Santa Clara River should be divided into a losing segment and a gaining segment for specific years, and both river seepage and discharge to the groundwater calculated separately. The terminology "non-extraction related outflow" should be better defined.*

Response: Groundwater interaction with the Santa Clara River is discussed in detail in Section 3.5. In response to this comment, the following clarifying text will be added to Section 4: "There is uncertainty regarding the net effect of groundwater interaction with surface water in the Santa Clara River over time, and throughout its reach within the Basin, as discussed in Section 3.5. However, the limited available data suggest that groundwater discharging to the Santa Clara River in the west part of the basin may be the dominant interchange between surface water and groundwater. Therefore, the Santa Clara River is generally considered to receive groundwater discharge and not be a net source of groundwater recharge (Section 3.5) and net groundwater discharge to the Santa Clara River is grouped within the natural groundwater outflow term."

The term 'non-extraction related outflow' will be rephrased as "all groundwater outflow from the Basin besides extraction from production wells."

Specific Comment #10: *Section 4.1, Hydrologic Base Period (page 39). Trends in streamflow should also be examined, not just precipitation.*

Response: GEI Consultants submitted a letter on August 13, 2015 that generally agreed with our selection of a base period and stated that it appears to be "reflective of the long-term record of rainfall at Santa Paula and streamflow for Santa Paula Creek." No changes will be made based on this comment.

Specific Comment #11: *Section 4.2, Groundwater Inflow from Fillmore Basin (page 41). How were the specific capacity data converted to hydraulic conductivities? How were the transmissivity values from aquifer tests converted to hydraulic conductivity?*

Response: Methods are listed in Appendix D and Section 3. No changes will be made based on this comment.

Specific Comment #12: *Section 4.2.1, Comparison to Santa Paula Basin Pumper's Association Inflow Estimate (page 44). After discussing the variable flow estimates, some type of conclusion should be reached.*

Response: As explained in Section 4.2.1, this section is intended to compare the values calculated for underflow and explain the reason behind the differences. In response to this comment, Section 4.2.1 will be edited to state: "Groundwater inflow from the Fillmore Basin into the Santa Paula Basin was estimated by Bachman (2015) on behalf of the Santa Paula Basin Pumper's Association. Bachman presents an average underflow value of 19,700 ac-ft/yr, using Equation 4-2, compared to an average of 25,200 ac-ft/yr used for this study. Below is a discussion of how the Bachman assumptions differ from those used for this study for each of the three variables in the equation. Differences are primarily due to Bachman's application of a lower hydraulic conductivity of 30 ft/d for the San Pedro Formation (with reference to KDSA, 2015, which does not include the 30 ft/d value or specific discussion of hydraulic conductivity) compared to the value of 118 ft/d applied by RCS, and Bachman's assumption that hydraulic gradients in the San Pedro Formation can be assumed to be the same as gradients in the undifferentiated alluvium. Because RCS applied a hydraulic conductivity for the San Pedro Formation based on cited observed test results (Section 3, Appendix D), and independently calculated vertical hydraulic gradients for the San Pedro Formation, the RCS value is considered to be more consistent with available data and is used in the groundwater balance.

Specific Comment #13: *Section 4.3.3, DPWM Domain and Input Parameters (page 49). Is it also necessary to know the unsaturated hydraulic conductivity? Also, last paragraph, second line, the word "vertical" should be placed before "saturated".*

Response: DWPM uses the field capacity method to distribute water vertically between nodes based on the saturated soil hydraulic conductivity (see Appendix G). The word vertical will be inserted, as requested.

Specific Comment #14: *Section 4.3.4, Areas Contributing Deep Percolation of Precipitation (page 50). Were hardpan layers considered, particularly in the upland areas? Also, the discussion in the first full paragraph implies that one can determine the lateral extent of sub-surface confining beds by mapping only the surficial geology. There may be discharge from the Santa Clara River at the western end of the basin, but the referenced section 4.7.1 does not discuss the recharge at the eastern end of the basin, which has been characterized as the largest recharge source to the basin in some past studies.*

Response: Hydraulic conductivity of bedrock and soil units were determined based on available data, as discussed in the report (see Tables G-2, G-3). Hydraulic conductivity values are considered to be representative of vertical averages that consider low-permeability layers based on underlying data availability of the cited sources. Reference to Figure 6 does not imply that the lateral continuity of confining units can be determined based on a surficial geologic map; rather, the map displays surficial geologic units and the Basin boundaries. As stated, recharge to Tertiary-aged bedrock units is not considered to be recharge to the Basin. In response to this comment, the reference to Section 4.7.1 will be revised to reference Section 4.0 (see response to Specific Comment #9, above). Although there may be losing reaches of the river, it is assumed to be a net gaining reach for the purpose of the groundwater balance.

Specific Comment #15: *Section 4.5, Groundwater Storage (page 57). The water-level change evaluated to determine groundwater storage change should be based only on wells tapping the unconfined groundwater. The analysis should separate the groundwater into unconfined and confined, with the change in storage evaluation based on the unconfined groundwater.*

Response: See response to General Comment #3, above. No changes will be made based on this comment.

Specific Comment #16: *Section 4.7, Natural Groundwater Outflow (page 61+). The word "natural" is not really correct, because the outflow depends on hydraulic gradients, which are affected by man-made factors (like pumpage).*

Response: Comment noted; however, terminology was adopted from the standard text “Applied Hydrogeology” by Fetter (2001) and will be retained. No changes will be made based on this comment.

Specific Comment #17: *Section 4.7.2, Estimated Natural Groundwater Outflow (page 65). More explanation needs to be provided with regard to the groundwater outflow value. The outflow value could be off by thousands of acre-feet per year. We recommend that a reference to future investigations of downstream basins may help to inform the estimated outflow.*

Response: Reference to future investigations will be added, as requested.

Specific Comment #18: *Section 5.1, Safe Yield Methodology (page 69). In DBS&A’s response to SPBPA’s General Comment #2, it is suggested that the 2003 Study assumed that the change in water levels was relatively small, which is not the case. Rather, measured water levels were compiled and reviewed. There are other factors besides pumpage (such as stream channel lowering) that contributed to the water-level declines, and these should be acknowledged.*

Response: Comment noted; however Section 5.1 specifies that the that water level measurements for 14 wells with adequate data indicated an average decline of 4.9 feet over the base period for the 2003 study, and the study is additionally summarized and directly quoted regarding this topic in Section 2.3. No changes will be made based on this comment.

Specific Comment #19: *Section 5.3 Safe Yield Determination (page 73 and Figure 16). This illustration was apparently intended to help explain the development of the range in recommended safe yield of 24,000 to 25,000 acre-feet per year. The 24,000 value is near the intersection of the 25th percentile water-level decline and a storage coefficient of 0.2; however, this was not explained. On the other hand, the 25,500 value appears to be based on an almost totally confined aquifer, but this was not clearly stated. Accordingly, more explanation is suggested.*

Response: Additional clarifying text will be added to Section 5.3, as requested.

