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July 25, 2012

VIA HAND DELIVERY

Mr. Bill Ellett, Unit Manager
Superfund Program Unit
Southern Regional Office, ADEQ
400 W. Congress St., Suite 433
Tucson, AZ 85701

Re: Los Reales Landfill Water Quality Revolving Fund Site, Tucson, AZ –Evaluation of Remedial Strategies and Recommendations for Future Operations

Dear Mr. Ellett:

The City of Tucson, Environmental Services (COT-ES) retained Engineering and Environmental Consultants, Inc. (EEC) and their subcontractor Montgomery and Associates (M&A) for an evaluation of remedial strategies for the Los Reales Landfill Water Quality Revolving Fund (WQARF) site. The purpose of the review was to provide recommendations for future operations in accordance with the approved Remedial Action Plan (RAP), the Remedial Objectives (ROs) for the site and the "old" WQARF rules. Attached is a copy of the final report, dated July 24, 2012 for your review. COT-ES is seeking approval from the Arizona Department of Environmental Quality (ADEQ) to implement the report recommendations of M&A.

The evaluation included a review the site history, lithology, water level data, sampling data, and operations of the existing treatment system. M&A also constructed a new groundwater flow/fate and transport model in order to rank alternative strategies for meeting the ROs as developed in the 1994 *Los Reales Landfill Phase II Remedial Action Plan – Feasibility Study,* (CDM, September 1994). The ROs are:

- prevent human exposure to groundwater contaminants in excess of their associated Maximum Contaminant Level (MCLs)
- limit further lateral migration of the plume
- reduce, to the extent practical, the contaminant levels in the aquifer

Based on the data review, M&A ranked five strategies with respect to ability to meet ROs, ease of implementation and general cost. Based on the results of the groundwater flow/fate and transport modeling, M&A recommended that COT-ES continue system operations with a modified pump and treat system in the short term (2012 to approximately 2024), install additional monitoring wells to verify model results in 2013, develop a contingency plan for renewed operation of the treatment system if necessary, and begin transition to monitored natural attenuation (MNA) by allowing extraction wells to fail without rehabilitation or replacement. According to the model results, modified pump and treat and long term transition to MNA are consistent with the site ROs and with WQARF rules.

If ADEQ approves the proposed modified pump and treat approach, COT-ES will begin implementation during the third quarter of 2012 by shutting off wells that produce less than 2 gallons per minute. These wells are costly to operate but do not provide containment or remove a significant amount of mass from the aquifer. The wells COT-ES proposes to shut off in 2012 are: R-063A, WR-376A, LLM-537, LLM-538, LLM-548 and LLM-549. These wells will be sampled during the next scheduled semiannual sample event in January 2013. The remainder of the extraction wells will continue to be rehabilitated as needed while COT-ES proceeds with installation of the monitoring network and preparation of a contingency plan. COT-ES will install the 6 new monitoring wells in early 2013. Figure 3 of the attached report shows the proposed locations. The wells will be used to verify the results of the groundwater flow/fate and transport model and to develop a contingency plan for returning wells to operation or evaluating other treatment strategies, if needed.

Thank you for your ongoing review of the site. If you have any questions, please contact Molly Collins at (520) 837-3703. We look forward to obtaining your comments and approval.

Sincerely,

Nancy Petersen
Interim Director

NP/MC/cj

Enclosures
Montgomery and Associates: *Evaluation of Remediation Strategies, Los Reales Landfill Water Quality Revolving Fund Site,* July 24, 2012

cc: Gretchen Wagenseller, Arizona Department of Environmental Quality (CD Copy)
Wally Wilson, COT, Tucson Water (Email Link)
John Kmiec, COT, Tucson Water (Email Link)
Molly Collins, COT-ES (Email Link)
Jeffrey Drumm, COT-ES (Email Link)
Los Reales Operations Record (CD Copy only)
Los Reales File (Hard Copy)

MONTGOMERY & ASSOCIATES
Water Resource Consultants

Report

July 24, 2012

Prepared for:
City of Tucson, Environmental Services

Evaluation of Remediation Strategies
Los Reales Landfill
Water Quality Assurance Revolving Fund Site

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MONTGOMERY & ASSOCIATES

July 24, 2012
REPORT

EVALUATION OF REMEDIATION STRATEGIES
LOS REALES LANDFILL WATER QUALITY ASSURANCE REVOLVING FUND SITE

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July 24, 2012
REPORT

EVALUATION OF REMEDIATION STRATEGIES
LOS REALES LANDFILL WATER QUALITY ASSURANCE REVOLVING FUND SITE

INTRODUCTION

Montgomery & Associates (M&A) conducted an evaluation of remediation strategies for the Los Reales Landfill (Site). The project was conducted for the City of Tucson, Environmental Services Department (COT-ES) in accordance with a scope of work outlined in a request for proposal dated October 10, 2011. The project goal was to evaluate the existing remedial action plan (RAP) and provide a ranked list of remedial strategies to more cost effectively address groundwater contamination at the Site. All remedial strategies considered were consistent with the Arizona Water Quality Assurance Revolving Fund (WQARF) rules. Any changes to the remedial operations must be acceptable to the Arizona Department of Environmental Quality (ADEQ).

BACKGROUND

Selected maps prepared by COT-ES are included in **Appendix A** to support the narrative discussion on project approach and data evaluation. COT-ES Figure 2 in **Appendix A** shows a Site map. The Los Reales Landfill began operating in 1967 for the disposal of municipal waste. From 1977 to 1980, low-level hazardous waste was disposed of in the Southwest Disposal Area (SWDA), which comprises an area of about 4 acres in the southwestern portion of the landfill.

The SWDA and the main landfill cell are unlined. Groundwater contamination was first discovered at the Site in 1988. The Site was first registered in the WQARF in 1989. The original remedial investigation was completed in 1991 by the Tucson Water Department (Wilson and Meyerson, 1991). The Remedial Investigation (RI) identified a volatile organic compound (VOC) plume that extended to the northwest about one quarter of a mile beyond the landfill property. Between 1991 and 1994, additional site characterization and analyses were conducted to support evaluation and development of a remedial action. A Phase II Remedial Action Plan – Feasibility Study was completed in 1994 (RAP/FS; Camp, Dresser, and McKee [CDM], 1994) and a pump and treat remedial action for the Site was approved by ADEQ in 1995. From 1995 through 1999, the pump and treat system was designed, permitted, and constructed.

The pump and treat groundwater remediation system began operating in 1999. Operation of the pump and treat system has encountered several challenges since startup. The operational challenges include fouling and scaling in the extraction wells and a declining regional water table[1]. In response, the COT-ES has actively managed and evaluated the remedial operation since startup. These challenges increase the operation and maintenance costs for the system. Fouling and scaling of the extraction wells has been addressed with reasonable success through periodic aggressive rehabilitation efforts. The declining regional water table is reducing the available drawdown in the extraction wells, which reduces the extraction rate over time. Over the past several years, many of the extraction wells have been replaced because extraction rates had declined to ineffective rates due to fouling, scaling, and small screen slot size. Overall, these challenges and the high cost of continued remedial operations led the COT-ES to implement this evaluation.

The mechanism for impact to groundwater from the landfill is believed to be vapor migration through the vadose zone and not leachate infiltration. A “gas to energy” program exists at the landfill, where landfill gas is collected from a network of gas wells and conveyed to a nearby Tucson Electric Power plant for use. Removing the landfill gas helps depressurize the

[1] The water table at the site has declined approximately 25 feet since 1982 (about 0.8 feet per year [ft/y]). Recent water level data indicate that the water table is declining about 1.2 ft/y.

landfill, which reduces the potential for landfill gas to migrate into the vadose zone. A soil vapor extraction (SVE) system has operated periodically in the SWDA since 2003, with a total run time of about 760 days. To date, a total of about 490 pounds (lbs) of VOCs have been removed by the SVE system, including about 17 lbs in 2011.

PROJECT APPROACH

The project approach was outlined in our proposal dated December 21, 2011. The project included the following activities:

- Evaluation of 1994 RAP
- Data Evaluation
- Groundwater Modeling
- Development, Screening and Analysis of Remedial Alternatives
- Development of Recommended Alternative

The following sections summarize these activities.

EVALUATION OF 1994 REMEDIAL ACTION PLAN

The 1994 RAP was a combination of the RAP and FS (CDM, 1994). The RAP/FS included proposed remedial objectives (ROs), identification and screening of remedial technologies and process options, development and analysis of remedial alternatives, a recommended remedial action. The 1994 RAP/FS proposed the following ROs:

- Prevent human exposure (through ingestion, inhalation, and dermal adsorption) to contaminated groundwater in excess of Federal Drinking Water Maximum Contaminant Levels (MCLs) for VOCs
- Limit further lateral migration of VOCs in groundwater beyond existing affected area
- Reduce, to the extent practicable, the concentration of VOCs in groundwater within the defined affected area

To achieve these ROs, the RAP/FS considered a range of general response actions, remedial technologies, and process options to develop remedial alternatives. Ten remedial alternatives were developed and analyzed in the FS. Based on detailed and comparative analyses of the alternatives, *Contaminant Mass Control with Treatment and Reinjection* was selected as the preferred remedial action. Specifically, the preferred remedial action recommended continuous groundwater extraction from three wells, treatment by air stripping, and treated water reuse by injection and dust control at the Site. The preferred remedial action was considered conceptual and recommendations were made to build a modular and flexible system so that it could be readily adapted to changes in site conditions observed during operations.

DATA EVALUATION

A substantial amount of data and information was reviewed by M&A during this project, including:

- Lithologic logs and well construction schematics
- Water level data
- Water quality data
- Pump and treat operational and cost data
- SVE system operational data
- Well rehabilitation records
- Monitor well sampling records
- Selected groundwater monitoring reports
- Document and files from a previous groundwater modeling effort
- Previous Site investigation reports

The following subsections briefly summarize relevant results of the data evaluation:

Hydrogeologic Conditions

The most comprehensive previous evaluation of hydrogeologic conditions at the Site was conducted by M&A in 1994 (M&A, 1994). At the time of this evaluation, only 12 monitor wells existed at the Site. The 1994 evaluation included an inventory of data from other nearby wells, which were used to supplement the Site-specific information. The principal geologic unit beneath the Site is the Fort Lowell Formation. At the Site, the Fort Lowell Formation is composed of a complex and heterogeneous assemblage of coarse- and fine-grained strata. Two groundwater zones were identified at the Site in Fort Lowell Formation: (1) and upper coarse-grained zone and (2) a lower fine-grained zone.

Since the 1994 study, many more monitor and extraction wells were installed at the Site. M&A reviewed over 60 lithologic logs and well construction diagrams during this project to:

- Assess the areal extent of the previously conceptualized coarse-grained and fine-grained groundwater zones;
- Characterize the heterogeneity of the groundwater zone being actively remediated; and
- Develop a conceptual framework of the hydrostratigraphy and screened intervals of the wells for the groundwater model.

It is important to note that the lithologic logs were prepared by several different geologists. The level of detail and nomenclature reported on the logs varies widely, which limits the degree to which stratigraphic zones can be spatially correlated in some areas. Even with this limitation, M&A believes that the evaluation conducted for this study improved upon the 1994 characterization.

Review of logs during this study broadly confirmed the characterization developed in the 1994 M&A study. The hydrostratigraphy beneath the Site is a complex and heterogeneous assemblage of fine- and coarse-grained zones. Areally extensive continuous zones of fine- and coarse-grained zones are generally not present beneath the Site. The hydrostratigraphic zone where most of the extraction and monitor wells are screened becomes more fine-grained with increasing depth. Additional information about the hydrostratigraphy is presented in the summary of groundwater modeling included in **Appendix B**.

Slug tests and constant rate pumping tests have been conducted in selected wells at the Site. The estimated horizontal hydraulic conductivity of the hydrostratigraphic zones screened by the wells ranges from approximately 1 to 250 feet per day (ft/d) (Clear Creek Associates (CCA), 2004), with a geometric mean value of approximately 23 ft/d. The wide range in estimated horizontal hydraulic conductivities reflects the heterogeneous conditions at the Site. Data do not exist to estimate vertical hydraulic conductivity at the Site. Values used in the model were assumed based on experience on similar sites and typical ratios of horizontal to vertical hydraulic conductivity. Horizontal to vertical hydraulic conductivity ratios ranged from 5:1 for coarse-grained sediments to 100:1 for fine-grained sediments.

Groundwater Conditions

Regional groundwater is currently encountered in the Fort Lowell Formation at a depth ranging from about 185 to 310 feet below ground surface, with an average depth of approximately 210 feet. Groundwater flow is generally to the northwest across the Site. Groundwater levels at the Site have steadily declined over the past 30 years. The rate of decline during this period has been about 0.8 feet per year (ft/y). Water level data over the past 10 years indicate a steeper average decline of about 1.2 ft/y. The water table decline appears to be a regional condition, but some portion of the decline at the Site may be due to local dewatering caused by the remedial extraction. In general, the water table at the Site has declined from the upper coarse-grained groundwater zone into the lower fine-grained groundwater zone. Declining water levels have made sustained operation of the remedial extraction wells challenging.

Discussions with Tucson Water staff indicate that water levels in the vicinity of the Site are expected to continue to decline over the next several to many years.

The average horizontal hydraulic gradient at the Site is approximately 0.003 (COT-ES Figure 3 in **Appendix A**). Water level data indicate that areas of upward and downward vertical gradients exist at the Site. In addition, spinner logging in selected wells during previous investigations indicated areas of upward and downward vertical gradients (CCA, 2006). Using the average horizontal gradient of 0.003 and geometric mean horizontal hydraulic conductivity value of 23 ft/d, and assuming an effective porosity of 0.2, the average groundwater velocity at the site is estimated to be on the order of 100 ft/y. Groundwater velocities vary across the Site as a result of variations in horizontal hydraulic conductivity. Based on the current understanding of Site conditions, groundwater velocities probably range from a few ft/y to localized areas of several hundred ft/y.

Based on a review of the groundwater sampling records, groundwater at the Site is aerobic and neutral.

Water Quality

The primary contaminants of concern in groundwater are tetrachloroethene (PCE) and trichloroethene (TCE). COT-ES Figure 5 in **Appendix A** shows the January 2012 extent of PCE and TCE in groundwater at the Site. Based on the January 2012 groundwater sampling event, detectable PCE and TCE concentrations in groundwater ranged from 0.6 to 26.1 micrograms per liter (µg/L) and 0.6 to 12.2 µg/L, respectively. The highest PCE and TCE concentrations were detected in monitor well WR-049A, located in the SWDA. PCE and TCE concentrations beneath the landfill are only characterized by one well, LLM-500. The distribution of PCE in groundwater suggests a broad source area, possibly indicative of a PCE vapor plume in the vadose zone. Laboratory analyses of landfill gas during this study indicated low concentrations of PCE. These data suggest that the landfill gas that migrates into the vadose zone beneath the landfill probably still contains PCE, at least in some areas of the landfill. The existing landfill gas extraction system results in some degree of source control by removing a portion of the landfill gas and reducing pressure in the landfill. The PCE groundwater plume has two distinct lobes that may indicate that more PCE mass flux to groundwater occurs in the southwest and north-central portions of the landfill.

Graphs of extraction rate, PCE, and TCE concentrations were prepared for the extraction wells to determine whether trends have been observed between extraction rate and water quality. These graphs are included in **Appendix C**. In general, there does not appear to be a strong or obvious correlation between extraction rates and PCE and TCE concentrations.

Graphs of water level, PCE, and TCE concentrations in groundwater were prepared for the monitor wells (**Appendix C**). In general, there does not appear to be a strong or obvious correlation between groundwater level and PCE and TCE concentration. Monitor wells with notable decreasing PCE concentrations over the past 10 years or so include WR-373A, WR-374A, R-062A, R-065A, and WR-136B (although recent increasing trends are observed in this well). WR-373A and WR-374A are located near the intersection of Los Reales Road and Swan Road; concentration decreases in these wells may be the result of remedial extraction from wells with higher pumping rates along Swan Road (e.g., LLM-530), where a notable cone of depression exists based on the January 2012 water level data. R-062A and WR-136B are located in the eastern PCE plume lobe and are adjacent to or near R-062B, a former deep monitor well that was retrofitted to an extraction well in early 2010. R-062B had an increasing PCE concentration trend over the similar period that R-062A and WR-136B had a decreasing PCE concentration trend. There reason for these observed trends is inconclusive based on the available data. Extraction from R-62B appears to have stabilized PCE concentrations.

Monitor wells with notable long-term or recent increasing PCE trends include WR-184A, WR-361A, LLM-500, and WR-049A. WR-184A is located adjacent to extraction well WR-470A; increasing PCE concentrations could be result of WR-470A capturing groundwater with higher PCE concentrations. WR-361A and WR-049A are located in the SWDA; increasing concentrations could indicate increasing PCE vapor mass flux coming from the vadose zone beneath the SWDA or other areas of the landfill near this well. The SVE system in the SWDA was operated in 2011 to abate the observed increasing concentration trends. LLM-500 is a dual vadose zone/groundwater zone monitor well located near the center of the landfill; increasing concentrations could indicate an increasing PCE vapor mass flux near the well.

Overall, water quality data collected over the past 5 years or so indicate that the PCE and TCE plumes are relatively stable, with the exception of two areas: (1) in deep groundwater near R-062B and (2) near the SWDA. Response actions to mitigate increasing concentrations in these areas have been implemented. Pumping from R-062B since early 2010 has stabilized PCE concentrations in this well. In 2012, pumping was initiated in WR-355A to expand hydraulic capture near the SWDA. Future water quality data will indicate whether pumping from this well is sufficient to mitigate increasing concentrations near the SWDA.

Seven monitor wells serve as sentinel sampling locations: WR-185A, WR-175A, LLM-513, WR-176A, WR-172A, WR-468A, and LLM-543. LLM-513 and LLM-543 are deep monitor wells; the others are shallow monitor wells. PCE and TCE concentrations have been less than detection limits in all of these wells except WR-175A and WR-468A. Low concentrations (approximately 1 µg/L or less) of PCE and TCE have been consistently detected in WR-175A since 2002. PCE concentrations in WR-175A have declined in the last few years and TCE concentrations have been less than detection limits since 2010. Low concentrations of PCE have been periodically detected in WR-468A since about 2005; current PCE concentrations in this well are less than detection limits. Overall, the water quality data from the seven sentinel monitor wells indicates that the current extent of PCE and TCE in groundwater does not appear to pose a threat to any known water supply wells. The nearest active water supply well downgradient of the Site is the Town and Country Well located over 1 mile from the Site boundary and over one-half mile from the inferred extent of detectable PCE concentrations in groundwater (COT-ES Figure 2 in **Appendix A**).

Remedial Operations

Remedial operations began in 1999 with the initiation of extraction in 10 wells. The total volume treated in 2000, the first full year of operation, was approximately 13 million gallons (MG). The extracted groundwater is treated by air stripping and the treated water is either injected into a deep groundwater zone or used for dust control at the Site. Between startup in 1999 and 2011, the number of extraction wells increased to 21, and the total annual volume of groundwater treatment increased to approximately 47 MG. The current system also includes about 50 monitor wells and 3 injection wells. In 2011, the average extraction rate for the system was approximately 92 gallons per minute (gpm), with a runtime of greater 95 percent[2]. In early 2012, the COT-ES brought several new wells online and increased the total extraction rate to as high as 140 gpm. To date, approximately 325 MG of groundwater have been treated and approximately 19 lbs of PCE and 7 lbs of TCE have been removed[3].

During the 12 year operation, fouling and scaling of the extraction wells, in combination with declining regional water levels, have made sustained operation of some of the extraction wells difficult and expensive. Added operational expense resulted from periodic and aggressive rehabilitation measures in the wells. Over the operational period, many of the original extraction wells have been replaced due to low pumping capacity. The challenging operational conditions are not optimal for maintaining effective capture and removal of contaminants from the groundwater. Operations in the future are projected to become more challenging as the water table declines further into fine-grained sediments.