Comments provided by Ventura Water, November 17, 2016

Comment 1. *The City understands that it was requested by SPBPA that numbers be rounded, "so as not to imply more accuracy than is appropriate." Initially, the City did not oppose such rounding. However, upon reviewing the Revised Draft Study, the City is concerned about the impact of the rounding. For example, on page ES-5, in the first sentence, the rounding changes the difference between inflows and outflows by 4 7 ac-f/yr (difference between 53 ac-f/yr. and the rounded 100 ac-f/yr.). Another example, rounding of the safe yield value on page 74 (i.e., decreasing it by 52 ac-f/yr.). The City requests that, instead of rounding, the following sentence be added to the end of the last paragraph on page ES-4 to address SPBPA's concerns: "Although numbers are reported to the nearest acre-foot per year, the authors are not asserting that level of accuracy in the findings of this Study." If this change is made, then the added sentences at the bottom of pages 38 and 73 are unnecessary. Otherwise, the rounding methodology needs to be consistent throughout the Study. For example, on page 67, the first paragraph, rounding methodology is inconsistent between the modified numbers. On that same page, in the third paragraph, the rounding has a dramatic impact on the difference between the base and small storage decline cases.*

Response: The report will be edited as suggested.

Comment 2: *On page ES-1, the paragraph in quotations, fifth line down, the word "basin" should be capitalized.*

Response: The report will be edited as suggested.

Comment 3. *On page ES-1, the City requests the last paragraph be modified to read in full as follows: The goal of this Safe Yield Study was to estimate safe yield of the Basin with available information and analytical methods conventionally used to estimate safe yield in the absence of a comprehensive, numerical groundwater flow model. In initiating this Safe Yield Study, the TAC recognized that certain limitations would be associated with this level of study, but that it could be part of informed Basin management prior to completion of a comprehensive, numerical groundwater flow model. In parallel with planning and execution of the Safe Yield Study, the SPBPA initiated a study to identify opportunities and develop programs for enhancing the operating safe yield of the Basin and improving Basin conditions (Practical Measures/Yield Enhancement Options Study). Together, the Safe Yield Study and Practical Measures/Yield Enhancement Options Study are expected to further the ability of the TAC to guide basin management efforts that will help in "meeting the reasonable water supply needs of the parties, including protection for historic users, without harm to the Basin" as stated in the Judgment.*

Response: This “Foreword” text was provided by UWCD and therefore we understand that UWCD will provide response to this comment.

Comment 4: *The page numbering for the Foreword should be "v" and "vi", rather than part of the Executive Summary (i.e., "ES-1" and "ES-2").*

Response: The report will be edited as suggested.

Comment 5: *On page ES-3, the City does not think the new language in the second paragraph should be included because this Study does not thoroughly discuss overdraft or surplus.*

Response: The report will be edited as suggested.

Comment 6: *On page ES-5, the City requests the second paragraph be modified to read in full as follows: Study limitations are discussed in Section 4.9, and specific DPWM limiting assumptions are discussed in Section 4.3.2. Of particular note, uncertainties in the Study are due to data limitations and* *necessary assumptions inherent to Basin-scale hydrologic analyses where a comprehensive, numerical groundwater flow model is unavailable, and are typical of similar studies in arid and semi-arid environments. Data gaps and limitations include the relatively short base period (fourteen years), limited gage data for Santa Paula Creek and the Santa Clara River, lack of Basin-specific storativity values representative of the unconfined or semiconfined undifferentiated alluvium, and the generally poorly understood conditions that govern outflow to the Mound and Oxnard Forebay Basins. In addition, the DPWM incorporates simplifying assumptions necessary for Basin-scale watershed modeling, including the assumption of constant annual irrigation rates and land use over time during the base period, and homogenous properties (e.g., vegetation, soil type) within each 295-ft x 295-ft model grid cell. These limitations can be addressed in future Basin studies.*

Response: The executive summary has already been edited to clarify and list the primary sources of uncertainty in our analysis. We do not agree that the City's suggested edits provide additional clarity or value to the report. We note that even those hydrologic analyses that make use of a numerical model can be subject to similar limitations and assumptions if there are significant data gaps. No changes will be made to the report based on this comment.

***Comment 7**: The City has concerns with the added sentence asserting a 6 percent level of accuracy, and requests it be removed in the Executive Summary.*

Response: The text will be edited to remove this sentence and the end of the Executive Summary will be edited to state: "Based on this analysis, a current safe yield range of 24,000 to 25,500 ac-ft/yr is recommended. ~~Therefore, despite limitations in the groundwater balance, this sensitivity analysis indicates that the range of uncertainty in the resulting safe yield estimate is 1,500 ac-ft/yr, (average percent difference of 6 percent).~~

***Comment 8**: On page 1, the City requests the new language be rejected and the removed sentence reinstated because this Study does not thoroughly discuss overdraft or surplus.*

Response: The report will be edited as suggested.

***Comment 9**: Section 2.1 On page 5 - Add the following as the second sentence, 'The hydrogeology of the basin was found to be considerably more complex than depicted in earlier reports.'*

Response: This section is intended as brief summary of the earlier Law-Crandall (1993) report; the reader can refer to the earlier study for additional detail. No changes will be made based on this comment.

***Comment 10**: Section 2.1 Add the following as the second to last sentence, "The average net pumpage demand from the basin was 22,000 ac-ft/yr." Add the word "cumulative" before the words "loss of 27,000 ac-ft" in the last sentence. At the end of the last sentence delete the words "state of overdraft" and add the following, "threatened state of overdraft over this relatively dry period."*

Response: The text will be modified to note the pumpage during this period, add the word 'cumulative' before loss of 27,000 ac-ft, and add the phrase 'threatened state of overdraft.' The text will not be edited to add the words 'over this relatively dry period.' As noted in the Law-Crandall report (p.50), their base period was chosen to have similar climatic conditions at the beginning and end of the analysis ("dry-to-dry period approach"), to "reduce the chances of errors due to water in transit in the zone of aeration of the system."

***Comment 11**: Section 2.2 On page 6, the last sentence of the third paragraph states: "Groundwater levels for monitoring wells at all depths in this location responded similarly to seasonal pumping patterns." The City requests this sentence be clarified to indicate whether "similarly" means similarly in trend, in magnitude, or in elevation, or any combination of these groundwater conditions.*

Response: The text will be clarified to note that the trend is similar in response to seasonal pumping patterns. Figure 4 displays the hydrographs for these wells for the reader's review.

***Comment 12:** Section 3.8. On page 34, in the bullet point entitled "Map 5", the word "potted" should be revised to "plotted".*

Response: The report will be edited as suggested.

***Comment 13**: Section 4.1. One page 39, in the last sentence of the third paragraph, the word "our" should be revised to "the hydrologic". The City's requests Hopkins Groundwater Consultants, Inc. letter of October 21, 2015 "Hydrologic Base Period 1999 to 2012 for Santa Paula Basin" be included in the Study's appendices. A copy of said letter is attached hereto for reference.*

Response: The word 'our' will be replaced with 'the hydrologic.' The City's comments, including the Hopkins October 21, 2015 memo, will be included as an appendix to the final report.

We reiterate the following response from our July 21, 2016 response-to-comments on this topic, and will reattach the cited figures in our final response-to-comments:

"DBS&A has reviewed the Hopkins memo dated 10/21/15. The memorandum notes that the years preceding the beginning of the base period of 1999 – 2012 were wetter than the years preceding the end of the base period. The Hopkins memo further notes that this may be significant because there may be a 'slower response to recharge events' in the Santa Paula Basin unlike the Piru and Fillmore Basins, which are 'observed to fill much more quickly within a single wet year.' First, we note that according to our groundwater balance the majority of groundwater inflow into the Santa Paula Basin (68-percent) is from underflow from the Fillmore Basin, and the rate of this recharge during wet years is not impacted by the Santa Paula Basin being partially confined as stated in the Hopkins memorandum.

In addition, review of hydrographs from Basin index wells and precipitation data (Figures RTC-3 through RTC-6) indicate that the groundwater elevation in the Santa Paula Basin increases concurrently with winter precipitation. Similarly, groundwater elevations decline quickly in the Basin during dry periods. Figure RTC-7 from the UWCD 2012 Santa Paula Basin Annual Report compares average groundwater level from index wells and the cumulative departure curve from 123-year average precipitation, and also indicates that groundwater levels in the Basin respond to wet/dry conditions within a single water-year.

The primary reason the years preceding the base period 1999 – 2012 are exceptionally wet was because of the water year 1998, which exhibited the greatest precipitation from 1957 to 2014 as measured at rain gages in Saticoy and Ventura (see Figure 8 of the safe yield study). Review of the attached hydrographs (Figures RTC-3 through RTC-7) indicates that groundwater elevations did not increase to levels significantly greater than other periods during the beginning of the 1998 water year (October 1997 to March 1998), and declined by the beginning of the 1999 water year (October 1998). Therefore, by the beginning of our base period (October 1998), groundwater elevations were not elevated above historical norms due to the exceptionally wet year in 1998. Also, note that the second-wettest year from 1957 – 2014 as measured at rain gages in Saticoy and Ventura was 2005, and therefore occurred during the base period (see Figure 8 of the safe yield study).

Groundwater elevation decline calculated for our base period is generally similar to declines calculated by UWCD for other base periods (see Sections 2.5, 4.5, and Table 1). For example, UWCD estimated an average annual decline of 0.22 ft/yr for 1944 – 2005, the longest base period in their study (see Table 1), compared to a median area-weighted decline of 0.23 ft/yr in our study."

Comment 14*: Section 4.9. On page 68, the City requests the first sentence be removed.*

Response: The sentence will be revised to: "The groundwater balance was performed using standard hydrogeologic approaches and available Basin data."

Comment 15*: Section 4.9. The City requests the second sentence be revised to read as follows: "Uncertainties in the Study are due to data limitations and necessary assumptions inherent to Basin scale hydrologic analyses where a comprehensive, numerical groundwater flow model is unavailable, and are typical of similar studies in arid and semi-arid environments."*

Response: We do not agree that this edit adds value or clarification to the report, and no changes will be made based on this comment.

Comment 16*: Section 4.9. The City requests the first bullet point be revised to read as follows: "While safe yield analyses generally include a base period on the order of 30 to 50 years, or more, the hydrologic base period for this Study was only fourteen years, out of necessity, and was chosen because it was a period that reflects changes in Basin hydrologic conditions following construction of the Freeman Diversion (1991) and U.S. Army Corps of Engineers projects on lower Santa Paula Creek (1998)."*

Response: The report will be edited as suggested.

Comment 17: *Section 4.9. The City requests the following paragraph be added as a new bullet point in this section: Further study is necessary to determine the impact of historical production that was shifted circa 2014 from the Santa Paula Basin to the Fillmore Basin, within several hundred feet of the Santa Paula Basin-Fillmore Basin Boundary. The impact of these changes in production on water levels in the Santa Paula Basin is not analyzed in this Study.*

Response: The report will be edited as suggested.

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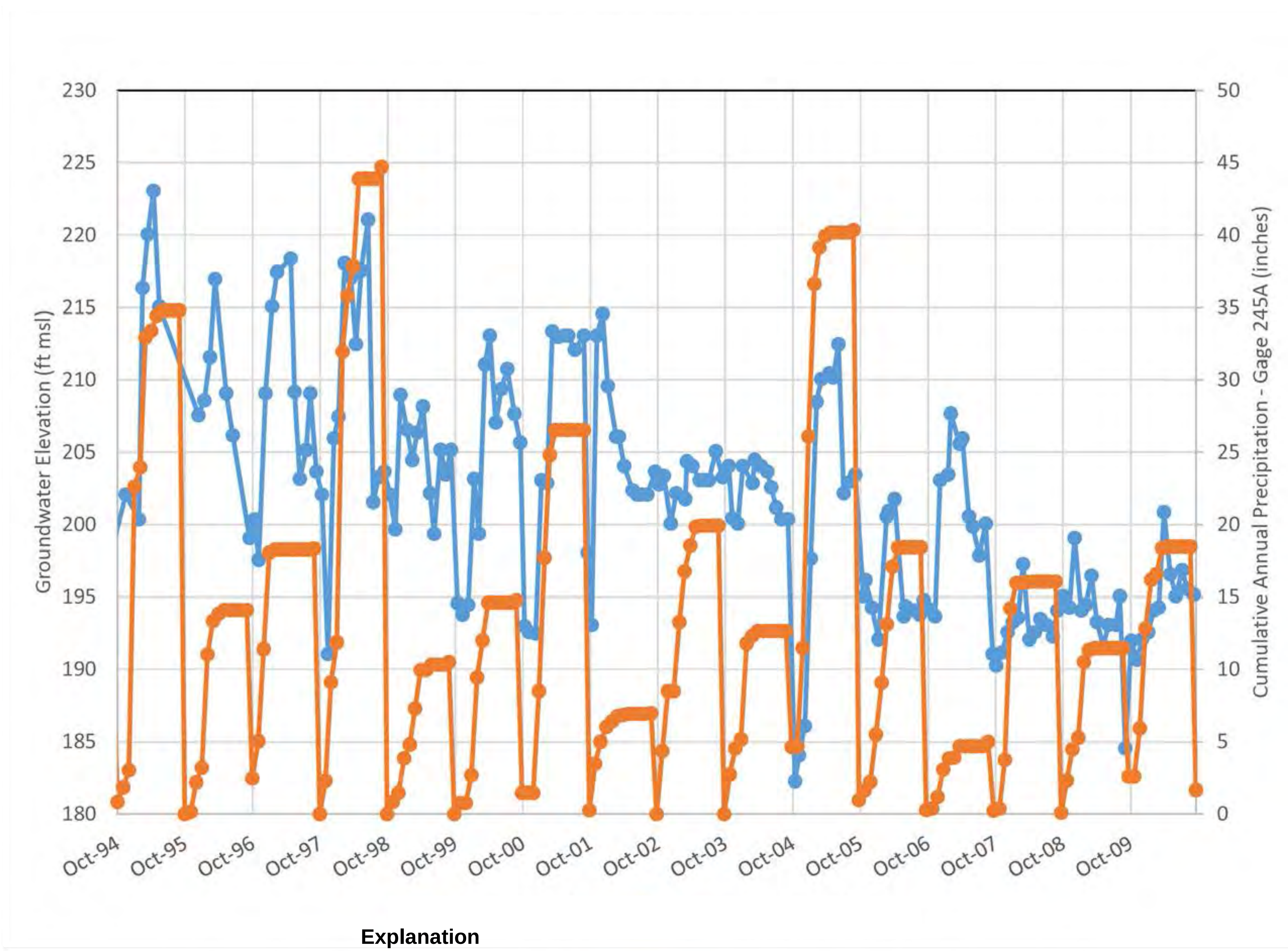


Explanation

Groundwater elevation (ft msl)