Annual operating costs for the system have ranged from approximately $200,000 in fiscal year 2010 to approximately $480,000 in fiscal year 2012. Over the period 2010 through 2012, the average annual cost for routine operation, maintenance, and monitoring is approximately $220,000. The additional costs incurred above this average cost have been primarily for

[2] Runtime estimated as the ratio of actual operational time and the available operational time.
[3] PCE and TCE are the primary contaminants of concern at the Site. Other VOCs detected in groundwater at lower frequency and concentrations include 1,1-dichloroethane, 1,1-dichloroethene, cis-1,2-dichloroethene, benzene, dichlorodifluoromethane, trichlorofluoromethane, and methylene chloride.

replacement and rehabilitation of the poorly performing extraction wells. Based on information provided by Tucson Water in May 2012 (Wilson, 2012), water levels are projected to continue declining at the Site. In addition, extraction well fouling is expected to continue. The effects of declining water levels and well fouling will lead to additional expenditures in the future for rehabilitation and replacement wells.

Currently, treated water is an economical source of dust control water at the landfill. A nominal 30 MG per year (MGY) are used for dust control and landscape irrigation. If treated water was not available, potable water would need to be purchased for dust control. Currently, 30 MGY of potable water would cost approximately $100,000[4]. The nominal 30 MGY rate equates to approximately 60 gpm of extraction and treatment.

Despite the challenging operational conditions, the current remedial objectives appear to be largely achieved. In particular, the threat of public exposure to contaminants in groundwater appears to be low because there no known active potable water supply wells impacted by the plume. Further, the plume appears to be relatively stable based on recent water quality data, and extraction and treatment have reduced the contaminant mass in groundwater compared to conditions that would exist without the remedial operations.

GROUNDWATER MODELING

Groundwater modeling was conducted to support analysis of selected remedial alternatives. Details of the groundwater modeling are included in **Appendix B**. M&A evaluated the previous groundwater flow and contaminant model constructed by CCA for potential use on this project. After this review, and evaluation of other site data, it was determined that a higher resolution flow and transport model was needed to adequately simulate the declining water table conditions, extraction well capture, and transport of contaminants. A comparison between the

[4] Cost and dust control usage rate provided by COT-ES; potable water would be the primary source of dust control water if treated water was not available; a small volume of blow-down water from the Tucson Electric Power Plant may be available to the landfill.

M&A and CCA models is included in **Appendix B**. M&A increased the model resolution by reducing the node spacing throughout the model domain and adding layers. The model was calibrated to groundwater level data from the monitor wells over the period 1999 through 2011. Model calibration was limited by the strong boundary head control imparted by the declining water table conditions. Despite this limitation, the model is adequate for comparative simulation of the selected remedial alternatives developed for this project.

DEVELOPMENT, SCREENING, AND ANALYSIS OF REMEDIAL ALTERNATIVES

Potential remedial alternatives for the Site were developed based on project objectives and general accordance with 1997 WQARF requirements. The COT-ES' project objective was to evaluate remedial alternatives that could reduce remedy costs while maintaining a remedy that would be protective of public health and the environment. The 1997 WQARF requirements most relevant to this study are those pertaining to the FS and remedy selection (AAC. R18-7-108).

DEVELOPMENT OF RECOMMENDED ALTERNATIVES

The remedial strategies and remedial measures that make up the remedial alternatives are summarized in **Table 1**. Remedial strategies considered included source control, plume containment, groundwater restoration, monitoring, and institutional controls. Remedial measures included groundwater extraction, in situ treatment, and ex situ treatment. The following five remedial alternatives were assembled from the remedial strategies and remedial measures:

1. **No Action** – cease all remedial operations including monitoring and eliminating institutional controls.
2. **Monitored Natural Attenuation** – rely on natural processes (in this case, dilution and dispersion) in the groundwater system to reduce contaminant mass and concentrations;

monitor groundwater conditions to ensure that public health and environment are protected.

3. **Modified Current Operation** – both ex situ and partial in situ treatment were considered for this alternative.
   A. Ex Situ Treatment – continue current extraction, ex situ treatment (air stripping), and reuse operation; retire and do not replace or aggressively rehabilitate wells that become inoperable due to declining water levels, fouling, or deterioration; rely on MNA in areas where extraction ceases; enhance monitoring network to support MNA; periodically operate SWDA SVE system to control SWDA source; and leave institutional controls in place. One important institutional control is limitations on well drilling near the Site, which results from interaction between the Arizona Department of Water Resources and ADEQ on well permits.
   B. Partial In Situ Treatment – same as Alternative 3A; implement in situ treatment along the landfill property boundary using bioremediation or a nanoscale zero-valent iron permeable reactive barrier wall; extract groundwater from the leading edge wells and treat using air stripper.
4. **Continued Current Operation** – both ex situ and in situ treatment were considered for this alternative.
   A. Ex Situ Treatment – continue current extraction, monitoring, ex situ treatment, and reuse operation; replace and rehabilitate extraction wells to maintain scale of remedial operation; leave institutional controls in place.
   B. Partial In Situ Treatment – same as Alternative 4A; implement in situ treatment along the landfill property boundary using bioremediation or a nanoscale zero-valent iron permeable reactive barrier wall; extract groundwater from the leading edge wells and treat using air stripper.
5. **Enhanced Active Remediation** – both ex situ and in situ treatment were considered for this alternative.

A. Ex Situ Treatment – same as Alternative 4A; begin operation of a landfill-wide source control remedy using SVE.
B. Partial In Situ Treatment – same as Alternative 4A; implement in situ treatment along the landfill property boundary using bioremediation or a nanoscale zero-valent iron permeable reactive barrier wall; extract groundwater from the leading edge wells and treat using air stripper.

Screening of Alternatives

The remedial alternatives were screened against the following three criteria: (1) Likelihood to achieve current ROs, (2) Implementability, and (3) Rough Order of Magnitude (ROM) costs. **Table 2** summarizes the results of the screening analysis. Alternatives 2 (Monitored Natural Attenuation[MNA]), 3A (Modified Current Operation), and 4A (Continued Current Operation) were retained for further analysis. Alternative 1, No Action, was not retained because it would not achieve the current ROs. Alternative 3B, Partial In Situ Treatment for the Current Operation and Alternative 4B, Partial In Situ Treatment for the Modified Operation, were not retained because pilot testing of the in situ treatment approaches would be required before their feasibility could be completely assessed. Pilot testing of in situ treatment could be beneficial in the future if passive remediation along the property boundary was required. The current network of extraction and monitor wells along the property boundary is particularly amenable to economical pilot testing of in situ treatment methods. Alternative 5, Enhanced Active Remediation, was not retained because implementing a landfill-wide source control remedy is believed to be impracticable.

Analysis of Alternatives

The retained alternatives were further analyzed to assess their feasibility for implementation at the Site. The primary objectives of this analysis were to assess the effect of the declining water table on remedy performance and whether MNA is feasible as a Site remedy.

Based on evaluation of regional water levels and discussions with Tucson Water staff about future pumping conditions near the Site, the water table is expected to continue declining at the Site over the next several years and possibly longer.

If the water table declines over the next 20 years (the planning timeframe used in this study), it would decline through predominantly silts and clays. As the water table declines, groundwater impacted by PCE and TCE would be move into deeper, fine-grained zones, where the rate of transport would be slow (on the order of feet per year). The effectiveness of the current pump and treat operation is expected to diminish as the water table declines, which will progressively reduce the pumping capacity and hydraulic capture of the extraction wells. Fouling, scaling, and deterioration of the wells could further diminish effectiveness and increase operational costs. Maintaining an effective pump and treat operation as the water table declines into more fine-grained zones would likely require many new, deeper, low flow rate extraction wells. Given the scenario of declining water table conditions and limited effectiveness of deeper extraction wells, it could become cost prohibitive, and probably impracticable, to maintain an effective pump and treat operation at the Site. Therefore, transition to an MNA remedy may become imminent, and may be the only practicable remedy, unless a yet to be determined remedial approach is identified.

The analysis included an empirical evaluation of existing data, groundwater modeling, and cost analyses. An empirical analysis of existing water level and well construction data was conducted to evaluate Alternative 3A (Modified Current Operation). Groundwater modeling was conducted to evaluate Alternatives 2 (MNA) and 3A (Modified Current Operation) (**Appendix B**). Cost analyses were conducted for Alternatives 3A and 4A (Current Operation). Groundwater modeling was not conducted for Alternative 4A because it is currently the active remedy at the Site and it has been demonstrated to be effective at achieving ROs and the operational costs are known.

Empirical Evaluation of Future Wellfield Performance

Future remedial wellfield performance empirically evaluated based on available data and assuming that the water table will continue to decline at the current rate (1.2 ft/y) over the next 20 years. This evaluation was conducted to estimate the future operational duration of the extraction wells. **Tables 3 and 4** summarize the data and results of the empirical analysis, respectively[5]. The future operational duration of each extraction well was estimated based on the following information, data, and assumptions:

- January 2012 water level data; the water table elevation at each extraction well was estimated based on a January 2012 water level contour map; interpolated water levels were used because pumping depths to water in the extraction wells are not recorded during operation due to the temporal variability of the depth to water.
- Depth of the pump intakes for each extraction well.
- Extraction wells have an assumed well efficiency[6] of 75 percent.
- Extraction wells become inoperable when the water level in the well drops below 2 feet above the pump intake.

The following observations were made based on the empirical evaluation:

- Average 2011-2012 extraction rates[7] range from 0.1 gpm at WR-376A to 17.8 gpm at LLM-530.
- Seven extraction wells had an extraction rate less than 2 gpm during 2011 and early 2012.
- Estimated future operational duration of the extraction wells ranges from approximately 2 to 17 years.

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[5] R-062B is not included in **Table 3** because it is screened in a deeper groundwater zone and is not expected to become inoperable due to the declining water table in the next 20 years.
[6] For this study, well efficiency was assumed to be the ratio of water level elevation in the extraction well and the water level elevation in the aquifer formation immediately outside the filter pack. Site-specific data do not exist to estimate well efficiency.
[7] Average extraction rates were assumed to be continuous and computed as the ratio of total volume pumped and operational time.

- Extraction wells WR-174A, R-061A, LLM-530, WR-376A, and WR-135A have an estimated future operational duration of 5 years or less.
- Fourteen of the 20 extraction wells screened in the shallow groundwater zone are projected to become inoperable in the next 10 years.
- During the next 10 years, the total extraction rate of the remedial wellfield is projected to decline to approximately 35 gpm.
- For seven extraction wells, it appears that sufficient distance exists (greater than 5 feet) between the current pump intake depth and the bottom of the well to lower the pump and prolong well operation.

Groundwater Modeling Evaluation

The groundwater flow and transport model was used to evaluate and compare Alternative 2 (MNA) and Alternative 3A (Modified Current Operation). **Appendix B** summarizes the model development and the methods and limitation of model calibration. This section of the report summarizes use of the model for comparative evaluation of the two remedial alternatives.

The following model conditions were common to simulation of both alternatives:

- A future simulation period of 20 years (2012 through 2031).
- Two different boundary conditions were simulated - one with declining boundary heads and one with steady boundary heads at 2011 groundwater levels.
- Simulated PCE transport processes included retardation and dispersion; natural biodegradation of PCE in groundwater is negligible at the Site and was therefore not simulated.
- A constant PCE source was assumed beneath the landfill.

For Alternative 2 (MNA), the model was used to simulate groundwater flow and PCE transport in groundwater without operation of the pump and treat system. For Alternative 3A (Modified Current Operation), the model was used to simulate groundwater flow and PCE transport in groundwater with the remedial wellfield initially operating at current extraction rates.

Under Alternative 3A, extraction wells that become inoperable due to the declining water table, severe fouling, or deterioration will be retired and not replaced. This differs from the ongoing remedial operation where extraction wells with severely declining performance are rehabilitated or replaced. In order to simulate the expected decline in remedial extraction for Alternative 3A, the Multi-Node Well 2 (MNW2) package was used. The MNW2 package is a more robust simulator of extraction well operation than the original MODFLOW well package. The MNW2 package was used because it could sustain or progressively reduce the extraction well flow rates as the boundary heads decline, which is an important for projecting the future performance of the modified pump and treat operation under Alternative 3A.

Figures 1 and 2 compare the projected extent of PCE concentration in groundwater above the Arizona Aquifer Water Quality Standard of 5 μg/L (PCE plume) for Alternatives 2 and 3A for both boundary condition simulations. The figures show the concentration contours from the shallowest model layer that is fully saturated over the plume area at 5-year increments. The model results indicate the following:

- The projected expansion of the PCE plume over the next 20 years for the MNA alternative is minimal for both declining and steady boundary conditions; the projected extent of the PCE plume in 20 years is within the existing monitor well network.
- The declining water table, combined with continued operation of the remedial wellfield with a progressively declining extraction rate, is projected to result in a reduction in the PCE plume compared to current conditions and the MNA alternative;

the reduction is most pronounced in the western plume lobe south of Los Reales Road and west of Swan Road.

- Remedial extraction along Swan Road is projected to be effective at reducing the extent of the PCE plume.
- Remedial extraction along and north of Los Reales Road is projected to minimally reduce the extent of the eastern PCE plume lobe.

The model results suggest that it would be feasible to transition the current remedy to an MNA remedy as extraction wells are retired due to poor performance.

Table 4 shows the model-projected decline in remedial wellfield extraction rate and number of operable extraction wells compared to that of the empirical data evaluation for the declining head boundary conditions. This comparison was only done for the declining boundary head simulation because the projected decline in remedial extraction rate for the steady boundary head simulation is minimal. Within the expected resolution of the analysis, the model-projected and empirically-projected future extraction rates and number of operable wells are consistent. The average percentage of remaining pumping and number of operable wells was computed for use in the cost analysis discussed below.

The model-projected decline in remedial wellfield pumping and number of operable extraction wells is more progressive and slower than the empirical analysis because the model is able to reduce extraction rate as the projected water level in the well declines. The average of the empirical evaluation and model results indicate that the total wellfield extraction rate would be less than 10 gpm after 2028 if the water table continues to decline at current rates.

As previously discussed, approximately 60 gpm of clean water supply are needed at the Site for dust control and irrigation. The empirical evaluation and modeling results suggest that this operational rate would be reached in about 2020 (**Table 4**). The model results also indicate that the projected PCE plume migration under the MNA alternative would be minimal and within the current monitor well network for both steady and declining boundary conditions. Based on these results, the following future operational scheme is projected to be feasible: (1) phase-out pump and treat system from 2013 to 2020 and use treated water for dust control and irrigation, and (2) in 2020 (or at time when total extraction rate drops below 60 gpm), cease pump and treat operation, adopt MNA remedy, and begin purchasing potable water for dust control and irrigation. This operational scheme will allow sufficient time to collect additional monitoring data to verify the model projections, install additional monitor wells in support of MNA, and develop a contingency plan to restart active remediation if needed. The number and location of additional monitor wells are provided in the recommendations.

Cost Analysis

Table 5 summarizes an analysis of estimated future remediation costs. The basis for the cost analysis was actual O&M expenditures for the fiscal years 2010 through 2012 provided by the COT-ES. Other key assumptions for each alternative are listed on the table. The analysis included estimating the annual future remedial costs for Alternatives 2, 3A, and 4A. Future remedial costs for Alternative 3A were reduced by an empirical *cost reduction factor*. The *cost reduction factor* was computed as the average of the projected percentage of remaining remedial extraction and operable extraction wells from the empirical and modeling analyses (**Table 4**). The *cost reduction factor* was only applied to electrical power and contractor costs.

The results of the cost analysis are summarized below:

- The estimated O&M cost over the next 20 years for the current operation (Alternative 4A) is approximately $6,000,000; contractor and sampling, well rehabilitation, and replacement are projected to comprise over 40 percent of future costs.
- The estimated O&M cost over the next 20 years for the MNA (Alternative 2) is approximately $3,400,000; laboratory and potable water costs comprise almost 80 percent of future costs.

- The estimated O&M cost over the next 20 years for the Modified Operation (Alternative 3A) is approximately $3,500,000; laboratory, contractor, and potable water costs comprise over 70 percent of future costs.
- Adopting Alternative 3A, with a progressive transition to MNA in about 2020, could result in an estimated reduction in future O&M costs of approximately $2,500,000; the majority of this reduction results from less contractor and well rehabilitation and replacement costs.
- The estimated future O&M costs from Alternative 2 (MNA) and Alternative 3A (Modified Operation) are similar because the cost of potable water for Alternative 2 during the period 2012 through 2020 ($800,000) is about the same as the difference in cost between Alternative 2 and 3A for the same time period.

SUMMARY AND CONCLUSIONS

This section summarizes the results and conclusions from the study:

HYDROGEOLOGIC/GROUNDWATER CONDITIONS

- Groundwater occurs in a complex heterogeneous assemblage of fine- to coarse-grained sediments within the Fort Lowell Formation; sediments appear to become more fine-grained with increasing depth over the interval screened by most of the extraction wells.
- Groundwater flow is to the northwest; groundwater flow velocities range from a few ft/y to several hundred ft/y, with an estimated average of 120 ft/y.
- Based on evaluation of regional water levels and discussions with Tucson Water staff about future pumping conditions near the Site, the water table is expected to continue declining at the Site over the next several years and possibly longer.

GROUNDWATER QUALITY

- PCE is the primary contaminant of concern because it is the most prevalent compound detected in groundwater and it is distributed over a large area in a relatively low concentration plume; TCE is also detected in groundwater in a relatively localized areas beneath and north of the SWDA.
- The source of PCE and TCE to groundwater is believed to be from vapor transport; sampling of landfill gas during this study indicated low concentrations of PCE, which suggests that a continuing source exists at the landfill.
- Overall, the PCE plume appears to be stable. Areas of recent increasing concentrations include the SWDA (WR-361A and WR-049A, the center of the landfill (LLM-500), and

in deep groundwater at R-062B. Extraction from R-062B appears to have stabilized PCE concentrations in that area.

- The current extent of PCE and TCE in groundwater does not appear to pose a threat to any known potable water supply wells. The nearest active potable water supply well downgradient of the Site is the Town and Country Well located over 1 mile from the Site boundary and over one-half mile from the inferred extent of detectable PCE concentrations in groundwater.

REMEDIAL OPERATIONS

- In 2011, the average wellfield extraction rate was approximately 92 gpm; the wellfield operated about 95 percent of the available time.
- To date, approximately 325 MG of groundwater have been treated, with the removal of approximately 19 lbs of PCE and 7 lbs of TCE.
- Recent annual O&M costs range from about $200,000 to $480,000, with an average annual cost of about $220,000.
- Treated water is an economical source of dust control water at the landfill; the cost of sufficient potable water for dust control would be about $100,000 per year.
- Future operation of the remedial wellfield is expected to become more challenging and expensive because the water table is expected to continue declining and fouling of the extraction wells is expected to require continued rehabilitation.
- The current remedial operations are achieving the ROs established in the 1994 RAP.

GROUNDWATER MODELING

- The spatial resolution of the existing groundwater model was too coarse to meet project objectives.

- A new groundwater model was constructed and calibrated to historical groundwater levels; limitations exist on use of the model due to limitations noted on model calibration.