Cumulative annual precipitation

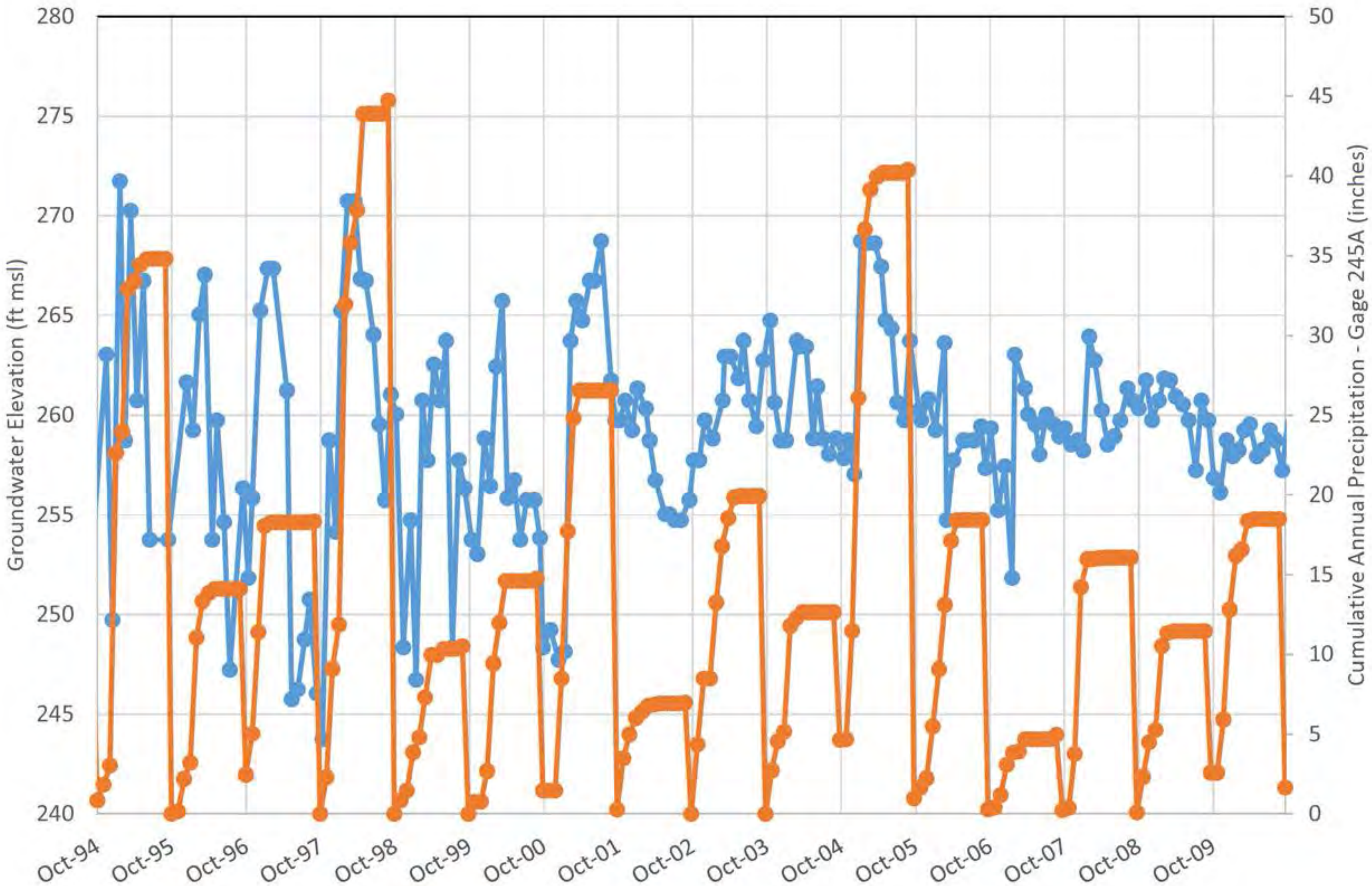
UWCD SAFE YIELD

Groundwater Elevation and Precipitation
Well 03N21W15C04S

Daniel B. Stephens & Associates, Inc.
7/20/2016 JN WR14.0110

Figure RTC-3

S:\PROJECTS\WR14.0110_UWCD_SAFE_YIELD\GIS\MXDS\RTC_JUL_2016\FIG_RTC-04_HYDROGRAPHS_PRECIP_E04S.MXD 7/20/2016



Explanation

Groundwater elevation (ft msl)

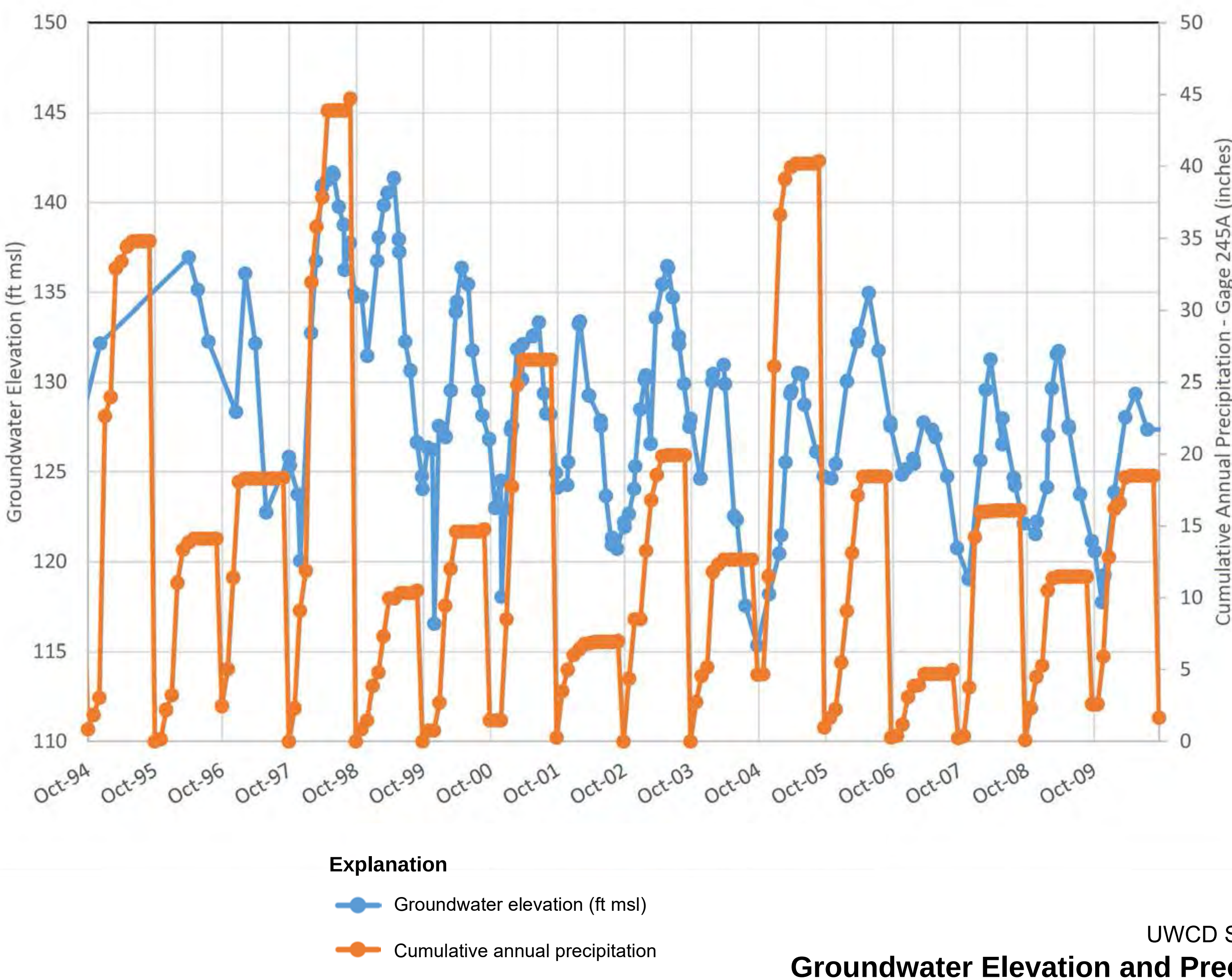
Cumulative annual precipitation

UWCD SAFE YIELD

Groundwater Elevation and Precipitation
Well 03N21W12E04S

Daniel B. Stephens & Associates, Inc.
7/20/2016 JN WR14.0110

Figure RTC-4



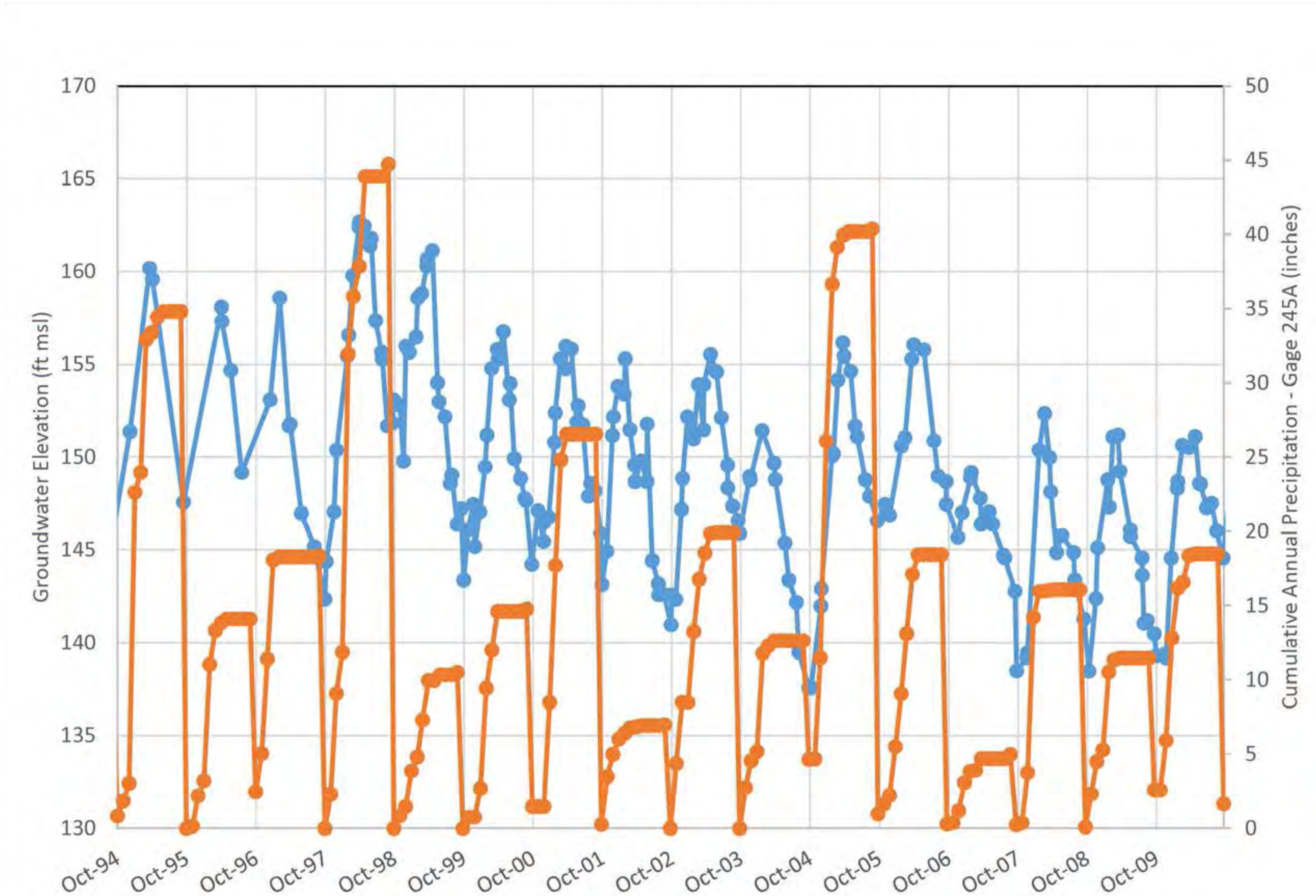
UWCD SAFE YIELD

Groundwater Elevation and Precipitation
Well 02N22W03K02S

Daniel B. Stephens & Associates, Inc.

7/20/2016 JN WR14.0110

Figure RTC-5



Explanation

Groundwater elevation (ft msl)