REMEDIAL ALTERNATIVES

- Development, screening, and analysis of remedial alternatives lead to the identification of three feasible remedial alternatives: (1) Alternative 4A - continuing current operations, which attempts to maintain extraction in about 20 well and a total wellfield extraction rate between 100 and 140 gpm; (2) Alternative 3A - modifying the current operations by retiring extraction wells that become inoperable due to declining water levels, fouling, or deterioration; and (3) Alternative 2 - monitored natural attenuation as a partial transition remedy when combined with Alternative 3A.
- MNA appears to be a potentially viable remedy at the Site. Groundwater model results indicate that downgradient expansion of the PCE plume over the next 20 years under either declining or steady water table conditions would be relatively minimal. The projected extent of PCE above AWQSs after 20 years is well within the existing monitor well network.
- In 2011, seven extraction wells had an average extraction rate less than 2 gpm, including WR-376A, R-063A, WR-379A, LLM-536, LLM-548, LLM-537, and LLM-549. All of these wells are located on the north side of the landfill along Los Reales Road. The total average extraction rate in 2011 from these seven wells was approximately 5 gpm. Except for WR-376A and WR-379A, all of these wells had PCE concentrations less than AWQSs. All of these wells had TCE concentrations less than AWQS. Using the January 2012 PCE and TCE concentrations from these wells, the total PCE and TCE mass extracted annually from these wells is about 0.1 lbs, or less than 4 percent of the total PCE and TCE mass removed in 2011. Based on this evaluation, these wells do not significantly benefit the remedial operations in achieving ROs.

- The effectiveness of the current pump and treat operation is expected to diminish as the water table declines into more fine-grained hydrostratigraphic zones, which will progressively reduce the pumping capacity and hydraulic capture of the extraction wells. Fouling, scaling, and deterioration of the wells will further diminish effectiveness and increase operational costs. Under declining water table conditions, it could become cost prohibitive, and probably impracticable, to maintain an effective pump and treat operation at the Site. Therefore, transition to an MNA remedy may become imminent, and may be the only practicable remedy, unless a yet to be determined remedial approach is identified.
- Empirical evaluation of future extraction well pumping and the results of groundwater modeling assuming the water table will continue to decline at current rates indicated that wellfield extraction will progressively decline to less than 10 gpm by 2028.
- Cost analyses indicated that adopting Alternative 3A, and transitioning to MNA by in about 2020 could reduce future O&M costs by approximately $2,500,000 compared to continuing the current remedial operations; the majority of this cost reduction results from reducing contractor and well replacement/rehabilitation costs.

RECOMMENDATIONS

The following specific recommendations are based on the results of this study:

- Continue the pump and treat operation until the total wellfield extraction rate decreases to less than 60 gpm, which is projected to be in about 2020. From now until 2020, retire extraction wells that become inoperable due to lost pumping capacity from the declining water table, fouling, or deterioration; continue treating groundwater with the air stripper; and use treated water for dust control and irrigation. Transitioning from pump and treat to MNA over the next 8 years or so is recommended instead of an immediate change to MNA because additional monitoring data are needed to verify the model projections, install additional monitor wells and collect additional monitoring data to evaluate the efficacy of MNA, and to develop a contingency plan for restart of active remediation if needed.
- From now until 2020, prioritize and modify remedial extraction as follows:
  - Operate extraction wells along Swan Road including WR-135A, LLM-544, LLM-530, LLM-550, LLM-538, LLM-539, LLM-540, and WR-355A. Site data and groundwater model results indicate that these wells are effective at removing PCE and TCE mass from the groundwater. In addition, operating these wells will initially provide about 55 gpm of dust control/irrigation water based on average 2011 rates. The total extraction rate of these wells is projected to decline due to the declining water table conditions.
  - Operate well R-061A located along Los Reales Road. This well currently has a PCE concentration of approximately 21 µg/L. This well will initially provide about 5 gpm of dust control/irrigation water.
  - Operate the downgradient extraction wells WR-174A, WR-466A, and WR-470A. These wells provide some degree of off-site plume containment and would initially provide about 23 gpm of dust control/irrigation water.

- Operate deep extraction well R-062B. This well is effective at controlling deep migration of PCE and TCE in the north-central area of the landfill along Los Reales Road.
- Cease operation of wells extracting less than 2 gpm including WR-376A, R-063A, WR-379A, LLM-536, LLM-548, LLM-537, and LLM-549. These wells currently pump a total of about 5 gpm and are not projected to provide a substantial benefit to the remedy. Continue monitoring water quality in these wells.
- Cease operation of downgradient extraction well WR-173A because PCE and TCE concentrations in this well are less than AWQSs. Continue groundwater monitoring in WR-173A.

- Beginning in 2013, install additional monitor wells to enhance monitoring of the PCE and TCE plumes. Beginning installation of these new monitor wells in 2013 will enable sufficient time to collect additional monitoring data to verify the model projections and provide important data to assess the efficacy of MNA in the future. **Figure 3** shows areas where additional monitor wells are recommended and the depth and number of monitor wells recommended for each area. Monitor wells may be needed in other areas in the future depending on trends observed in water quality.
- Continue the current groundwater monitoring, data evaluation, and reporting program. Incorporate the new monitor wells into the monitoring program. Evaluate the monitoring data to determine whether the monitoring program can be revised to reduce cost while maintaining effectiveness.
- Evaluate VOC concentration trends in vapor and groundwater near the SWDA to determine if periodic source control is needed. If source control is needed, operate the SWDA SVE system as deemed appropriate.
- Develop a contingency plan that includes the conditions and criteria under which active remediation would be resumed.

REFERENCES CITED

Clear Creek Associates, 2004, **Groundwater Flow Model Documentation Report, Containment/Monitoring Plan for Los Reales Landfill**, prepared for City of Tucson, September 2, 2004.

Clear Creek Associates, 2006, **Completion Report for Installation and Testing of 6 New Groundwater Wells and the Modification of WR-184A**, prepared for City of Tucson, May 10, 2006.

Camp, Dresser, and McKee, 1994, **Final Draft Report, Los Reales Landfill, Phase II Remedial Action Plan – Feasibility Study**, prepared for the City of Tucson Office of Environmental Management, September 1994.

Errol L. Montgomery & Associates, Inc., 1994, **Assessment of Hydrogeologic Conditions and Migration of Volatile Organic Compounds in Groundwater, Los Reales Landfill, Pima County, Arizona**, prepared for City of Tucson, June 10, 1994.

Wilson and Meyerson, 1991, **Los Reales Landfill, Remedial Action Plan, Phase I - Remedial Investigation**, prepared by City of Tucson, Operations Department, Sanitation Division and Tucson Water, Planning and Technical Services Division, September 1991.

Wilson, W., 2012, Email communication from Wally Wilson, Lead Hydrologist, Tucson Water to Molly Collins, Project Manager, Environmental Services. May 31, 2012.

TABLE 1. REMEDIAL ALTERNATIVES
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

ALTERNATIVES		SOURCE CONTROL		PLUME CONTAINMENT	GROUNDWATER RESTORATION		MONITORING	INSTITUTIONAL CONTROLS
		Partial [a]	Complete [b]	Leading Edge P&T&D [c]	Property Boundary P&T&D	Property Boundary In Situ Treatment		
1	No Action							
2	Monitored Natural Attenuation						x	x
3	Modified Current Operation							
	A – Ex Situ Treatment by P&T	x		x	x [d]		x	x
	B – In Situ Treatment by ISB or PRBW [e]	x		x		x	x	x
4	Continue Current Operation							
	A – Ex Situ Treatment by P&T	x		x	x		x	x
	B – In Situ Treatment by ISB or PRBW	x		x		x	x	x
5	Enhanced Active Remediation							
	A – Ex Situ Treatment by P&T		x	x	x		x	x
	B – In Situ Treatment by ISB or PRBW		x	x		x	x	x

Notes:

[a] Partial source control would include periodic operation of the existing soil vapor extraction (SVE) system in the Southwest Disposal Area

[b] Complete source control would include operating the SWDA SVE system and implementing a landfill-wide SVE operation

[c] P&T&D - Pump, treat, and disposal

[d] For the Modified Current Operation (Alternative 3), wells that become inoperable due to declining water levels or lost capacity due to fouling or well deterioration would not be replaced

[e] In situ bioremediation (ISB) or permeable reactive barrier wall (PRBW) with nanoscale zero-valent iron along landfill property boundary; continue P&T operation for leading edge wells

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TABLE 2. SUMMARY OF REMEDIAL ALTERNATIVES SCREENING
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

ALTERNATIVES		LIKELIHOOD TO ACHIEVE CURRENT REMEDIAL OBJECTIVES	IMPLEMENTABILITY	ROUGH ORDER OF MAGNITUDE COSTS	RETAINED FOR FURTHER CONSIDERATION
1	No Action	Low	Easy	Low	No
2	Monitored Natural Attenuation	Moderate	Easy	Low	Yes
3	Modified Current Operation				
	A – Ex Situ Treatment by P&T [a]	Moderate to High	Easy	Moderate	Yes [b]
	B – In Situ Treatment by ISB or PRBW [c]	Moderate	Moderate to Difficult	Moderate to High	No
4	Continue Current Operation				
	A – Ex Situ Treatment by P&T	High	Moderate	High	Yes
	B – In Situ Treatment by ISB or PRBW	Moderate	Difficult	High	No
5	Enhanced Active Remediation				
	A – Ex Situ Treatment by P&T	High	Difficult	High	No
	B – In Situ Treatment by ISB or PRBW	Moderate	Difficult	High	No

Notes:

[a] Pump and treat with disposal
[b] Alternative 4A is currently operating at the Site. In the context of WQARF Feasibility Study rules, Alternative 4A is considered the reference remedy and was retained for comparison to other retained alternatives.
[c] In situ bioremediation (ISB) or permeable reactive barrier wall (PRBW) with nanoscale zero-valent iron along landfill property boundary; continue P&T operation for leading edge wells

P&T - Pump and treat
WQARF - Water Quality Assurance Revolving Fund

TABLE 3. EVALUATION OF REMEDIAL EXTRACTION WELL OPERATION
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

WELL NAME	EASTING	NORTHING	GROUND SURFACE ELEVATION (ft msl)	TOP OF CASING ELEVATION (ft msl)	ESTIMATED JANUARY 2012 WATER LEVEL ELEVATION AT PUMPING WELL LOCATION [a] (ft msl)	WELL DEPTH (ft bgs)	PUMP INTAKE DEPTH (ft btoc)	PUMP INTAKE ELEVATION (ft msl)	TOP OF SCREEN ELEVATION (ft msl)	WELL BOTTOM ELEVATION (ft msl)	WELL SCREEN SLOT [b]/MATERIAL	LITHOLOGIC STATA SCREENED	DISTANCE BETWEEN PUMP INTAKE AND WELL BOTTOM (ft)	HEIGHT OF WATER COLUMN ABOVE PUMP (ft)	HEIGHT OF WATER COLUMN ABOVE PUMP (WE = 75%) (ft)	HEIGHT OF WATER COLUMN ABOVE WELL BOTTOM (WE = 75%) (ft)	AVERAGE 2011 - 12 PUMPING RATE (gpm)	PROJECTED DURATION OF OPERATION [c] (years)
WR-174A	1,015,895	408,751	2,690	2687.70	2,484.2	221	210	2,478	2,506	2,469	Perf Steel?	sandy gravel; gravelly sand (15 ft); sandy clay; silty sand w/gravel; sandy clay	8	7	5	11	6.6	2
R-061A	1,019,333	408,588	2,715	2711.78	2,492.0	240	228	2,484	2,520	2,475	10; WRSS	gravelly sand; gravel/cobbles w/silt; silty clay	9	8	6	13	5.3	3
LLM-530	1,017,225	408,006	2,700	2698.82	2,484.3	232	223	2,476	2,508	2,468	60; WRSS	gravel and sand	8	8	6	12	17.8	4
WR-376A	1,020,787	408,603	2,721	2718.73	2,491.0	244	238	2,481	2,522	2,477	10; SS?	silty clay to clayey silt (clayey sand 260 275 ft in R-105 log)	3	10	8	10	0.1	5
WR-135A	1,017,256	408,520	2,696	2694.12	2,484.4	230	221	2,473	2,511	2,466	Perf Steel	mostly in sandy clay to clay; top 5 feet more coarse	7	11	8	14	2.2	5
LLM-537	1,017,673	408,594	2,697	2696.03	2,486.0	230	224	2,472	2,507	2,467	60; WRSS	clayey sand (10 ft), sandy silt, clay	5	14	10	14	0.4	7
LLM-536	1,018,135	408,574	2,699	2698.41	2,487.9	230	225	2,473	2,509	2,469	60; WRSS	clayey sand and gravels	4	14	11	14	1.0	7
WR-173A	1,016,972	410,034	2,691	2688.57	2,482.5	223	221	2,468	2,512	2,468	Perf Steel?	gravelly sand (silt) to 195; sandy clay and clay to 223	0	15	11	11	4.8	8
WR-466A	1,019,146	410,054	2,701	2698.24	2,486.2	240	228	2,470	2,506	2,461	60; WRSS	sandy clay, sand 215-220	9	16	12	19	7.5	8
WR-470A	1,019,844	410,033	2,706	2703.20	2,486.9	240	233	2,470	2,506	2,466	60; WRSS	clayey gravelly sand/sandy gravel/sand; silty clay bottom 10	4	17	13	16	9.3	9
LLM-551	1,017,229	407,714	2,698	2696.65	2,486.6	230	227	2,470	2,508	2,469	0.04 / WRSS	silty sand with gravel	1	17	13	13	15	9
R-063A	1,019,730	408,596	2,718	2715.27	2,493.5	245	239	2,476	2,518	2,473	10: wire wrap	sandy gravel w/silt; silty sand; silty clay w/sand; gravel dewatered?	3	17	13	15	0.3	9
LLM-549	1,017,458	408,600	2,697	2694.75	2,485.1	236	227	2,468	2,512	2,462	40; WRSS	dense sandy/clayey silt	6	17	13	18	1.0	9
LLM-544	1,017,222	408,254	2,702	2700.14	2,484.0	240	234	2,466	2,512	2,462	0.06 / WRSS	gravel; clayey gravel/ gravelly clay; clay	4	18	13	17	2	9
LLM-548	1,017,907	408,587	2,699	2697.37	2,486.9	236	229	2,468	2,513	2,463	0.04 / WRSS	sandy silt/silty sand w/gravel and clay	5	19	14	18	0.9	10
WR-379A	1,019,127	408,599	2,710	2707.69	2,490.6	244	238	2,470	2,511	2,466	unk?	no log; use IJ-02; silty gravel w/sand; silt,clay,sand mixture; well graded sand w/gravel	3	21	16	18	1.3	11
LLM-538	1,017,227	407,399	2,693	2691.33	2,488.8	230	225	2,466	2,503	2,463	60; WRSS	silty gravelly sand (10 ft), silt w/sand and gravel	4	22	17	20	9.4	12
LLM-539	1,017,238	407,113	2,692	2690.22	2,490.8	230	226	2,464	2,502	2,462	60; WRSS	clayey silt w/10-30% coarse fraction	3	27	20	22	3.0	15
LLM-540	1,017,244	406,801	2,691	2689.95	2,492.7	230	226	2,464	2,501	2,461	60; WRSS	clayey silt w/20-40% coarse fraction	3	29	22	24	3.7	16
WR-355A	1,017,235	406,353	2,689	2687.54	2,495.0	225	222	2,466	2,518	2,464	SCH 80 0.02 Slot	sand; gravel; clay	2	29	22	23	17.2	17

NOTES:
[a] The January 2012 water table elevations were contoured using Surfer; the approximate water table elevation at the extraction well locations was interpolated based on the contoured water table surface
[b] Well screen slot size in inches
[c] Projected based on a rate of water table decline of 1.2 feet per year, and assuming that well will become inoperable when water level in well drops to below 2 feet above pump intake

ft = feet
ft msl = feet above mean sea level
ft bgs = feet below ground surface
ft btoc = feet below top of casing
Perf = perforated
WRSS = wire wrap stainless steel
SS = stainless steel
unk = unknown
SCH = schedule
WE = well efficiency; assumed value to account for seepage face that exists between water level in well and water level in formation outside filter pack
gpm = gallons per minute

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TABLE 4. PROJECTED FUTURE REMEDIAL WELLFIELD PERFORMANCE
DECLINING WATER LEVELS
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

YEAR	EMPIRICAL ANALYSIS				GROUNDWATER MODELING				AVERAGE EXTRACTION RATE	AVERAGE PERCENTAGE [b]
	PROJECTED WELLFIELD EXTRACTION RATE (gpm)[a]	PERCENTAGE OF 2012 EXTRACTION RATE	PROJECTED NUMBER OF OPERABLE WELLS	PERCENTAGE OF OPERABLE WELLS	PROJECTED WELLFIELD EXTRACTION RATE (gpm)	PERCENTAGE OF 2012 EXTRACTION RATE	PROJECTED NUMBER OF OPERABLE WELLS	PERCENTAGE OF OPERABLE WELLS		
2012	109	100%	21	100%	109	100%	21	100%	109	100%
2013	109	100%	21	100%	99	91%	21	100%	104	98%
2014	102	94%	20	95%	90	82%	20	95%	96	92%
2015	79	73%	18	86%	79	73%	20	95%	79	82%
2016	79	73%	17	81%	71	65%	19	90%	75	77%
2017	77	71%	16	76%	67	62%	18	86%	72	74%
2018	77	71%	16	76%	64	59%	18	86%	70	73%
2019	71	65%	13	62%	60	55%	17	81%	65	66%
2020	39	36%	10	48%	54	50%	17	81%	46	53%
2021	35	32%	6	29%	48	44%	17	81%	41	46%
2022	35	32%	6	29%	42	39%	15	71%	38	43%
2023	33	31%	5	24%	37	34%	15	71%	35	40%
2024	24	22%	4	19%	33	30%	12	57%	28	32%
2025	24	22%	4	19%	29	27%	10	48%	26	29%
2026	21	19%	3	14%	25	23%	10	48%	23	26%
2027	21	19%	3	14%	22	20%	9	43%	21	24%
2028	0	0%	1	5%	19	17%	9	43%	9	16%
2029	0	0%	1	5%	17	15%	7	33%	8	13%
2030	0	0%	1	5%	15	14%	6	29%	8	12%
2031	0	0%	1	5%	14	13%	5	24%	7	10%

Notes:
[a] gpm = gallons per minute
[b] Average of percentage of 2012 extraction rate and percentage of operable wells for both methods; average percentage used to index future remedial costs

TABLE 5. ESTIMATED FUTURE OPERATION AND MAINTENANCE COSTS FOR REMEDIAL ALTERNATIVES 2, 3A AND 4A
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

REMEDIAL ALTERNATIVE	O&M COST [a]	BASE COST (x 1,000) [b]	UNIT	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	TOTAL	% of TOTAL COST
2 Monitored Natural Attenuation	Electrical Power: GW and SVE	$0	year	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	0%
Assumptions:	Laboratory Costs	$35	year	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$700	20%
Cease P&T operation	Programming and Electrical	$1	year	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$20	1%
Continue monitoring program	Professional Consultant Services	$0	year	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	0%
Purchase potable water for dust control/irrigation	Contractor (routine O&M services)	$10	year	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$200	6%
	Sampling	$10	year	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$200	6%
	Well Installation/Abandonment	$0	year	$0	$80	$80	$40	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$200	6%
	Miscellaneous	$5	year	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$100	3%
	SUBTOTAL	$61	year	$61	$141	$141	$101	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$1,420	
	Potable Water Cost (dust control/irrigation) [c]	$1.67	gpm	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$2,000	58%
	TOTAL		year	$161	$241	$241	$201	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$3,420	

REMEDIAL ALTERNATIVE	O&M COST	BASE COST (x 1,000)	UNIT	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	TOTAL	% of TOTAL COST
3A Modified Current Operation	Electrical Power: GW and SVE	$23	year	$23	$22	$21	$19	$18	$17	$17	$15	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$152	4%
Assumptions:	Laboratory Costs	$35	year	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$700	20%
Pump operable wells until 2020	Programming and Electrical	$25	year	$25	$25	$25	$25	$25	$25	$25	$25	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$212	6%
Shut down P&T system; transition to MNA in 2020	Professional Consultant Services	$0	year	$0	$0	$25	$0	$0	$25	$0	$0	$25	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$75	2%
Limited well rehabilitation	Contractor (routine O&M services)	$70	year	$70	$68	$64	$57	$54	$51	$51	$46	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$582	17%
Add 5 new monitor wells to enhance monitoring	Sampling	$15	year	$15	$15	$15	$15	$15	$15	$15	$15	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$240	7%
No well abandonment	Well Installation/Abandonment	$0	year	$0	$80	$80	$40	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$200	6%
Consultant evaluates system every 3 years	Miscellaneous	$5	year	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$5	$100	3%
Costs decline with extraction rate/no. operating wells	SUBTOTAL	$173	year	$173	$251	$270	$196	$152	$173	$148	$141	$86	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$61	$2,261	
Potable water purchased for dust control after 2019	Potable Water Cost (dust control/irrigation) [c]	$1.67	gpm	$0	$0	$0	$0	$0	$0	$0	$0	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$1,200	35%
Operate SWDA SVE (6 months every 3 years)	TOTAL		year	$173	$251	$270	$196	$152	$173	$148	$141	$186	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$161	$3,461	
	Cost Reduction Factor [d]			100%	98%	92%	82%	77%	74%	73%	66%	53%	46%	43%	40%	32%	29%	26%	24%	16%	13%	12%	10%		
	Projected Wellfield Extraction Rate [e]			109	104	96	79	75	72	70	65	46	41	38	35	28	26	23	21	9	8	8	7		

REMEDIAL ALTERNATIVE	O&M COST	BASE COST (x 1,000)	UNIT	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	TOTAL	% of TOTAL COST
4A Continue Current Operation	Electrical Power: GW and SVE	$23	year	$23	$23	$43	$23	$23	$43	$23	$23	$43	$23	$23	$43	$23	$23	$43	$23	$23	$43	$23	$23	$580	10%
Assumptions:	Laboratory Costs	$35	year	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$700	12%
Operate P&T system (~100-120 gpm)	Programming and Electrical	$25	year	$25	$25	$25	$45	$25	$45	$25	$45	$25	$45	$25	$45	$25	$45	$25	$45	$25	$45	$25	$45	$680	11%
Maintain 21 extraction wells	Professional Consultant Services	$0	year	$0	$0	$50	$0	$0	$50	$0	$0	$50	$0	$0	$50	$0	$0	$50	$0	$0	$50	$0	$0	$300	5%
Replace/add 2 wells biannually	Contractor (Routine O&M Services)	$70	year	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$70	$1,400	23%
Rehabilitate wells annually	Sampling, Well Rehab and Well Repair	$60	year	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$60	$1,200	20%
Operate SWDA SVE (6 months every 3 years)	Well Installation/Abandonment	$0	year	$0	$0	$0	$100	$0	$100	$0	$100	$0	$100	$0	$100	$0	$100	$0	$100	$0	$100	$0	$100	$900	15%
No new monitor wells	Miscellaneous	$10	year	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$10	$200	3%
Consultant evaluates system every 3 years	TOTAL	$223	year	$223	$223	$293	$343	$223	$413	$223	$343	$293	$343	$223	$413	$223	$343	$293	$343	$223	$413	$223	$343	$5,960	
	Operate SVE	$20	6 months	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0		
	Replace/Add EWs	$50	per well	0	0	0	2	0	2	0	2	0	2	0	2	0	2	0	2	0	2	0	2		
	Programming and Electrical	$10	per well	0	0	0	2	0	2	0	2	0	2	0	2	0	2	0	2	0	2	0	2		

Notes:
gpm = gallons per minute
O&M = operation and maintenance
P&T = pump and treat
MNA = Monitored Natural Attenuation
SWDA = Southwest Disposal Area
GW = groundwater
SVE = Soil vapor extraction
EWs= extraction wells
no. = number

[a] Operations and maintenance (O&M) cost information provided by City of Tucson, Environmental Services Department; inflation was not included in future costs
[b] Base costs estimated from 2010 through 2012 expenditures
[c] If total wellfield extraction rate is below 60 gpm, potable water would need to be purchased for dust control.
[d] Cost reduction factor based on empirical analysis of projected well performance and results of groundwater modeling (See **Table 4**).
System operations and maintenance costs were assumed to decline as system flowrate and number of operating wells decline.
[e] See **Table 4**

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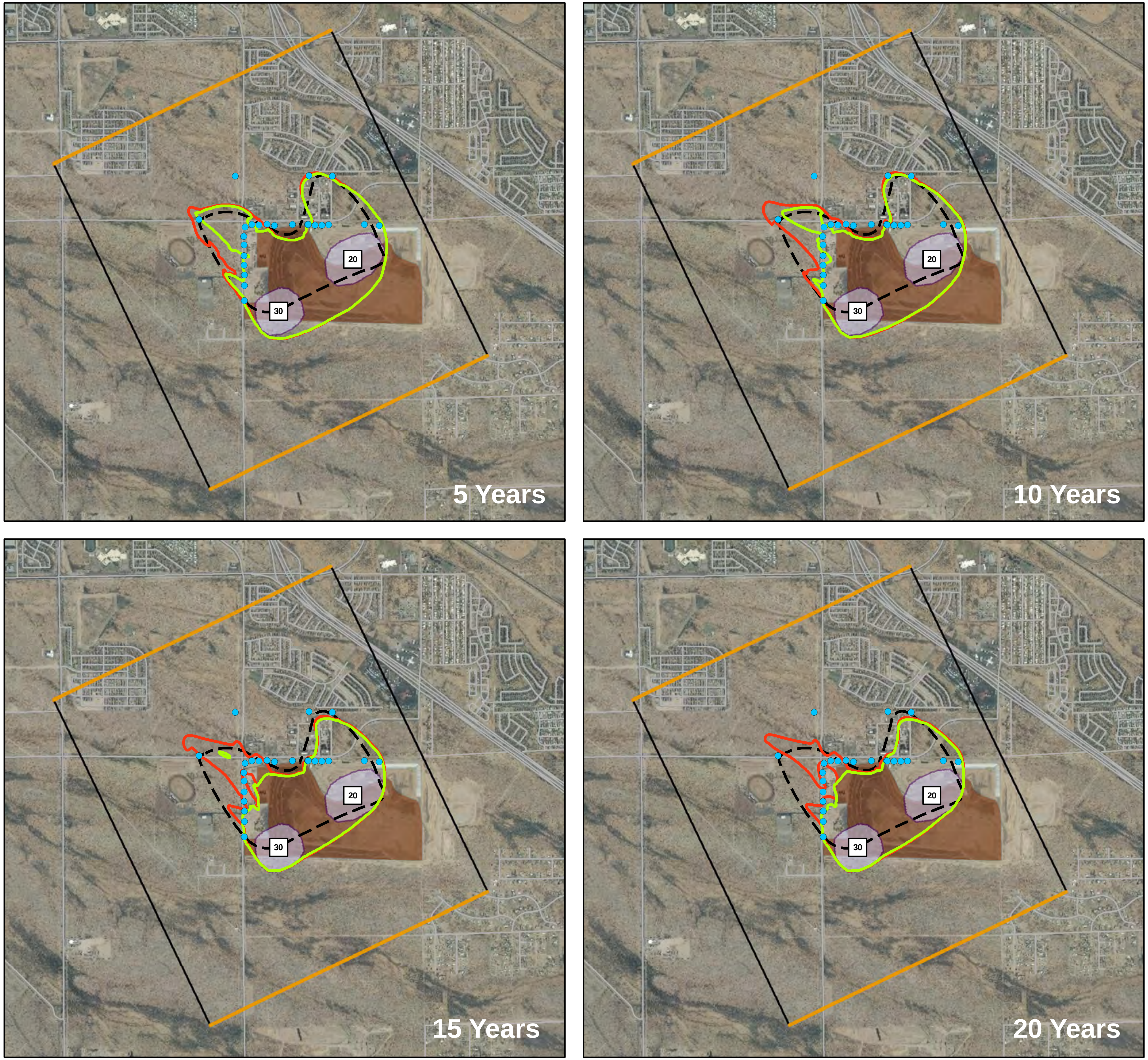

EXPLANATION

- Remediation Well
- Specified Head Boundary
- No Flow Boundary
- Los Reales Landfill
- Estimated Extent of 5 µg/L PCE Concentration Contour, January 2012
- Simulated Extent of 5 µg/L PCE Concentration Contour for Alternative 2, Monitored Natural Attenuation
- Simulated Extent of 5 µg/L PCE Concentration Contour for Alternative 3A, Modified Current Operation
- 20 Simulated Constant Concentration Source Area in Layers 1 through 3; concentration in µg/L shown in box

Notes:
µg/L = Micrograms per liter
PCE = Tetrachloroethene

0 1,200 2,400 3,600
Feet

City of Tucson, Environmental Services
Los Reales Landfill

MODEL RESULTS DECLINING HEAD BOUNDARIES

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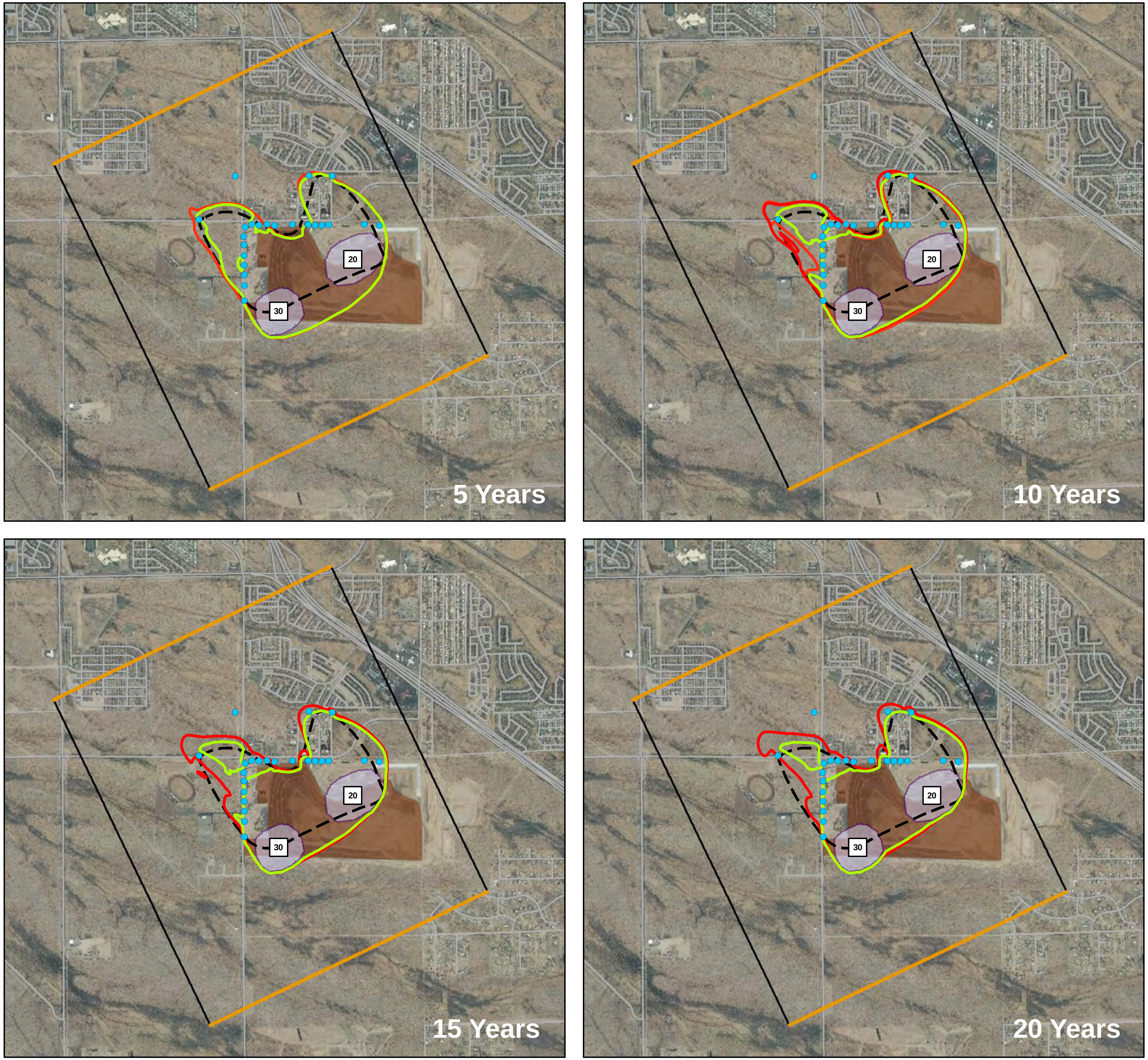
Water Resource Consultants

2012

FIGURE 1

GIS-Tuc\1373.03\Decline_5_20yr_SRC\23July2012



EXPLANATION

- Remediation Well
- Specified Head Boundary
- No Flow Boundary
- Los Reales Landfill
- Estimated Extent of 5 µg/L PCE Concentration Contour, January 2012
- Simulated Extent of 5 µg/L PCE Concentration Contour for Alternative 2, Monitored Natural Attenuation
- Simulated Extent of 5 µg/L PCE Concentration Contour for Alternative 3A, Modified Current Operation
- 20 Simulated Constant Concentration Source Area in Layers 1 through 3; concentration in µg/L shown in box

Notes:
µg/L = Micrograms per liter
PCE = Tetrachloroethene

0 1,200 2,400 3,600
Feet

City of Tucson, Environmental Services
Los Reales Landfill

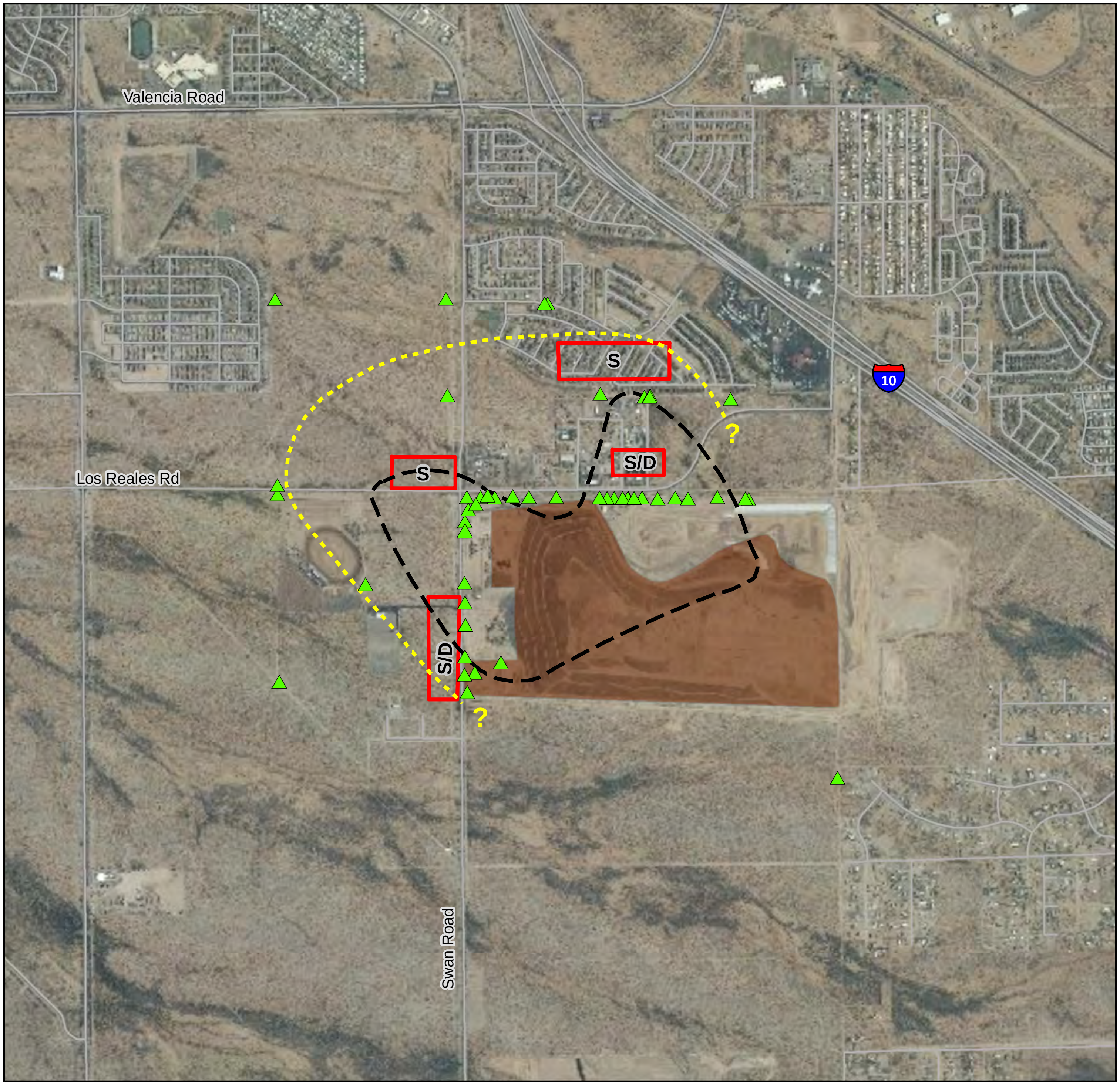
MODEL RESULTS CONSTANT HEAD BOUNDARIES

MONTGOMERY & ASSOCIATES
Water Resource Consultants

2012

FIGURE 2

GIS-Tuc\1373.03\Constant_5_20yr\23July2012



EXPLANATION

Monitor Well

Los Reales Landfill

Estimated Extent of 5 µg/L PCE Concentration Contour, January 2012

Area Where Additional Monitor Well(s) are Recommended

S = One shallow monitor well recommended

S/D = One shallow and deep monitor well recommended

Inferred Extent of PCE Concentration above 1 microgram per liter based on 2011 Water Quality Data

Notes:
µg/L = Micrograms per liter
PCE = Tetrachloroethene

0 1,200 2,400
Feet

City of Tucson, Environmental Services
Los Reales Landfill

RECOMMENDED NEW MONITOR WELLS

MONTGOMERY & ASSOCIATES
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2012