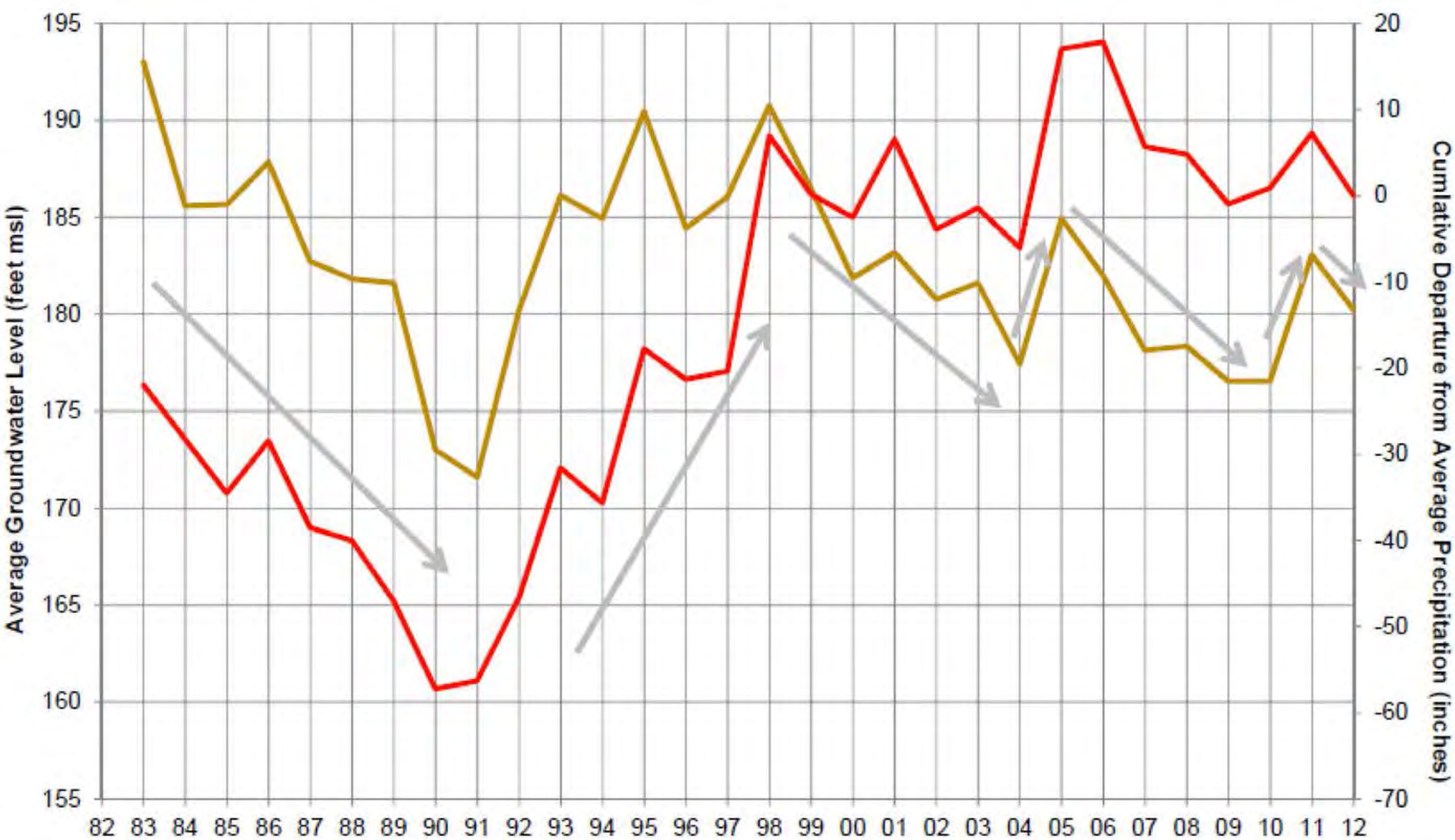
Cumulative annual precipitation

UWCD SAFE YIELD

Groundwater Elevation and Precipitation
Well 02N22W02C01S

Daniel B. Stephens & Associates, Inc.
7/20/2016 JN WR14.0110

Figure RTC-6



Source:
UWCD Prof. Paper 2015-01
2012 Santa Paula Basin Annual Report

Explanation

- Average groundwater level from groundwater level index wells (ft msl)
- Cumulative departure from 123 year average precipitation (Santa Paula Gage)

UWCD SAFE YIELD

Groundwater Level Index

1983 - 2012

Daniel B. Stephens & Associates, Inc.

7/20/2016 JN WR14.0110

Figure RTC-7

November 17, 2016

VIA E-MAIL: tonym@unitedwater.org

Tony Morgan, PG, CHG
Deputy General Manager/Groundwater & Water Resources Manager
United Water Conservation District
106 North Eighth Street
Santa Paula, CA 93060-2710

Re: **City of San Buenaventura Comments on the Revised "Preliminary Draft Santa Paula Basin Hydrogeologic Characterization and Safe Yield Study" Circulated In October 2016**

Dear Mr. Morgan:

This letter contains the City of San Buenaventura's ("City") comments on the Revised "Preliminary Draft Santa Paula Basin Hydrogeologic Characterization and Safe Yield Study," prepared by Daniel B. Stephens & Associates, Inc. (""DBS&A") for United Water Conservation District ("UWCD"), and circulated to the Santa Paula Basin Technical Advisory Committee ("TAC") in October 2016.

The Preliminary Draft Study was circulated to the TAC in March 2016. The City and the Santa Paula Basin Pumpers Association ("SPBPA") submitted comments on the Preliminary Draft Study in June 2016. These comments and requested revisions were discussed at the July 2016 TAC meeting. In response, DBS&A made certain changes and released the Revised Draft Study for review and comment.

The primary purpose of this letter is to provide comments on the Revised Draft Study in order for it to be finalized in a timely manner. The City would like to reiterate that based on the information presented in the Study, the City does not agree with the safe yield finding and the Study should not be used for any determination that the Basin is in overdraft condition. Generally, the City does not agree that the Study's hydrologic base period is sufficient for findings changing the existing safe yield estimate, and that a comprehensive, numerical groundwater model could address some of the concerns over the Study's hydrologic base period. Certainly, the Study should not be used to support requests for Basin management changes due to any claimed overdraft condition based on the Study's findings.

The City believes this Study can be utilized by the TAC as part of informed Basin management in conjunction with other TAC studies, including, but not limited to, the forthcoming Groundwater Sustainability Project Evaluation. Based on the limitations of this Study, coupled with the fact that it generally indicates that the Basin is in a relatively stable condition especially during drought conditions, the City is not prepared to agree upon a safe yield figure for the Basin at this time and recommends further analysis when more data becomes available, such as the comprehensive, numerical groundwater flow model expected to be completed within a few years.

Comments are provided section-by-section, other than the initial general comment. If a change was made and the City provides no comment, then no further change is requested.

General Comment

The City understands that it was requested by SPBPA that numbers be rounded, "so as not to imply more accuracy than is appropriate." Initially, the City did not oppose such rounding. However, upon reviewing the Revised Draft Study, the City is concerned about the impact of the rounding. For example, on page ES-5, in the first sentence, the rounding changes the difference between inflows and outflows by 47 ac-ft/yr (difference between 53 ac-ft./yr. and the rounded 100 ac-ft./yr.). Another example, rounding of the safe yield value on page 74 (i.e., decreasing it by 52 ac-ft./yr.). The City requests that, instead of rounding, the following sentence be added to the end of the last paragraph on page ES-4 to address SPBPA's concerns: "Although numbers are reported to the nearest acre-foot per year, the authors are not asserting that level of accuracy in the findings of this Study." If this change is made, then the added sentences at the bottom of pages 38 and 73 are unnecessary.

Otherwise, the rounding methodology needs to be consistent throughout the Study. For example, on page 67, the first paragraph, rounding methodology is inconsistent between the modified numbers. On that same page, in the third paragraph, the rounding has a dramatic impact on the difference between the base and small storage decline cases.

Foreword

On page ES-1, the paragraph in quotations, fifth line down, the word "basin" should be capitalized.

On page ES-1, the City requests the last paragraph be modified to read in full as follows:

> The goal of this Safe Yield Study was to estimate safe yield of the Basin with available information and analytical methods conventionally used to estimate safe yield in the absence of a comprehensive, numerical groundwater flow model. In initiating this Safe Yield Study, the TAC recognized that certain limitations would be associated with this level of

> study, but that it could be part of informed Basin management prior to completion of a comprehensive, numerical groundwater flow model. In parallel with planning and execution of the Safe Yield Study, the SPBPA initiated a study to identify opportunities and develop programs for enhancing the operating safe yield of the Basin and improving Basin conditions (Practical Measures/Yield Enhancement Options Study). Together, the Safe Yield Study and Practical Measures/Yield Enhancement Options Study are expected to further the ability of the TAC to guide basin management efforts that will help in "meeting the reasonable water supply needs of the parties, including protection for historic users, without harm to the Basin" as stated in the Judgment.

The page numbering for the Foreword should be "v" and "vi", rather than part of the Executive Summary (i.e., "ES-1" and "ES-2").

Executive Summary

On page ES-3, the City does not think the new language in the second paragraph should be included because this Study does not thoroughly discuss overdraft or surplus.

On page ES-5, the City requests the second paragraph be modified to read in full as follows:

> Study limitations are discussed in Section 4.9, and specific DPWM limiting assumptions are discussed in Section 4.3.2. Of particular note, uncertainties in the Study are due to data limitations and necessary assumptions inherent to Basin-scale hydrologic analyses where a comprehensive, numerical groundwater flow model is unavailable, and are typical of similar studies in arid and semi-arid environments. Data gaps and limitations include the relatively short base period (fourteen years), limited gage data for Santa Paula Creek and the Santa Clara River, lack of Basin-specific storativity values representative of the unconfined or semiconfined undifferentiated alluvium, and the generally poorly understood conditions that govern outflow to the Mound and Oxnard Forebay Basins. In addition, the DPWM incorporates simplifying assumptions necessary for Basin-scale watershed modeling, including the assumption of constant annual irrigation rates and land use over time during the base period, and homogenous properties (e.g., vegetation, soil-type) within each 295-ft x 295-ft model grid cell. These limitations can be addressed in future Basin studies.

The City has concerns with the added sentence asserting a 6 percent level of accuracy, and requests it be removed in the Executive Summary.

1.1 Introduction

On page 1, the City requests the new language be rejected and the removed sentence reinstated because this Study does not thoroughly discuss overdraft or surplus.