FIGURE 3

GIS-Tuc\1373.03\Recommended_Monwells\23July2012

APPENDIX A

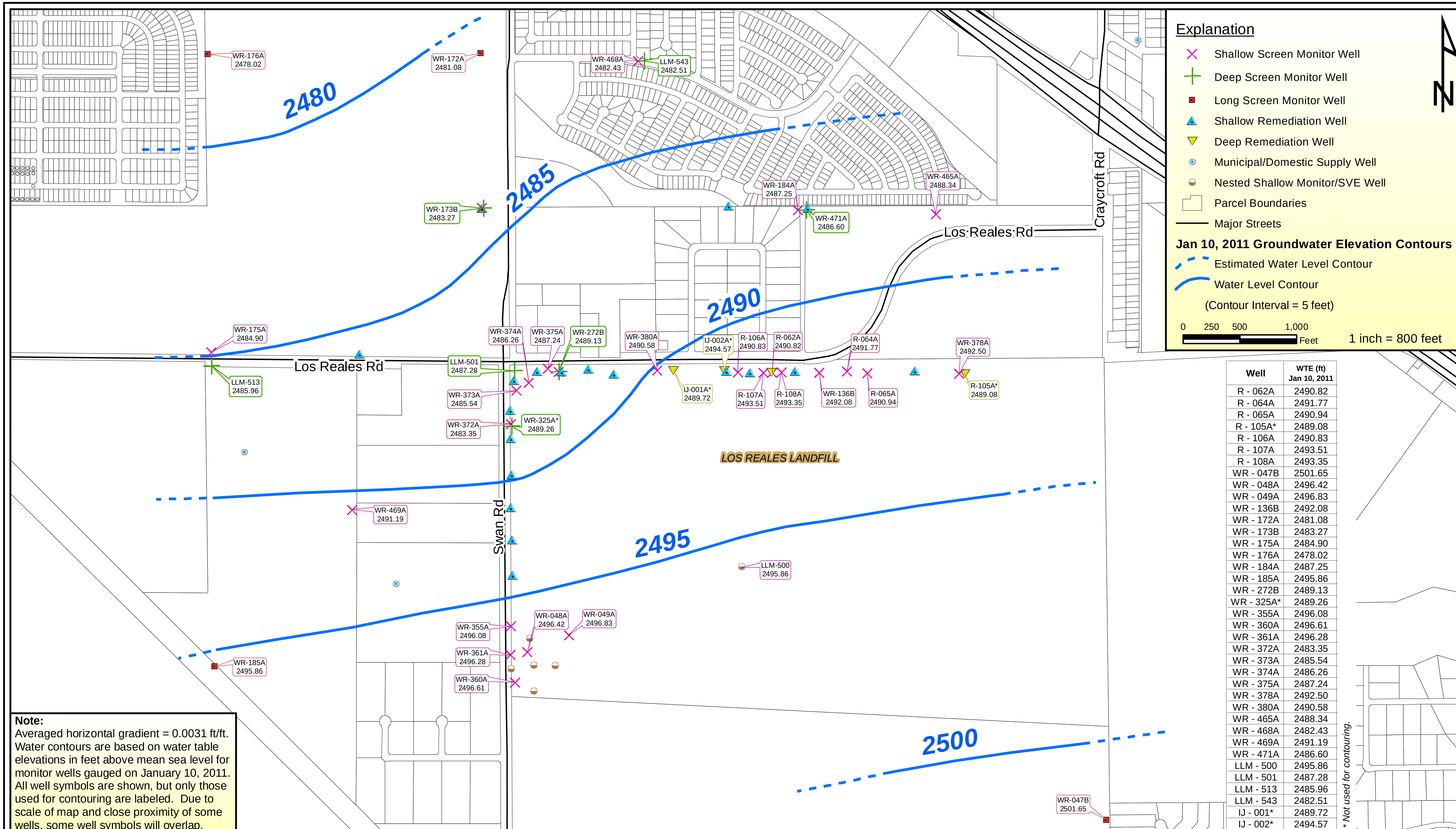
SUPPORT MAPS
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

CITY OF TUCSON
ENVIRONMENTAL SERVICES

FIGURE 2
SITE MAP
LOS REALES LANDFILL

Drawn By:	LE
Checked:	MC
Approved:	JD
Date:	1/6/2011
File:	See Below

J:GIS\LosReales2010sitemapv2.mxd



Well	WTE (ft) Jan 10, 2011
R - 062A	2490.82
R - 064A	2491.77
R - 065A	2490.94
R - 105A*	2489.08
R - 106A	2490.83
R - 107A	2493.51
R - 108A	2493.35
WR - 047B	2501.65
WR - 048A	2496.42
WR - 049A	2496.83
WR - 136B	2492.08
WR - 172A	2481.08
WR - 173B	2483.27
WR - 175A	2484.90
WR - 176A	2478.02
WR - 184A	2487.25
WR - 185A	2495.86
WR - 272B	2489.13
WR - 325A*	2489.26
WR - 355A	2496.08
WR - 360A	2496.61
WR - 361A	2496.28
WR - 372A	2483.35
WR - 373A	2485.54
WR - 374A	2486.26
WR - 375A	2487.24
WR - 378A	2492.50
WR - 380A	2490.58
WR - 465A	2488.34
WR - 468A	2482.43
WR - 469A	2491.19
WR - 471A	2486.60
LLM - 500	2495.86
LLM - 501	2487.28
LLM - 513	2485.96
LLM - 543	2482.51
IJ - 001*	2489.72
IJ - 002*	2494.57

Note:
Averaged horizontal gradient = 0.0031 ft/ft. Water contours are based on water table elevations in feet above mean sea level for monitor wells gauged on January 10, 2011. All well symbols are shown, but only those used for contouring are labeled. Due to scale of map and close proximity of some wells, some well symbols will overlap.

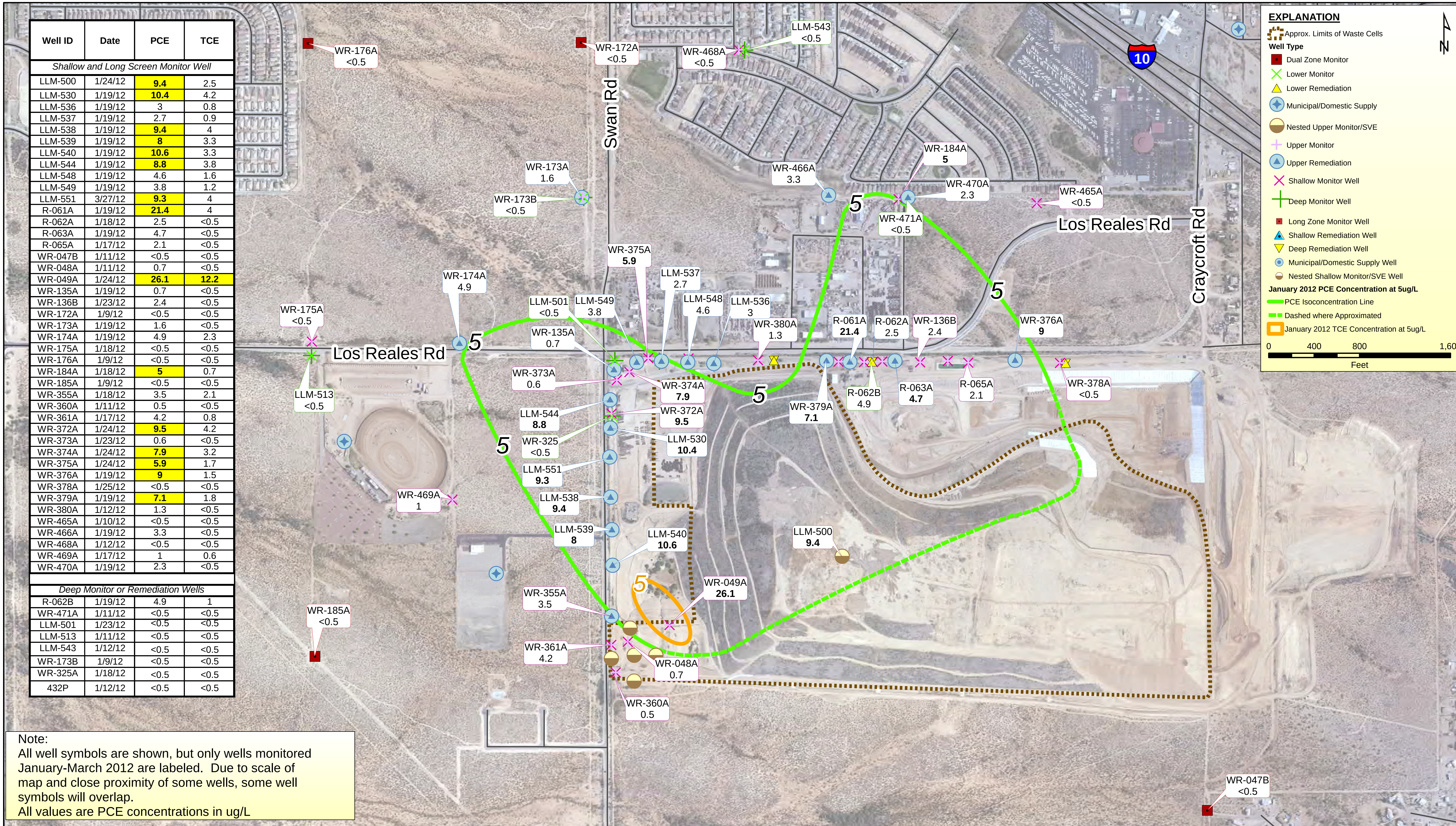
CITY OF TUCSON
ENVIRONMENTAL SERVICES

FIGURE 3
LOS REALES LANDFILL GROUNDWATER CONTOUR MAP
JANUARY 2011

Drawn By:	LE
Checked:	MC
Approved:	JD
Date:	6/22/2011
File:	See Below

J:\GIS\LosReales\2011\WL_Jan2011.mxd

Well ID	Date	PCE	TCE
Shallow and Long Screen Monitor Well			
LLM-500	1/24/12	**9.4**	2.5
LLM-530	1/19/12	**10.4**	4.2
LLM-536	1/19/12	3	0.8
LLM-537	1/19/12	2.7	0.9
LLM-538	1/19/12	**9.4**	4
LLM-539	1/19/12	**8**	3.3
LLM-540	1/19/12	**10.6**	3.3
LLM-544	1/19/12	**8.8**	3.8
LLM-548	1/19/12	4.6	1.6
LLM-549	1/19/12	3.8	1.2
LLM-551	3/27/12	**9.3**	4
R-061A	1/19/12	**21.4**	4
R-062A	1/18/12	2.5	<0.5
R-063A	1/19/12	4.7	<0.5
R-065A	1/17/12	2.1	<0.5
WR-047B	1/11/12	<0.5	<0.5
WR-048A	1/11/12	0.7	<0.5
WR-049A	1/24/12	**26.1**	**12.2**
WR-135A	1/19/12	0.7	<0.5
WR-136B	1/23/12	2.4	<0.5
WR-172A	1/9/12	<0.5	<0.5
WR-173A	1/19/12	1.6	<0.5
WR-174A	1/19/12	4.9	2.3
WR-175A	1/18/12	<0.5	<0.5
WR-176A	1/9/12	<0.5	<0.5
WR-184A	1/18/12	**5**	0.7
WR-185A	1/9/12	<0.5	<0.5
WR-355A	1/18/12	3.5	2.1
WR-360A	1/11/12	0.5	<0.5
WR-361A	1/17/12	4.2	0.8
WR-372A	1/24/12	**9.5**	4.2
WR-373A	1/23/12	0.6	<0.5
WR-374A	1/24/12	**7.9**	3.2
WR-375A	1/24/12	**5.9**	1.7
WR-376A	1/19/12	**9**	1.5
WR-378A	1/25/12	<0.5	<0.5
WR-379A	1/19/12	**7.1**	1.8
WR-380A	1/12/12	1.3	<0.5
WR-465A	1/10/12	<0.5	<0.5
WR-466A	1/19/12	3.3	<0.5
WR-468A	1/12/12	<0.5	<0.5
WR-469A	1/17/12	1	0.6
WR-470A	1/19/12	2.3	<0.5
Deep Monitor or Remediation Wells			
R-062B	1/19/12	4.9	1
WR-471A	1/11/12	<0.5	<0.5
LLM-501	1/23/12	<0.5	<0.5
LLM-513	1/11/12	<0.5	<0.5
LLM-543	1/12/12	<0.5	<0.5
WR-173B	1/9/12	<0.5	<0.5
WR-325A	1/18/12	<0.5	<0.5
432P	1/12/12	<0.5	<0.5



Note:
All well symbols are shown, but only wells monitored January-March 2012 are labeled. Due to scale of map and close proximity of some wells, some well symbols will overlap.
All values are PCE concentrations in ug/L

CITY OF TUCSON
ENVIRONMENTAL SERVICES

FIGURE 5
LOS REALES LANDFILL
PCE AND TCE CONCENTRATIONS IN GROUNDWATER
JANUARY 2012

Drawn By:	MC
Checked:	LE
Approved:	JD
Date:	4/6/2012
File:	See Below

J:GIS\LosReales\2012\PCEMapJAN12.mxd

MONTGOMERY & ASSOCIATES

APPENDIX B

GROUNDWATER FLOW AND TRANSPORT MODELING CONDUCTED FOR EVALUATION OF REMEDIATION STRATEGIES
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

APPENDIX B

GROUNDWATER FLOW AND TRANSPORT MODELING CONDUCTED FOR EVALUATION OF REMEDIATION STRATEGIES LOS REALES LANDFILL CITY OF TUCSON, ENVIRONMENTAL SERVICES

INTRODUCTION

At the request of the City of Tucson, Environmental Services (COT-ES) and in accordance with the scope of work outlined in the October 10, 2011 Request for Proposal, Montgomery & Associates (M&A) has prepared this document to summarize review of the existing groundwater model, and construction of a new groundwater flow and transport model for the Los Reales Landfill (Site). The modeling was conducted to support evaluation of remediation strategies at the Site.

REVIEW OF EXISTING MODEL

The existing groundwater flow and transport model was developed by Clear Creek Associates (CCA) in 2004. The CCA model was reviewed using files provided by COT-ES and based on documentation of the model in a draft report and presentation prepared by CCA (CCA, 2004a and b). The CCA model was developed in the Visual Modflow graphical user interface. For the review, M&A imported the CCA model into the Groundwater Vistas graphical user interface. The model grid, layers, boundaries, hydraulic properties, transport parameters, and simulation results were evaluated.

Table B-1 summarizes the CCA model construction. The CCA model simulated the period from 1991 through 2003. The CCA model grid sizes range from 50 to 200 feet. The CCA model covers a 12.5 square mile area, is oriented parallel with the general groundwater flow direction, and has specified head boundaries assigned on the northwest and southeast boundaries and no flow boundaries assigned on the northeast and southwest boundaries. The model has 3 layers that generally correspond to an upper coarse-grained zone, a middle fine-grained zone, and a lower fine to coarse-grained zone. In layer 1, hydraulic varied from 2 to 80 feet per day in four zones. Layers 2 and 3 had uniform hydraulic conductivity values of 1 and 20 feet per day (ft/d), respectively.

M&A updated the CCA model to simulate remedial operations through 2011. The updated CCA model was run and the results were evaluated to determine their adequacy for achieving the current study objectives. Based on review of the model construction and the results of updated model run, it became apparent that the CCA model grid sizes were too big, the model included too few layers, and the hydraulic conductivity values in each layer were too generalized to achieve the study objectives. These model limitations were evident in the results of the updated model run, which had remedial extraction wells going dry and shutting off earlier than has been observed during actual operations. Because of this result, a new model was needed to meet project objectives.

NEW MODEL CONSTRUCTION

M&A constructed a new model to address the limitations identified in the CCA model. The new groundwater model was developed based on available data. **Table B-1** compares selected aspects of the new model to the original CCA model. The new model was constructed using the finite-difference code MODFLOW-2005 (Harbaugh, 2005) and contaminant transport code MT3DMS (Zheng and Wang, 1999). The modeling was conducted using the Groundwater Vistas graphical user interface (Rumbaugh and Rumbaugh, 2011). The new model has smaller grid sizes, more and thinner layers, and additional spatial variability in hydraulic conductivities based on the heterogeneity observed in lithologic logs for the wells.

FLOW MODEL

The following sections describe the new model grid, boundary conditions, and methods for simulating the remediation wells. The model was subdivided into two time periods: (1) historic model (1999 to 2011) and (2) predictive model (2012 to 2031).

Grid

The model domain is shown on **Figure B-1**. The model domain covers an area of 3.5 square miles, with a uniform grid size of 25 feet. The model grid has 428 rows and 364 columns for a total of 1,402,128 active nodes. The total thickness of the model is approximately 200 feet, and is divided into 9 layers. The water table, which varies with time, serves as the top boundary of the model, and the model bottom boundary is assumed to be horizontal plane at an elevation of 2,300 feet above mean sea level (ft amsl). With the exception of model layer 1, all layers have a uniform thickness and were selected to allow a reasonable representation of vertical heterogeneity. **Table B-2** summarizes model layer thicknesses and bottom elevations.

Boundary Conditions

Figure B-2 shows the model boundary conditions. Time-varying specified head are simulated along the northwestern and southeastern boundaries of the model. For the historical model, the specified head values at the boundaries were developed by first contouring the 2011 water levels and then assigning each previous year to 1999 by increasing the boundary head by 1.2 feet. This method was used to simulate the average water table decline over the historical model period. No-flow boundaries were specified along the northeastern and southwestern sides of the model.

Remediation Wells

Remediation wells were simulated using the Multi-Node Well 2 (MNW2) package (Konikow, L.F. et. al, 2009). **Figure B-2** shows the remediation wells simulated in the model. The MNW2 package is an updated well simulator that improves the capability of the model to simulate pumping under declining water level conditions. Use of this package assisted in model calibration by avoiding an artificial increase in hydraulic conductivities in an effort to maintain pumping.

Hydraulic Properties

Hydraulic properties specified for the model layers include hydraulic conductivity, specific yield, and storativity. For each layer, hydraulic conductivities were distributed within four generalized lithologic zones. The generalized lithologic zones were developed based on a detailed review and simplification of the spatial variability in lithology as described on 72 extraction and monitor well logs. The four generalized lithologic zones included clay, silt, sand, and gravel. Based on the detailed review of the well logs, it is observed that sediments beneath the Site have a high percentage of clay and tend to become more fine-grained with depth. **Figure B-3** shows this trend toward fine-grained sediments with depth by model layer. **Figures B-4 through B-12** show the generalized lithologic zones for each model layer.

Vertical hydraulic conductivity data do not exist for the Site. Based on experience at similar sites, vertical hydraulic conductivities were specified as a ratio of horizontal to vertical conductivity; the ratio varied by lithologic zone. The following ratios were used: clay (100:1), silt (50:1), sand (10:1), and gravel (5:1).

Specific yield and storativity values were not found in the documents reviewed for this project. Therefore specific yield and storativity were assigned based the CCA model, the Tucson Active Management Area model, and on M&A experience at similar sites (CCA, 2004a and ADWR, 2006). Uniform specific yield and storativity values of 0.12 and 0.005, respectively, were used.

TRANSPORT MODEL

A transport model was developed to simulate the migration of PCE in groundwater. The transport model includes the following parameters: effective porosity, retardation, dispersivity and source concentration. Site-specific data for these parameters do not exist. Transport parameters were assigned based on experience at similar sites. Values used for transport parameters are listed below:

- Effective porosity: 0.20
- Retardation: 2
- Longitudinal dispersivity: 20 feet
- Transverse dispersivity: 2 feet
- Vertical dispersivity: 0.2 feet
- Source concentration: 30 and 20 micrograms per liter (µg/L)

FLOW MODEL CALIBRATION

A transient flow model calibration was conducted using water levels over the period from 1999 through 2011. Attempts were made to calibrate the model to PCE concentration data over the same time period. However, uncertainties in the PCE concentrations between the source area beneath the landfill and the monitor wells along the property boundary limited the usefulness of the transport calibration. The final model calibration was based only on the flow calibration.

DATA

The data used for calibration consisted of water levels measurements from 50 wells over the period 1999 through 2011. The data were provided by COT-ES. **Figure B-13** shows the locations of each well used in the model calibration and **Table B-3** lists the wells and their respective coordinates, model layer, and number of water level measurements.

METHODS

The model was calibrated using the automated inversion software package, PEST (Parameter ESTimation; Doherty, 2005), and based on M&A experience calibrating similar models. Using an automated process in PEST, the model was calibrated by systematically changing hydraulic conductivities within the generalized lithologic zones described above while trying to match measured water levels. The horizontal hydraulic conductivities were modified during the PEST calibration within ranges developed from available data from aquifer tests reported by CCA (CCA, 2004c). During the PEST calibration process, horizontal hydraulic conductivity was modified, but the horizontal to vertical hydraulic conductivity ratios were held constant.

RESULTS AND LIMITATIONS

Based on industry-accepted conventions for assessing the adequacy of calibration, the model is considered well calibrated. However, it is important to note that the regional groundwater decline strongly influences the water level trends observed in the monitor wells at the Site. The hydrologic effect of remedial pumping on local water levels was difficult to identify with the available network of monitor wells and associated water level data. In recognizing this limitation, sensitivity simulations were conducted that verified that the model could be acceptably calibrated with wide variations in model parameters. Therefore, while the model adequately simulates trends in water levels of the period 1999 through 2011, the model is considered best suited for site-scale comparative simulations, such as analysis of distinct remedial alternatives.