2.1 1993 Santa Paula Basin Water Resource Evaluation

On page 5 –

Add the following as the second sentence, "The hydrogeology of the basin was found to be considerably more complex than depicted in earlier reports."

Add the following as the second to last sentence, "The average net pumpage demand from the basin was 22,000 ac-ft/yr."

Add the word "cumulative" before the words "loss of 27,000 ac-ft" in the last sentence.

At the end of the last sentence delete the words "state of overdraft" and add the following, "threatened state of overdraft over this relatively dry period."

2.2 USGS Groundwater/Surface Water Study

On page 6, the last sentence of the third paragraph states: "Groundwater levels for monitoring wells at all depths in this location responded similarly to seasonal pumping patterns." The City requests this sentence be clarified to indicate whether "similarly" means similarly in trend, in magnitude, or in elevation, or any combination of these groundwater conditions.

3.8 Groundwater Flow Direction and Gradient

On page 34, in the bullet point entitled "Map 5", the word "potted" should be revised to "plotted".

4.1 Hydrologic Base Period

One page 39, in the last sentence of the third paragraph, the word "our" should be revised to "the hydrologic".

The City's requests Hopkins Groundwater Consultants, Inc. letter of October 21, 2015 "Hydrologic Base Period 1999 to 2012 for Santa Paula Basin" be included in the Study's appendices. A copy of said letter is attached hereto for reference.

4.9 Limitations.

On page 68, the City requests the first sentence be removed.

The City requests the second sentence be revised to read as follows: "Uncertainties in the Study are due to data limitations and necessary assumptions inherent to Basin-scale hydrologic analyses where a comprehensive, numerical groundwater flow model is unavailable, and are typical of similar studies in arid and semi-arid environments."

The City requests the first bullet point be revised to read as follows: "While safe yield analyses generally include a base period on the order of 30 to 50 years, or more, the hydrologic base period for this Study was only fourteen years, out of necessity, and was chosen because it was a period that reflects changes in Basin hydrologic conditions following construction of the Freeman Diversion (1991) and U.S. Army Corps of Engineers projects on lower Santa Paula Creek (1998)."

The City requests the following paragraph be added as a new bullet point in this section:

> Further study is necessary to determine the impact of historical production that was shifted circa 2014 from the Santa Paula Basin to the Fillmore Basin, within several hundred feet of the Santa Paula Basin-Fillmore Basin Boundary. The impact of these changes in production on water levels in the Santa Paula Basin is not analyzed in this Study.

The City appreciates the opportunity to comment on the Revised Draft Study.

Sincerely,

Shana E. Epstein
General Manager
Ventura Water

Enclosure

Cc: John Lindquist, United Water Conservation District, johnl@unitedwater.org
Frank Brommenschenkel, Santa Paula Pumpers Association, frank.brommen@verizon.net
Russell McGlothlin, Brownstein Hyatt Farber Schreck, rmcglothlin@bhfs.com

HOPKINS
GROUNDWATER
CONSULTANTS, INC.
THE WATER RESOURCE SPECIALISTS

October 21, 2015
Project No. 01-009-09C

City of San Buenaventura
Post Office Box 99
Ventura, California 93002-0099

Attention: Ms. Susan Rungren
Principal Engineer

Subject: Hydrologic Base Period 1999 to 2012 for Santa Paula Basin.

Dear Ms Rungren:

As requested Hopkins Groundwater Consultants, Inc. (Hopkins) has reviewed the subject hydrologic base period 1999 to 2012 proposed for the Santa Paula Basin safe yield study and is providing the following comments for consideration by the Santa Paula Basin Technical Advisory Committee (TAC). We agree that the beginning and ending years 1999 and 2012 that were selected for the proposed base period received comparable rainfall 12.74 inches and 12.55 inches, respectively, however, hydrologic conditions affecting groundwater levels at the beginning and the end of this period are not the same.

For comparison we are providing a summary of the rainfall and streamflow data available for the years preceding the years that begin and end the base period in Table 1 – Hydrologic Conditions Prior to 1999 and 2012.

Table 1 – Hydrologic Conditions Prior to 1999 and 2012

MEASUREMENT LOCATION (UNITS)	BASE YEAR	BASE YEAR	PRECEDING 5-YEAR AVERAGE	PRECEDING 4-YEAR AVERAGE	PRECEDING 3-YEAR AVERAGE	PRECEDING 2-YEAR AVERAGE	PRECEDING YEAR
RAINFALL STATION NO 225 (INCHES)	1999	11.87	30.98	34.99	31.36	38.77	55.02
	2012	11.98	19.77	22.80	22.55	27.18	29.57
RAINFALL STATION NO 173A (INCHES)	1999	12.74	30.82	35.10	31.75	38.58	53.29
	2012	12.55	20.82	24.77	24.47	29.43	31.76
STREAMFLOW STATION NO 11113500 (CFS)[1]	1999	7.7	49.48	58.98	49.53	68.25	111.6
	2012	6.15	23.43	28.14	24.69	34.00	45.4

1 – ANNUAL AVERAGE FLOW RATES

C:\HGC\JOB FILES 2015\01-009-09C\BASE PERIOD 1999-2012\LETTER 10-21-15.DOCX

P.O. Box 3596, Ventura, California 93006 Phone: (805) 653-5306 e-mail: chop4@earthlink.net

Water level trends in the Santa Paula Basin indicate that high and low water level conditions take years to develop and result from multiple dry or wet years. While seasonal oscillations are apparent in the data, the confined nature of the basin results in a slower response to recharge events unlike the Piru and Fillmore Basins that are observed to fill much more quickly within a single wet year. The data provided in Table 1 indicate that the years preceding the beginning of the base period were far wetter than the years preceding the end of the base period. This occurrence alone would indicate that water levels would be anticipated to be higher at the beginning of the period in 1999 than at the end in 2012.

Additionally, a major hydrologic change occurred in the Santa Paula Basin during this base period, which likely changed the amount of recharge received from the Santa Paula Creek. The Santa Paula Creek channel improvement project was conducted between 1998 and 2001. The results of the flood control project effectively removed potential creek percolation from being a significant recharge source. Creek recharge may have provided substantial recharge in the years leading up to the base period (prior to 1999), but not during the base period. The typical response to this type of hydrologic change is a lowering of water levels. When water levels in the basin decline, less groundwater is discharged from the basin (less driving head) and more groundwater is induced to flow into the basin. The effects that will result from this type of change in recharge will likely take years to be realized in a basin the size of the Santa Paula Basin.

With this in mind, the interpretation of water level responses in the Santa Paula Basin over this base period should consider these changes in hydrologic conditions. If you have any questions, please give us a call.

Sincerely,

HOPKINS GROUNDWATER CONSULTANTS, INC.

Curtis J. Hopkins
Principal Hydrogeologist

Attachment:

c:

Santa Paula Basin Pumpers Association, Inc.

A Non-Profit Mutual Benefit Corporation

Emailed

November 23, 2016

United Water Conservation District
Attn. Tony Morgan/John Lindquist
106 North 8th Street
Santa Paula, CA 93060

Subject: Comments on the October 2016 Revised Draft of Santa Paula Basin Yield Study

Thank you for the opportunity to comment on the October 19, 2016 draft of the *Santa Paula Basin Hydrogeologic Characterization and Safe Yield Study* ("revised draft"), which was prepared by Daniel B. Stephens & Associates, Inc. and Richard C. Slade & Associates LLC. The following comments were developed in consultation with Frank Brommenschenkel, Steven Bachman, Ken Schmidt, and Ron Eid. We have again included both general comments and specific comments.