One additional calibration measure that used was the ability of the model to maintain pumping throughout the historical period. The MNW2 package preserved most of the pumping during the historical calibration period; however, the minimum hydraulic conductivities derived from the PEST calibration in the clay and silt zones were increased by a factor of 2 to maintain at least 90% of the actual pumping that occurred during the period 1999 through 2011. This increase was considered well within the range of uncertainty in the available hydraulic conductivity data. This secondary calibration measure improved confidence on the model.

Table B-4 presents a summary of the hydraulic conductivities determined during model calibration. Given the limitations in calibration, it was decided not to present the typical calibration graphics such as cross-plots of measured versus projected water levels, hydrographs of measured and projected water levels for the monitor wells, or present summary calibration statistics. However, this information is readily interrogated in the model output files using Groundwater Vistas. The model input and output files are included on a DVD contained in this report.

REFERENCES

Arizona Department of Water Resources, 2006, **Regional Groundwater Flow Model of the Tucson Active Management Area Tucson, Arizona: Simulation and Application,** Modeling Report 13, Arizona Department of Water Resources, Hydrology Division, Phoenix, Arizona.

Clear Creek Associates, 2004a, **Groundwater Flow Model Documentation Report Containment/Monitoring Plan for Los Reales Landfill,** Tucson, Arizona.

_____, 2004b, **Los Reales Landfill MODFLOW Groundwater Flow Model Construction and Calibration,** Tucson, Arizona.

_____, 2004c, **Phase I – Hydrologic Containment Plan Data Review and Analysis Technical Memorandum,** Tucson, Arizona.

Doherty, J., 2005, **PEST User Manual: 5th Edition,** Brisbane, Queensland, Australia: Watermark Numerical Computing.

Harbaugh, A.W., 2005, **The U.S. Geological Survey Modular Ground-Water Model--the Ground-Water Flow Process,** USGS, Reston, Virginia.

Konikow, L.F. et. al, 2009, **Revised Multi-Node Well (MNW2) Package for MODFLOW Ground-Water Flow Model,** USGS, Reston, Virginia.

Rumbaugh, J.O., and D.B. Rumbaugh, 2011, **Groundwater Vistas (Version 6.17),** Environmental Simulations Inc., Reinholds, Pennsylvania.

Zheng, C., and P.P. Wang, 1999, **MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide,** University of Alabama.

TABLE B-1. COMPARISON OF CLEAR CREEK ASSOCIATES
AND MONTGOMERY & ASSOCIATES GROUNDWATER MODELS
LOS REALES LANDFILL, CITY OF TUCSON, ENVIRONMENTAL SERVICES

MODEL ASPECT	CLEAR CREEK ASSOCIATES MODEL	MONTGOMERY & ASSOCIATES MODEL
Model Codes	MODFLOW-2000/MT3DMS	MODFLOW-2005/MT3DMS
Area (sq. mi)	12.5	3.5
Grid	Minimum spacing 50 x 50 feet Maximum spacing 200 x 200 feet Number of nodes ~ 96,000	Uniform spacing 25 x 25 feet Number of nodes ~1.4 million
Boundary Conditions	Constant head; no-flow; declining; steady	Constant head; no-flow; declining; steady
Layers	3	9
Hydraulic properties	Zoned; uniform value in each zone	Zoned; Spatially variable in each zone
Calibration Methods	Transient; manual; flow only	Transient; PEST/manual; flow (transport attempted)
Landfill source	Constant concentration (layer 1)	Constant concentration (layers 1 – 3)

Notes:
sq. mi. = square miles
PEST = Parameter ESTimation software

TABLE B-2. MODEL LAYER SUMMARY
LOS REALES LANDFILL
CITY OF TUCSON, ENVIRONMENTAL SERVICES

MODEL LAYER	THICKNESS (feet)	BOTTOM ELEVATION (ft amsl)
1	1.4 - 26.9*	2,490
2	10	2,480
3	10	2,470
4	10	2,460
5	10	2,450
6	10	2,440
7	10	2,430
8	30	2,400
9	100	2,300

Notes:
* Thickness varies because the water table serves as the model top
ft amsl = feet above mean sea level

MONTGOMERY & ASSOCIATES

TABLE B-3. MONITOR WELLS USED IN MODEL CALIBRATION
LOS REALES LANDFILL, CITY OF TUCSON, ENVIRONMENTAL SERVICES

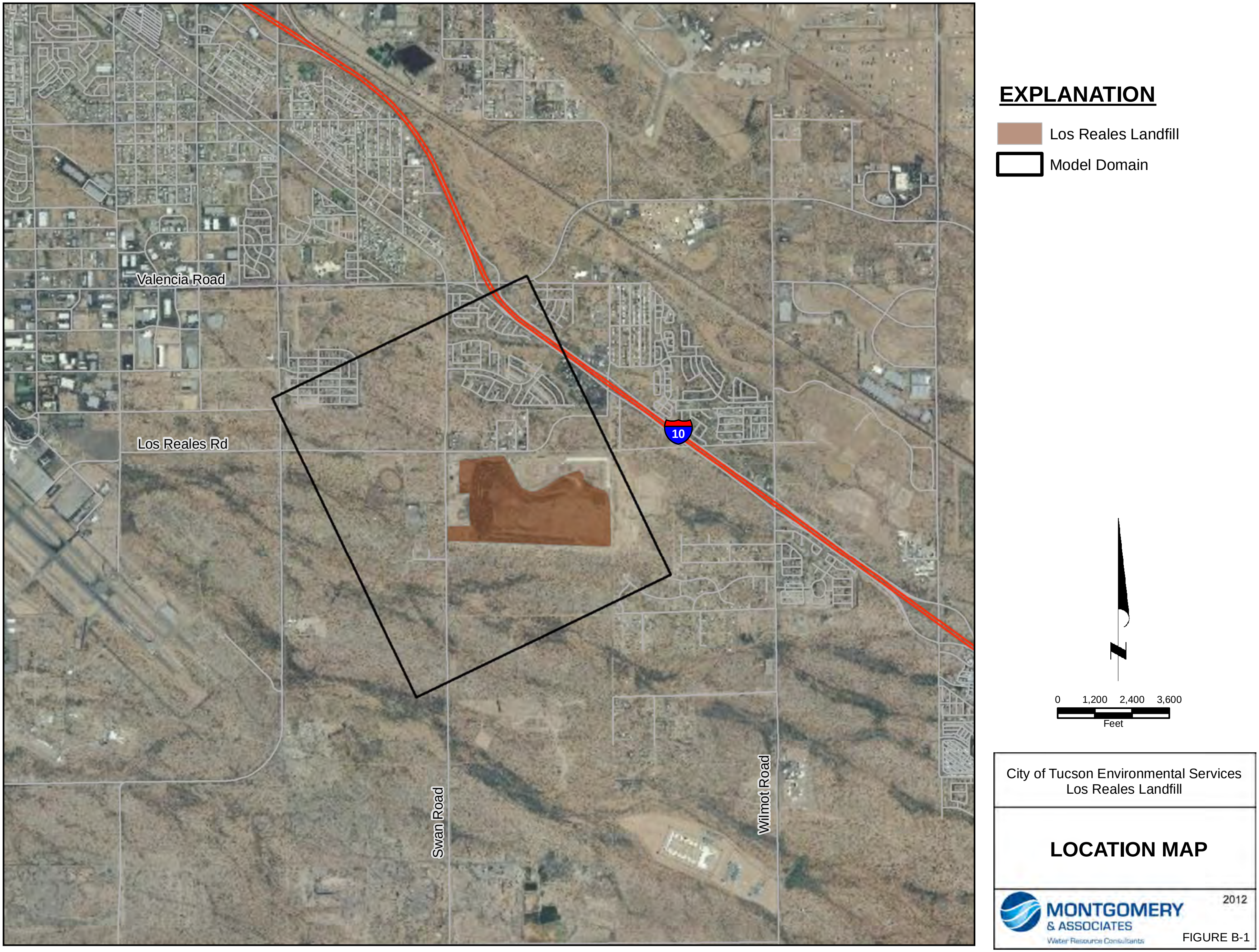
WELL NAME	WATER LEVEL MEASUREMENT COUNT	MODEL LAYER	X	Y
LLM-501	11	8	1017264	408600.3
LLM-513	5	9	1014593	408644.3
LLM-538	1	3	1017227	407398.8
LLM-539	1	3	1017238	407112.7
LLM-540	1	3	1017244	406800.8
LLM-543	2	8	1018406	411329.9
R-011A	2	2	1018137	408599.6
R-023A	1	2	1017458	408599.6
R-024A	1	2	1017913	408618.4
R-025A	2	2	1017233	408265.9
R-061A	4	2	1019333	408588.1
R-062A	9	2	1019535	408587.4
R-062B	11	7	1019526	408588
R-063A	4	2	1019730	408596.4
R-064A	13	2	1020196	408596.7
R-065A	14	1	1020376	408581.5
R-105A	3	9	1021233	408575.5
R-106A	4	1	1019233	408590
R-107A	4	1	1019458	408586.7
R-108A	3	1	1019619	408591.8
WR-047B	24	5	1022481	404646.6
WR-048A	17	3	1017378	406127.7
WR-049A	17	3	1017746	406275.7
WR-136B	14	2	1019952	408585
WR-172A	16	7	1016967	411396.4
WR-173B	26	8	1016991	410033.5
WR-175A	26	4	1014596	408766.5
WR-176A	17	8	1014562	411388.2
WR-184A	26	3	1019762	410019
WR-185A	17	7	1014623	405999.3
WR-272A	8	1	1017656	408594.6
WR-272B	14	7	1017656	408594.8
WR-325A	14	7	1017238	408112.7
WR-355A	17	3	1017235	406353.1
WR-360A	18	3	1017272	405858.6
WR-361A	22	3	1017232	406100.4
WR-372A	14	2	1017235	408133.8
WR-373A	14	3	1017281	408428.2
WR-374A	14	2	1017392	408499.4
WR-375A	14	2	1017558	408621.6
WR-376A	5	1	1020787	408603
WR-378A	14	1	1021183	408579.6
WR-379A	5	2	1019127	408598.8
WR-380A	14	3	1018524	408604.4
WR-465A	13	2	1020978	409983.7
WR-466A	4	3	1019146	410053.8
WR-468A	13	4	1018356	411330.9
WR-469A	13	5	1015834	407377.4
WR-470A	4	3	1019844	410032.9
WR-471A	13	8	1019835	410016.8

Notes:

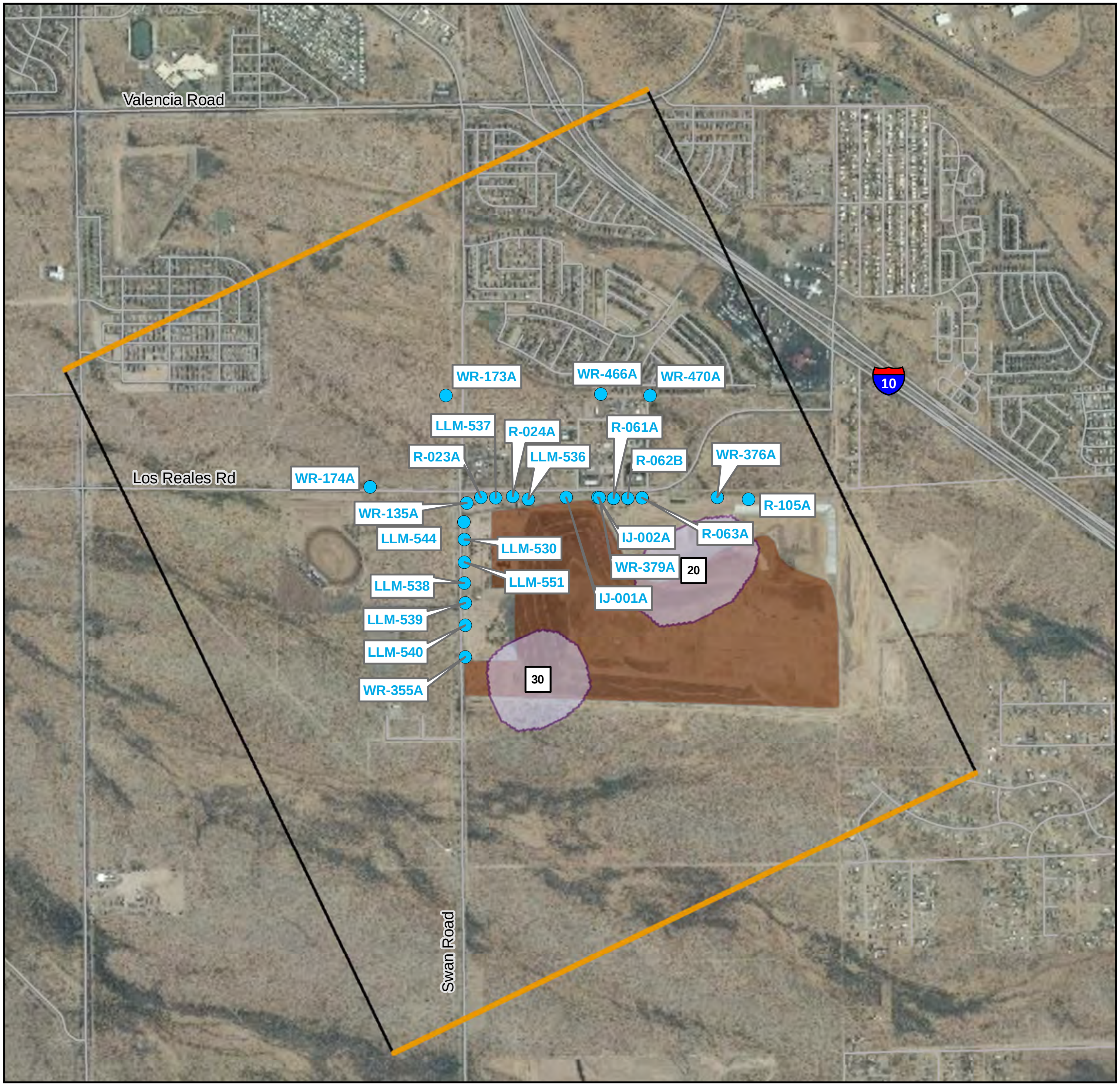
X & Y coordinates are in State Plane Arizona Central NAD83 HARN (feet)

TABLE B-4. SUMMARY OF HYDRAULIC CONDUCTIVITY USED IN MODEL LOS REALES LANDFILL, CITY OF TUCSON, ENVIRONMENTAL SERVICES

LAYER	LITHOLOGIC GROUP	HORIZONTAL HYDRAULIC CONDUCTIVITY (feet/day)				HORIZONTAL TO VERTICAL RATIO
		MINIMUM VALUE	GEOMETRIC MEAN	ARITHMETIC MEAN	MAXIMUM VALUE	
1	Clay	1.4	7.8	8.2	11.8	100:1
1	Silt	2.0	13.0	13.8	21.8	50:1
1	Sand	4.4	10.7	14.0	49.8	10:1
1	Gravel	25.1	67.6	88.8	248.6	5:1
2	Clay	0.7	9.9	10.2	13.1	100:1
2	Silt	2.4	5.9	7.2	20.4	50:1
2	Sand	4.8	20.2	28.3	50.4	10:1
2	Gravel	25.0	52.5	58.7	249.4	5:1
3	Clay	0.9	7.3	7.7	11.4	100:1
3	Silt	3.9	13.0	13.8	20.7	50:1
3	Sand	11.7	45.7	46.6	51.2	10:1
3	Gravel	35.0	210.2	221.3	268.3	5:1
4	Clay	10.0	10.0	10.0	10.0	100:1
4	Silt	2.0	7.1	8.5	19.9	50:1
4	Sand	5.0	37.5	41.0	50.8	10:1
4	Gravel	25.1	126.4	142.2	249.8	5:1
5	Clay	0.2	4.5	5.9	11.5	100:1
5	Silt	2.5	8.0	9.5	20.0	50:1
5	Sand	21.1	29.4	29.9	38.7	10:1
5	Gravel	39.0	116.1	125.5	247.1	5:1
6	Clay	10.0	10.0	10.0	10.0	100:1
6	Silt	2.0	4.7	5.1	7.4	50:1
6	Sand	36.1	46.9	47.1	50.0	10:1
6	Gravel	137.8	171.5	175.0	249.9	5:1
7	Clay	0.5	3.9	5.5	12.8	100:1
7	Silt	2.0	12.1	12.5	19.7	50:1
7	Sand	5.1	12.1	14.0	35.0	10:1
7	Gravel	31.3	97.4	108.4	196.4	5:1
8	Clay	0.2	8.0	9.1	15.1	100:1
8	Silt	1.8	6.3	8.6	19.9	50:1
8	Sand	5.0	7.0	9.7	49.9	10:1
8	Gravel	25.5	70.7	75.7	133.6	5:1
9	Clay	0.7	8.4	9.2	12.3	100:1
9	Silt	1.0	3.3	4.9	11.2	50:1
9	Sand	5.0	7.6	10.0	49.8	10:1
9	Gravel	25.0	65.4	82.0	233.8	5:1



GIS-Tuc\1373.03\LocationMap\23July2012



EXPLANATION

Remediation Well

Specified Head Boundary

No Flow Boundary

Los Reales Landfill

20 Simulated Constant Concentration Source Area in Layers 1 through 3; concentration in µg/L shown in box

0 1,200 2,400
Feet

City of Tucson, Envionmental Services
Los Reales Landfill

MODEL FEATURES

MONTGOMERY & ASSOCIATES Water Resource Consultants

2012

FIGURE B-2

GIS-Tuc\1373.03\ModelGrid\24July2012

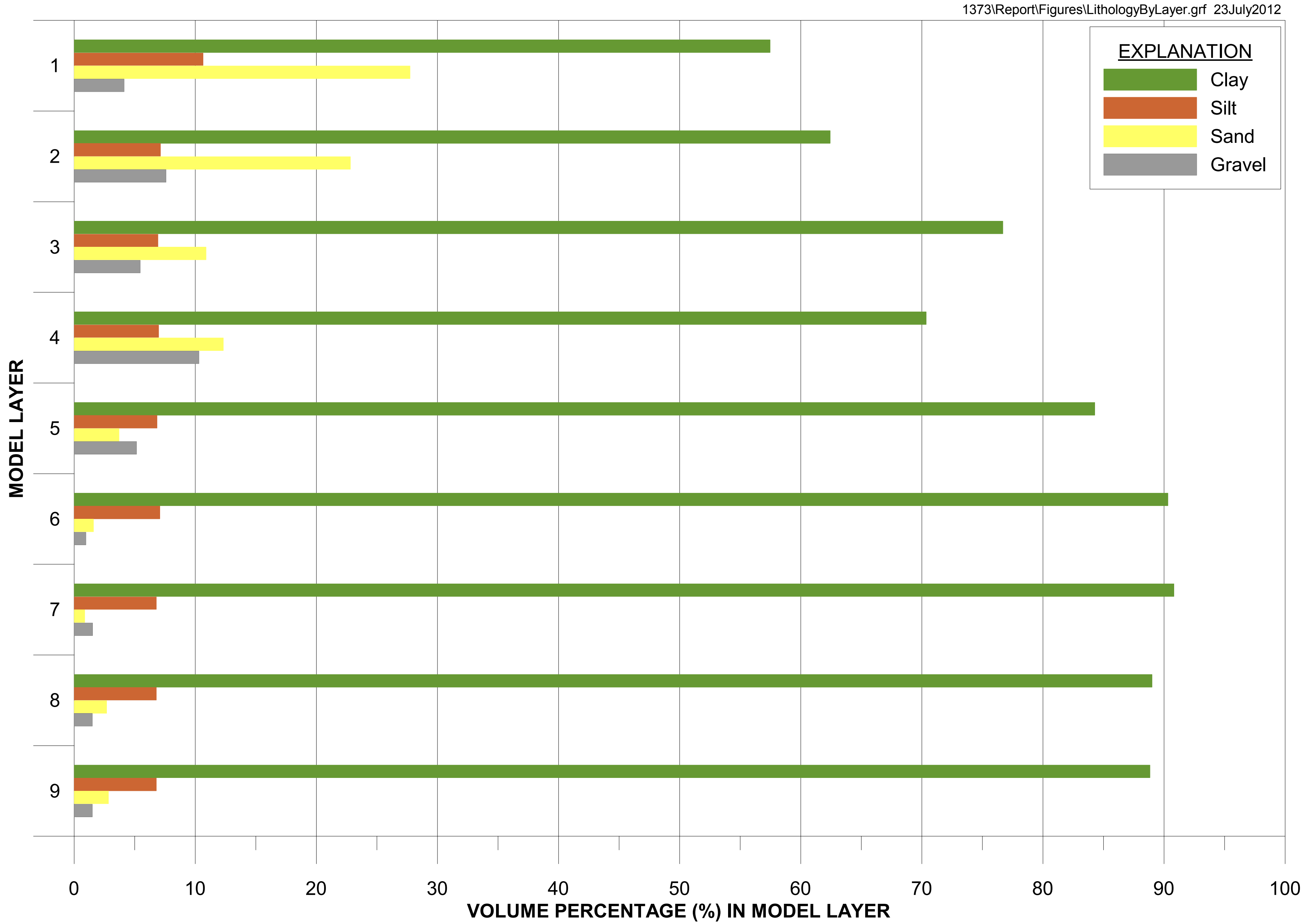
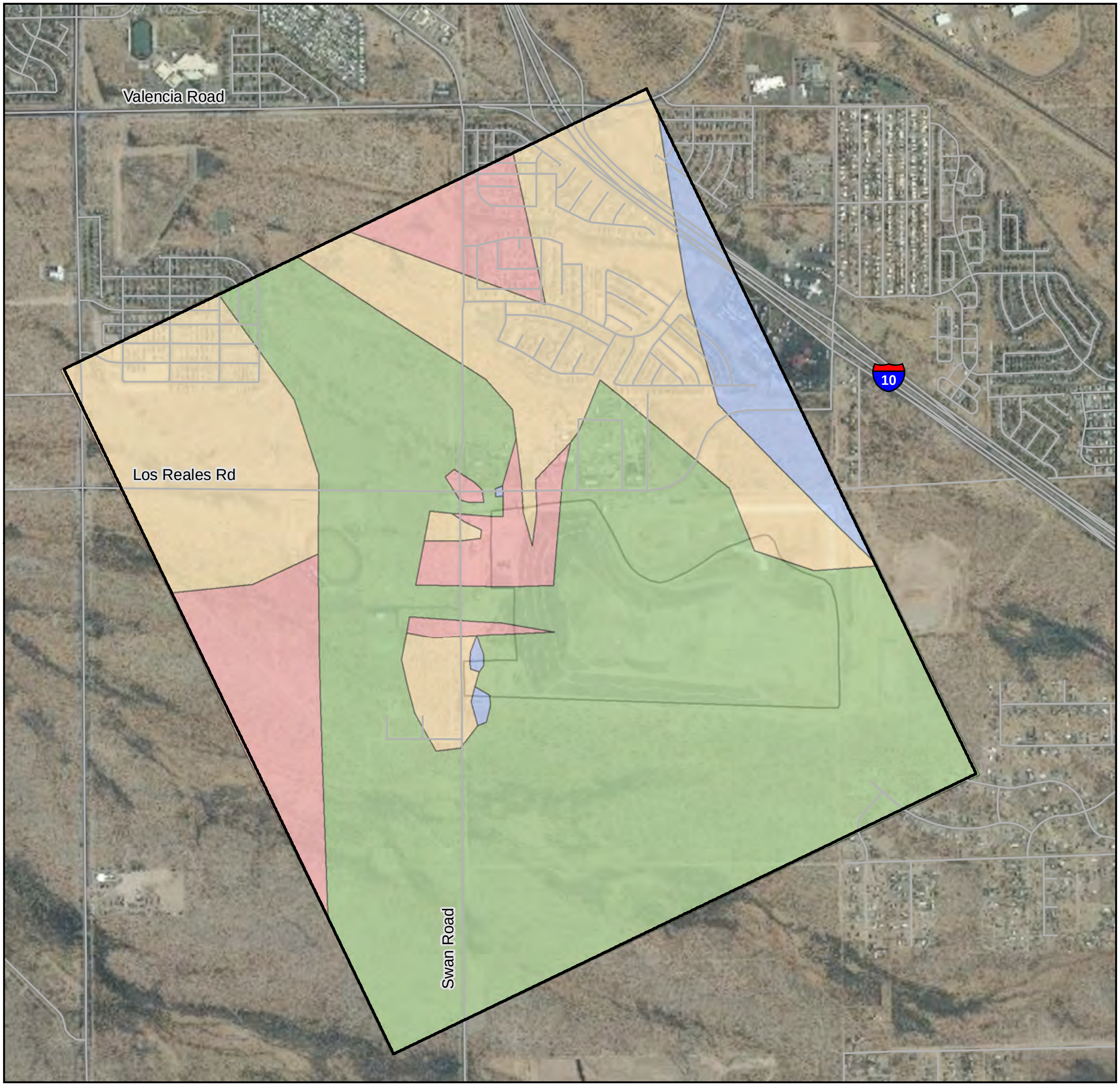
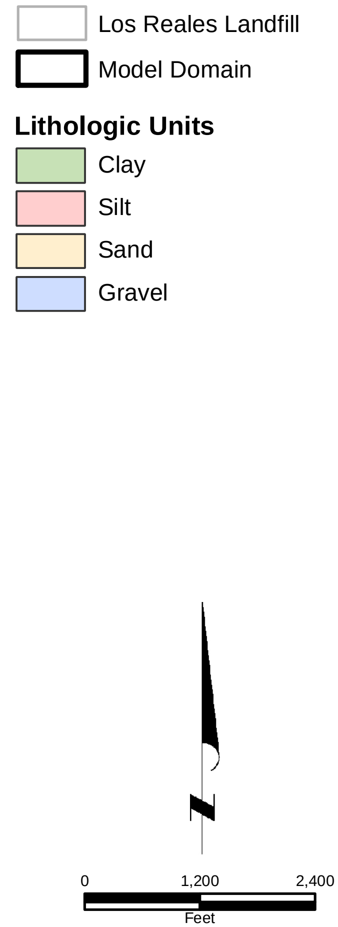


FIGURE B-3. OCCURENCE OF LITHOLOGIC UNITS AS A PERCENTAGE OF VOLUME IN EACH MODEL LAYER

MONTGOMERY & ASSOCIATES



EXPLANATION



City of Tucson, Environmental Services
Los Reales Landfill

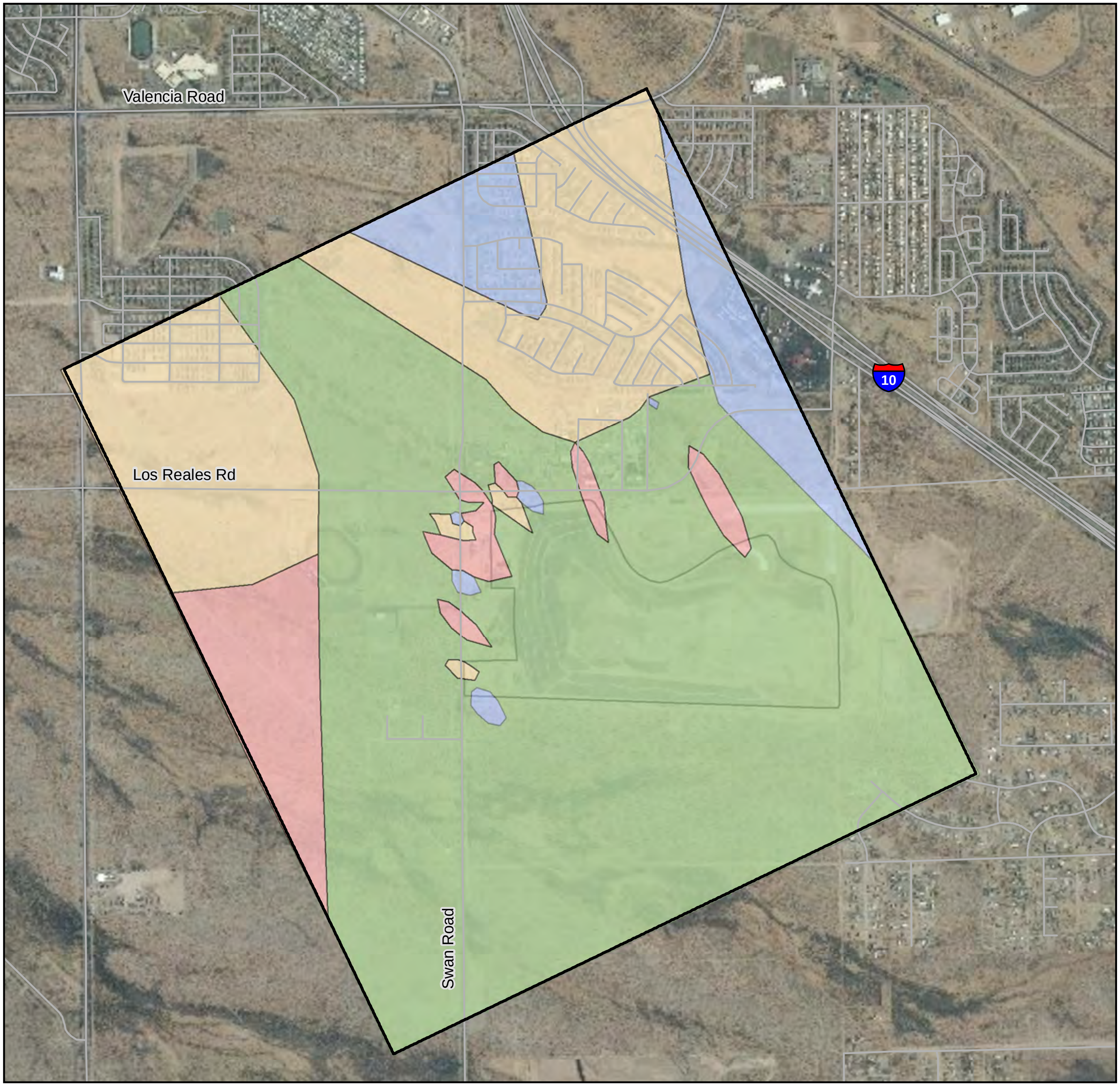
MODEL LITHOLOGY LAYER 1

MONTGOMERY & ASSOCIATES
Water Resource Consultants

2012

FIGURE B-4

GIS-Tuc\1373.03\LITH_Layer1\25June2012



EXPLANATION

Los Reales Landfill

Model Domain

Lithologic Units

Clay

Silt

Sand

Gravel

0 1,200 2,400

Feet

City of Tucson, Environmental Services
Los Reales Landfill

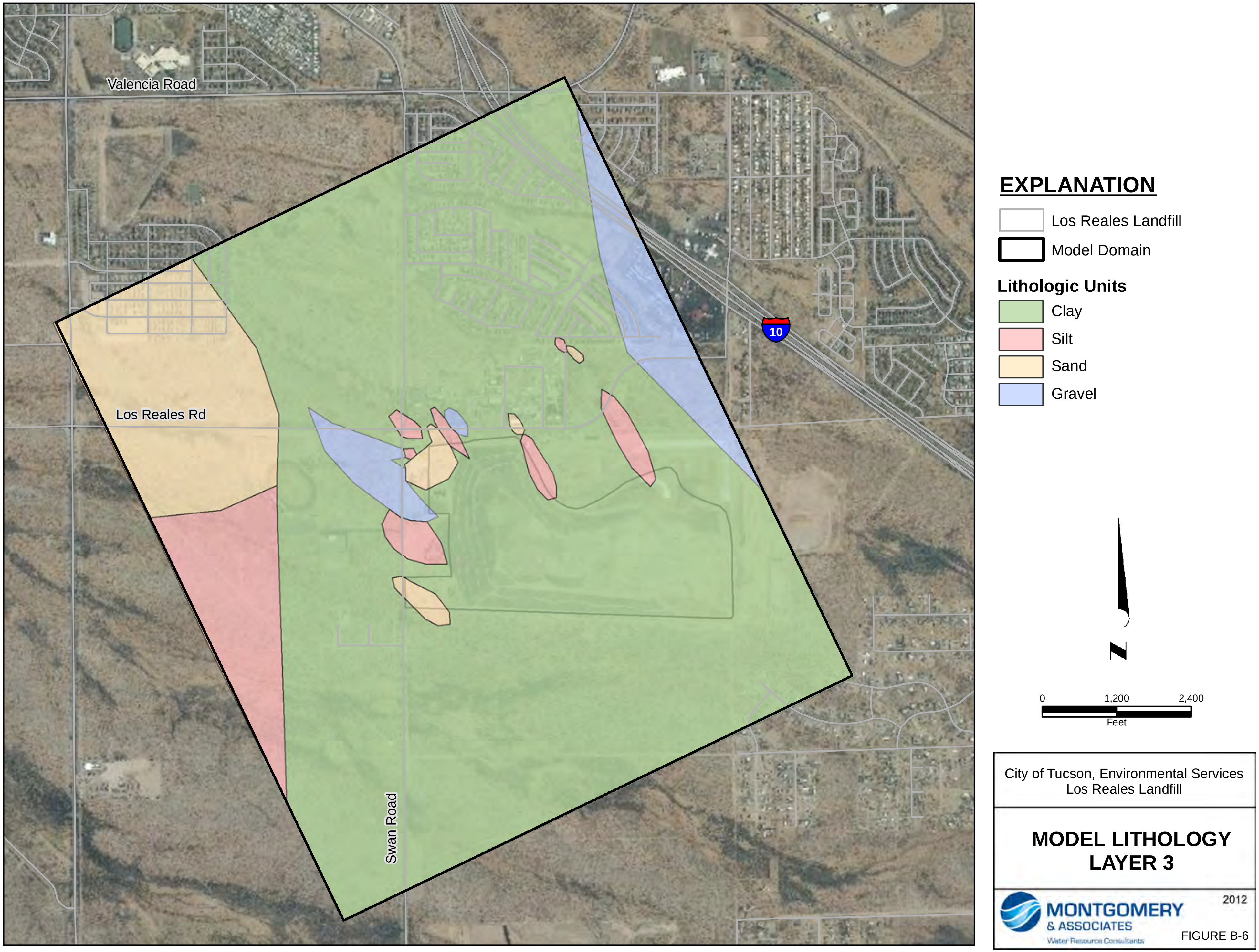
MODEL LITHOLOGY LAYER 2

MONTGOMERY & ASSOCIATES
Water Resource Consultants

2012

FIGURE B-5

GIS-Tuc\1373.03\LITH_Layer2\23July2012



City of Tucson, Environmental Services
Los Reales Landfill

MODEL LITHOLOGY LAYER 3

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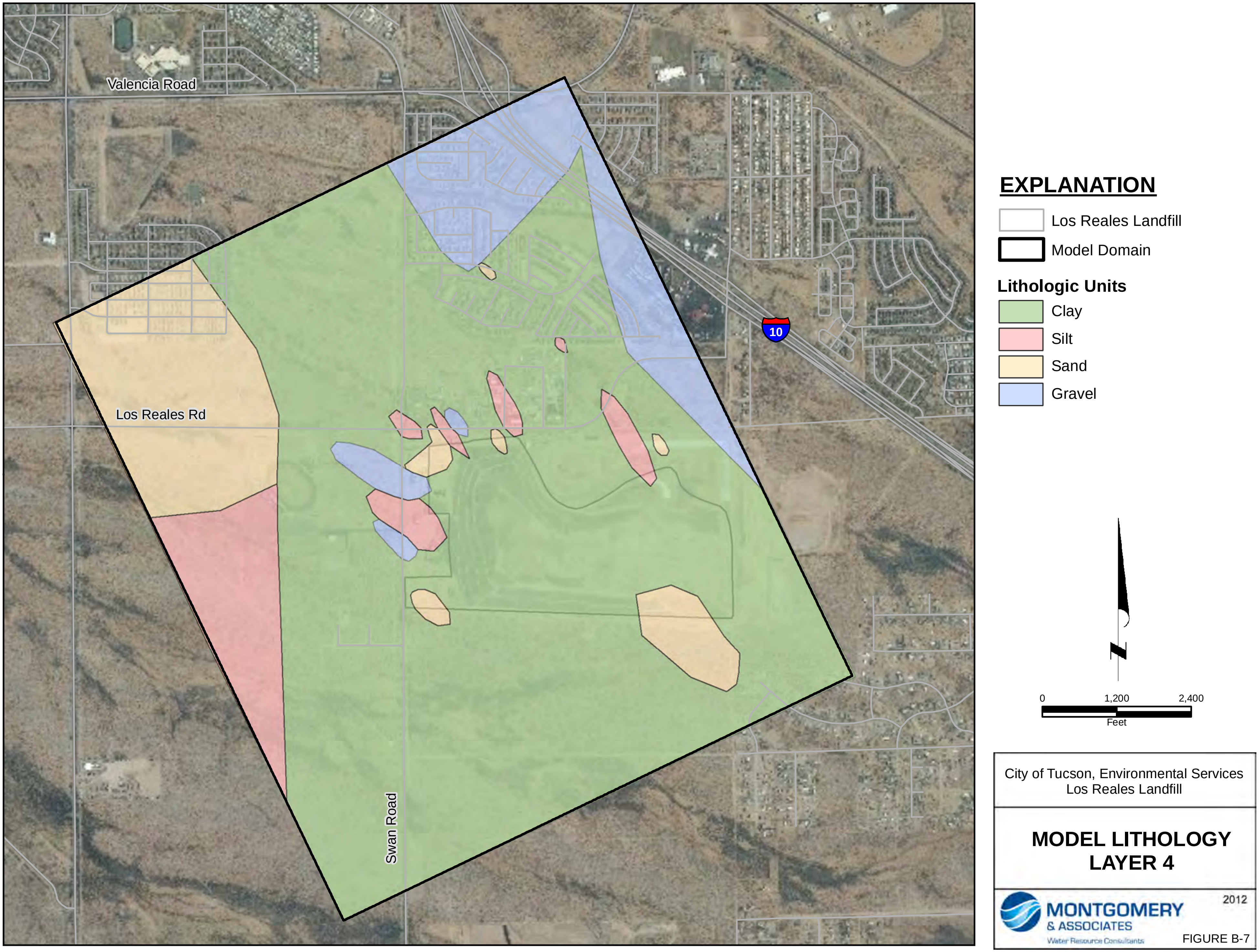
Water Resource Consultants