GENERAL COMMENTS:

1) The revised draft has tightened some of the language that we commented on previously (June 14, 2016). However, we still feel that the revised draft does not clearly articulate the approach which was ultimately relied upon to develop the estimate of safe yield. In particular, the estimate relied upon reported pumpage and the estimated change in storage, and this should be made clear. While the subject draft reflects a change to the Executive Summary in this regard, the change did not make it clear, so it remains misleading. Further, as noted in the SPBPA's previous comments, this should be made clear, not only in the Executive Summary, but also wherever it appears in the main body of the report, including tables.

2) We also believe that the range in the safe yield is not correctly presented. The range of storativity values used in the storage calculation is 0.01 to 0.2 (the latter implying the entire basin is unconfined) – both numbers represent values that are higher than many of those referenced in the report. A more-defensible range would include the lower numbers reported (perhaps as low as 10^{-3}) and a higher number that was short of a completely unconfined basin (e.g., something between 0.01 and 0.1).

3) We recommend calculating the actual storage change for only the unconfined part of the groundwater basin. This can be done using the Confining Bed Evaluation performed as part of the overall yield analysis. Water level data can then be used in calculating storage change in only the groundwater that is unconfined.

4) It is important that the change in storage could be as low as near-zero, resulting in current pumping being within safe yield. It is then up to the TAC to decide whether to manage the basin to the lower or higher of the yield calculations.

5) There continues to be a problem with significant figures and not correctly rounding off. For example, the hydraulic conductivity values on page ES-4 were presented to the nearest 1 foot per day. Another example on page ES-5 is water budget values to the nearest 10 acre-feet by year. These are highly misleading in terms of the accuracy of the estimates. In this regard, Ventura's November 18, 2016 comments include the suggestion that a qualifying statement or disclaimer be added to the Executive Summary. This would be acceptable if use of the disclaimer is extended to the narrative and tables that follow in the main body of the report.

6) Wherever "standard methods" are referred to in the report, the source should be identified.

SPECIFIC COMMENTS:

1) **Section 2.6**, **Santa Paula Basin Groundwater Elevation Trend Assessment** (page 9). The UWCD 2013 evaluation was discussed, but other factors besides pumpage, such as reservoir releases (from the Curtis Hopkins report) that could cause water-level declines weren't mentioned. Other factors should be acknowledged.

2) **Section 2.9, Ventura County Watershed Protection District Groundwater Section Annual Reports, 2008 to 2013 (**page 11). The number of wells sampled by VCWPD in the basin should be provided, along with the specific constituents that were determined. This would help the reader put the results in perspective.

3) **Section 3.1, Electric Log Correlations** (page 14). It is suggested that the locations and the cross sections themselves be presented in the text of the report, not just in an appendix.

4) **Section 3.3, Low-Permeability Units** (page 18). The depths to the top of the electric logs should be provided. For example, many logs from the DOG&GR start hundreds of feet deep or deeper. Also, calling a low-permeability layer a "lens" is not technically correct, as this infers that they are not laterally continuous.

5) **Section 3.6, Aquifer Transmissivity, Hydraulic Conductivity, and Storativity** (page 24**).** Specific yields should be determined only for the unconfined groundwater based on textural descriptions. This should provide a more correct estimate of storage change.

6) **Section 3.6.2, Supply Well Aquifer Test Reports** (pages 27-30). Transmissivities were discussed based on results of pump tests for a number of wells. At the end of the discussion, the conversion factors between specific capacity and transmissivity should be discussed. For example, factors for Santa Paula Wells No. 13 and 14 are within the expected range of 1,500 and 2,000. However, the factors for Saticoy Wells No. 2 and 3 are much greater than expected (by 2 to 3 times). The purpose of the exercise was to compare the conversion factors determined from pump tests in the basin to more general values developed elsewhere. Then, a more applicable range in conversion factors could be used (for example in the Saticoy area).

   On page 28, the very high transmissivity values which result from the use of "late-time" drawdown data are not considered meaningful because a positive boundary was encountered. For the FICO Well No. 12 test, specific capacities were not provided.

7) **Section 3.8, Groundwater Flow Direction and Gradient** (page 34). The cited maps (particularly 1, 2, and 3) should be provided in the text, not just in an appendix.

8) **Section 3.9, Vertical Gradient Evaluation** (page 36). The method of determining vertical gradients should be provided. For example, was the water-level difference divided by the thickness of the confining bed? Conventional USGS units for expressing vertical gradients are "feet per 100 feet".

9) **Section 4, Groundwater Balance** (page 38+). The Santa Clara River should be divided into a losing segment and a gaining segment for specific years, and both river seepage and discharge to the groundwater calculated separately. The terminology "non-extraction related outflow" should be better defined.

10) **Section 4.1, Hydrologic Base Period** (page 39). Trends in streamflow should also be examined, not just precipitation.

11) **Section 4.2, Groundwater Inflow from Fillmore Basin** (page 41). How were the specific capacity data converted to hydraulic conductivities? How were the transmissivity values from aquifer tests converted to hydraulic conductivity?

12) **Section 4.2.1, Comparison to Santa Paula Basin Pumper's Association Inflow Estimate** (page 44). After discussing the variable flow estimates, some type of conclusion should be reached.

13) **Section 4.3.3, DPWM Domain and Input Parameters** (page 49). Is it also necessary to know the unsaturated hydraulic conductivity? Also, last paragraph, second line, the word "vertical" should be placed before "saturated".

14) **Section 4.3.4, Areas Contributing Deep Percolation of Precipitation** (page 50). Were hardpan layers considered, particularly in the upland areas? Also, the discussion in the first full paragraph implies that one can determine the lateral extent of sub-surface confining beds by mapping only the surficial geology.

There may be discharge from the Santa Clara River at the western end of the basin, but the referenced section 4.7.1 does not discuss the recharge at the eastern end of the basin, which has been characterized as the largest recharge source to the basin in some past studies.

15) **Section 4.5, Groundwater Storage** (page 57). The water-level change evaluated to determine groundwater storage change should be based only on wells tapping the unconfined groundwater. The analysis should separate the groundwater into unconfined and confined, with the change in storage evaluation based on the unconfined groundwater.

16) **Section 4.7, Natural Groundwater Outflow (**page 61+). The word "natural" is not really correct, because the outflow depends on hydraulic gradients, which are affected by man-made factors (like pumpage).

17) **Section 4.7.2, Estimated Natural Groundwater Outflow (**page 65). More explanation needs to be provided with regard to the groundwater outflow value. The outflow value could be off by thousands of acre-feet per year. We recommend that a reference to future investigations of downstream basins may help to inform the estimated outflow.

18) **Section 5.1, Safe Yield Methodology** (page 69). In DBS&A's response to SPBPA's General Comment #2, it is suggested that the 2003 Study assumed that the change in water levels was relatively small, which is not the case. Rather, measured water levels were compiled and reviewed.

    There are other factors besides pumpage (such as stream channel lowering) that contributed to the water-level declines, and these should be acknowledged.

19) **Section 5.3 Safe Yield Determination** (page 73 and Figure 16). This illustration was apparently intended to help explain the development of the range in recommended safe yield of 24,000 to 25,000 acre-feet per year. The 24,000 value is near the intersection of the 25th percentile water-level decline and a storage coefficient of 0.2; however, this was not explained. On the other hand, the 25,500 value appears to be based on an almost totally confined aquifer, but this was not clearly stated. Accordingly, more explanation is suggested.

Thank You,

Alex Teague

Alex Teague, Chairman