2012

FIGURE B-6

GIS-Tuc\1373.03\LITH_Layer3\23July2012



City of Tucson, Environmental Services
Los Reales Landfill

MODEL LITHOLOGY
LAYER 4

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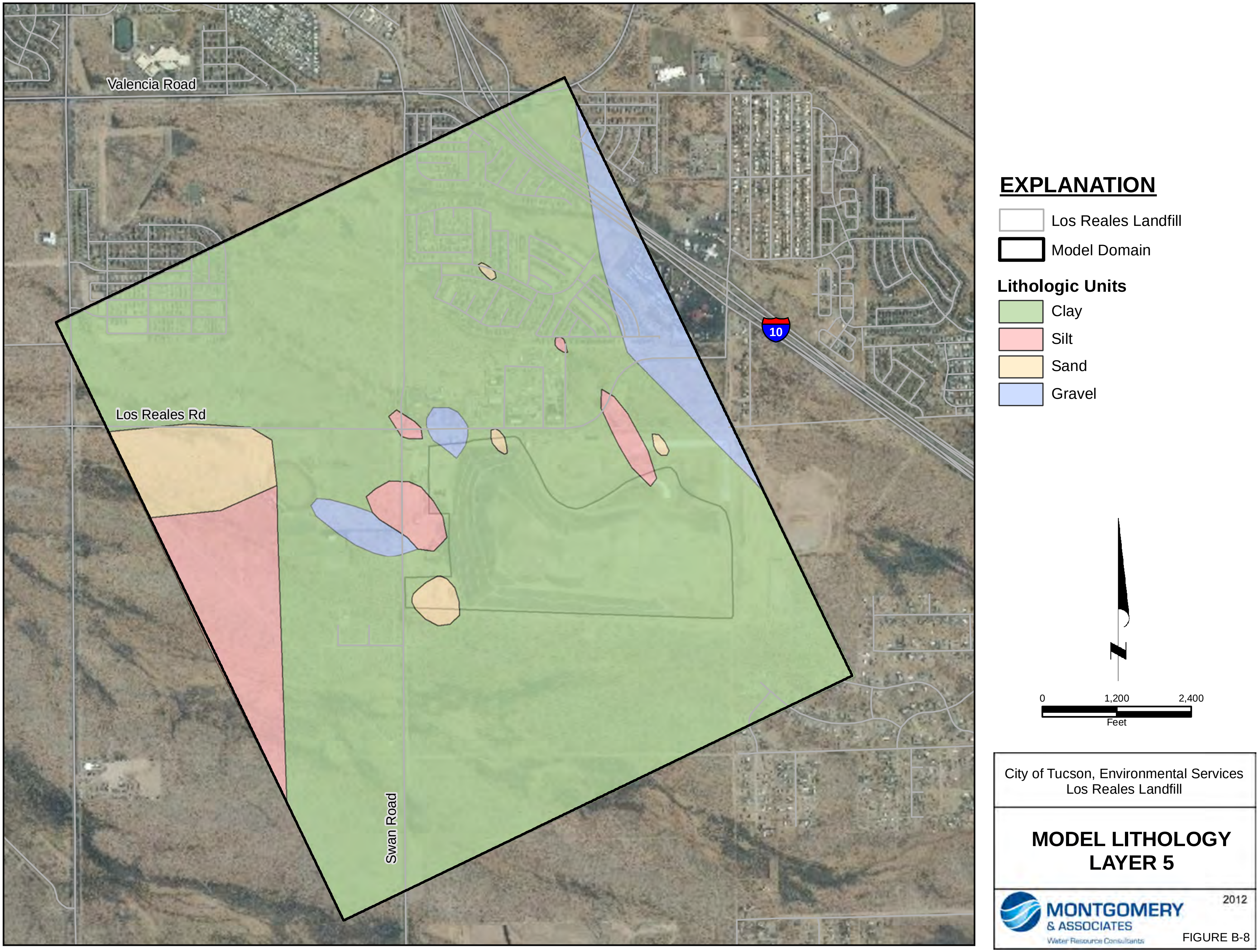
Water Resource Consultants

2012

FIGURE B-7

GIS-Tuc\1373.03\LITH_Layer4\23July2012



City of Tucson, Environmental Services
Los Reales Landfill

MODEL LITHOLOGY LAYER 5

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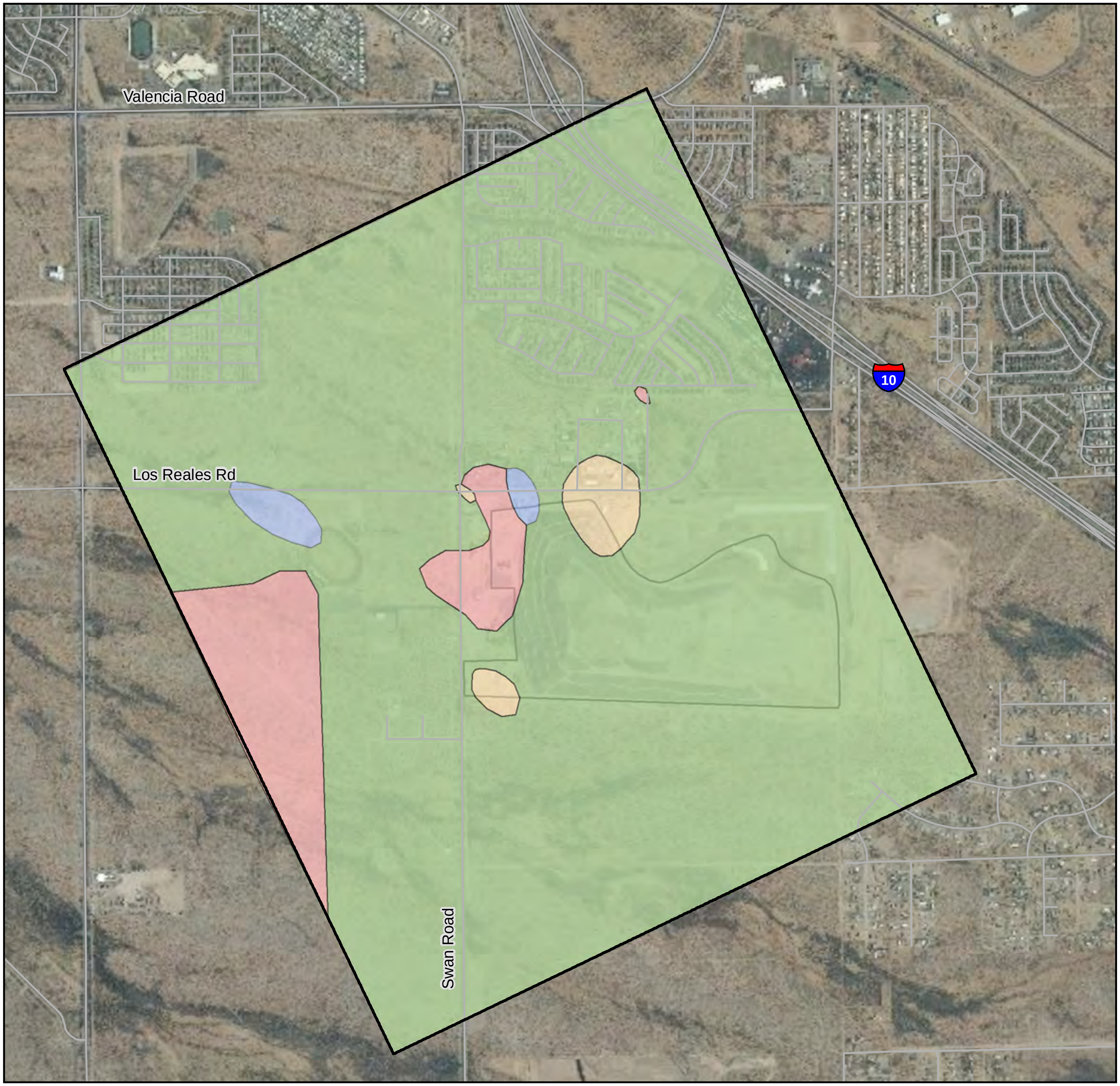
2012

FIGURE B-8

GIS-Tuc\1373.03\LITH_Layer5\23July2012



EXPLANATION

Los Reales Landfill

Model Domain

Lithologic Units

Clay

Silt

Sand

Gravel

0 1,200 2,400
Feet

City of Tucson, Environmental Services
Los Reales Landfill

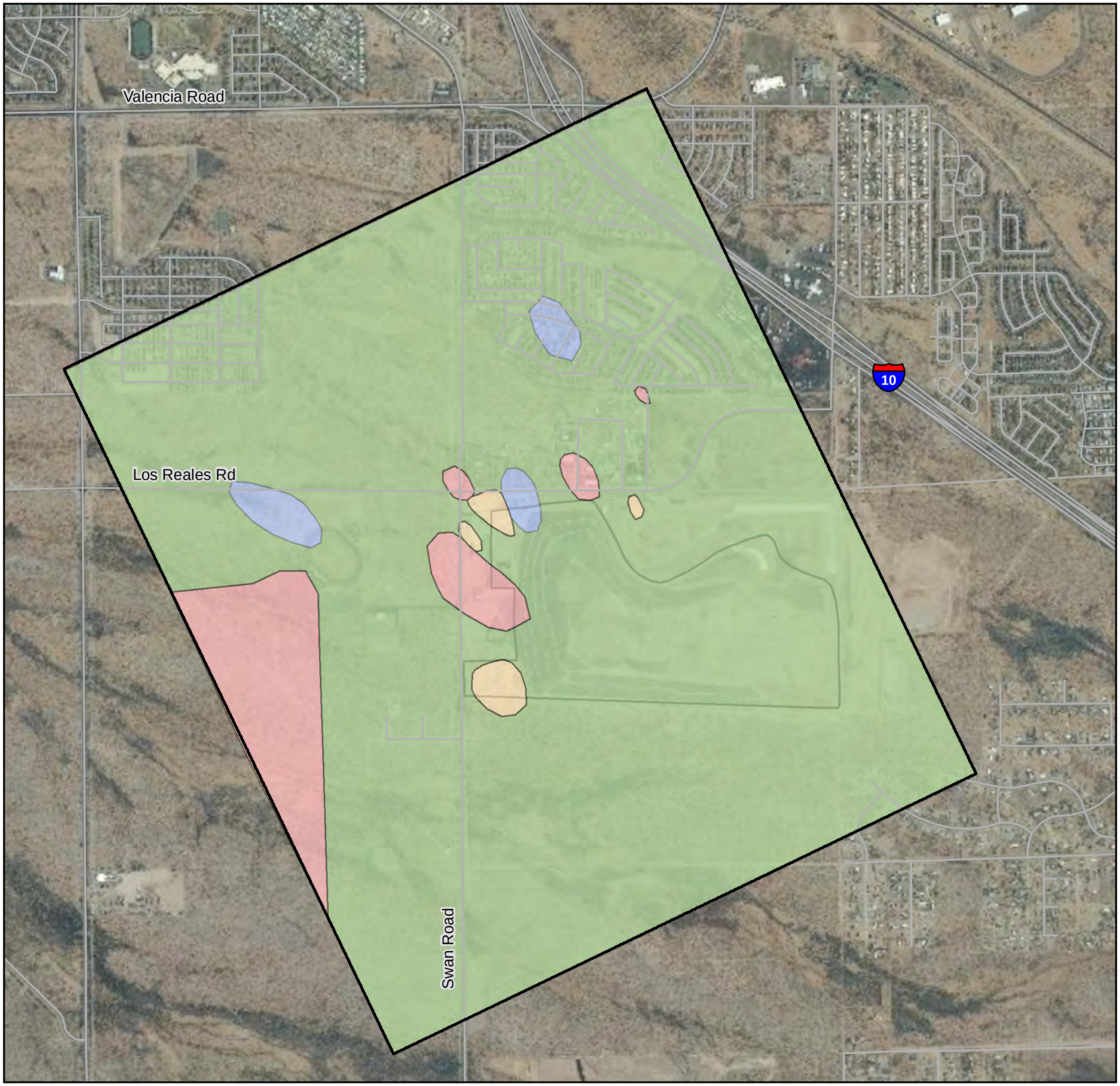
MODEL LITHOLOGY LAYER 6

MONTGOMERY & ASSOCIATES
Water Resource Consultants

2012

FIGURE B-9

GIS-Tuc\1373.03\LITH_Layer6\23July2012



EXPLANATION

Los Reales Landfill

Model Domain

Lithologic Units

Clay

Silt

Sand

Gravel

0 1,200 2,400
Feet

City of Tucson, Environmental Services
Los Reales Landfill

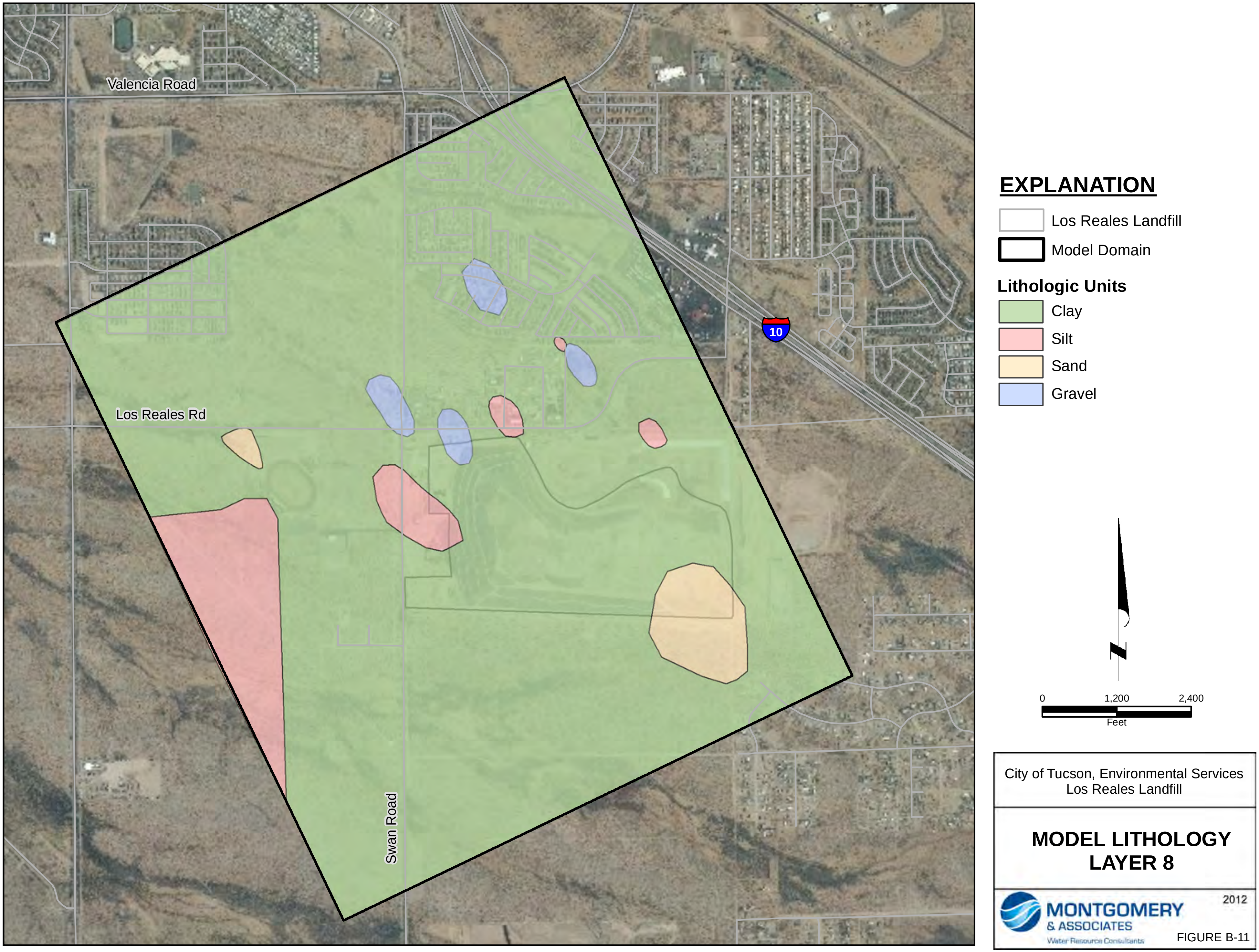
MODEL LITHOLOGY LAYER 7

MONTGOMERY & ASSOCIATES
Water Resource Consultants

2012

FIGURE B-10

GIS-Tuc\1373.03\LITH_Layer7\23July2012



City of Tucson, Environmental Services
Los Reales Landfill

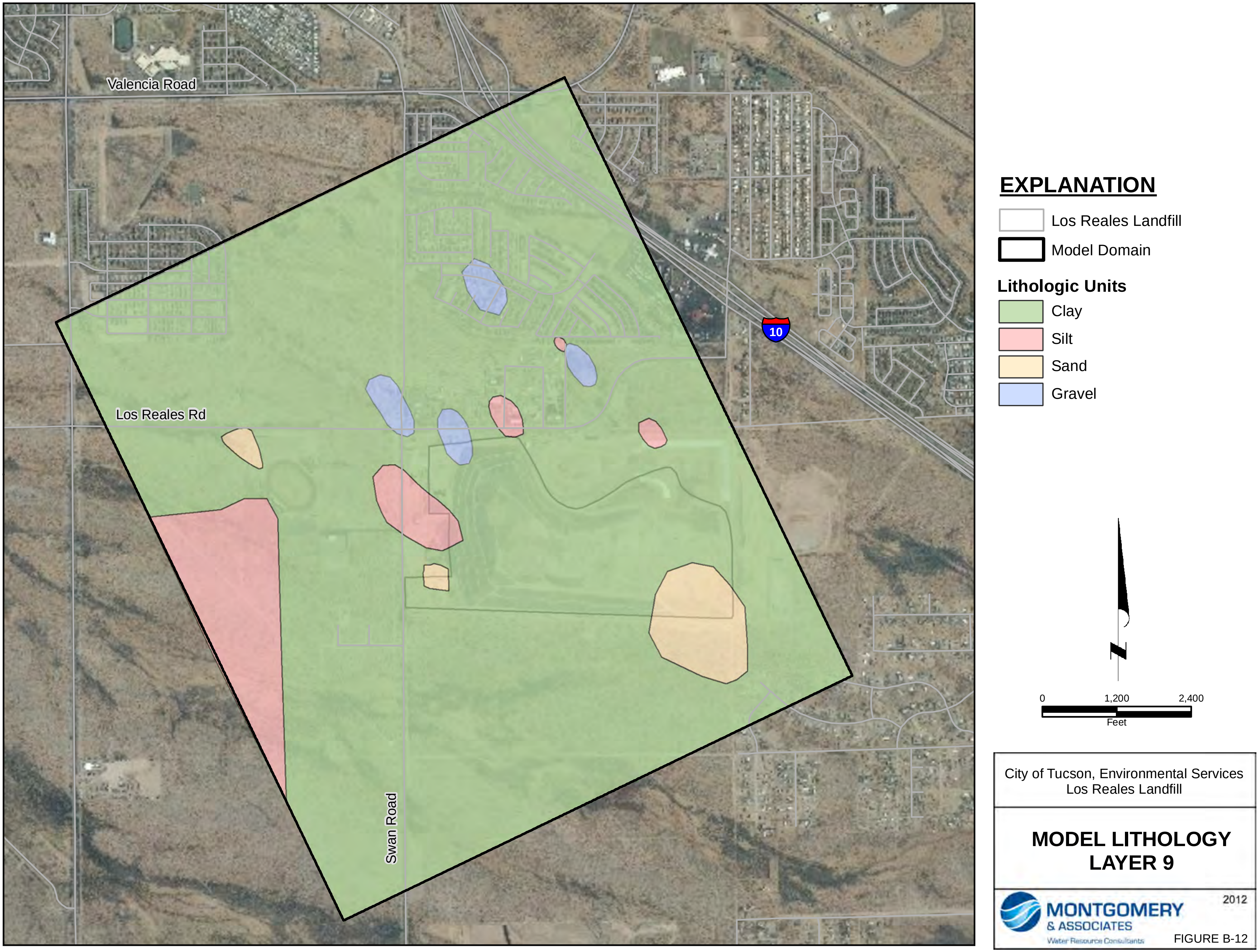
MODEL LITHOLOGY LAYER 8

2012

MONTGOMERY & ASSOCIATES
Water Resource Consultants

FIGURE B-11

GIS-Tuc\1373.03\LITH_Layer8\23July2012



City of Tucson, Environmental Services
Los Reales Landfill

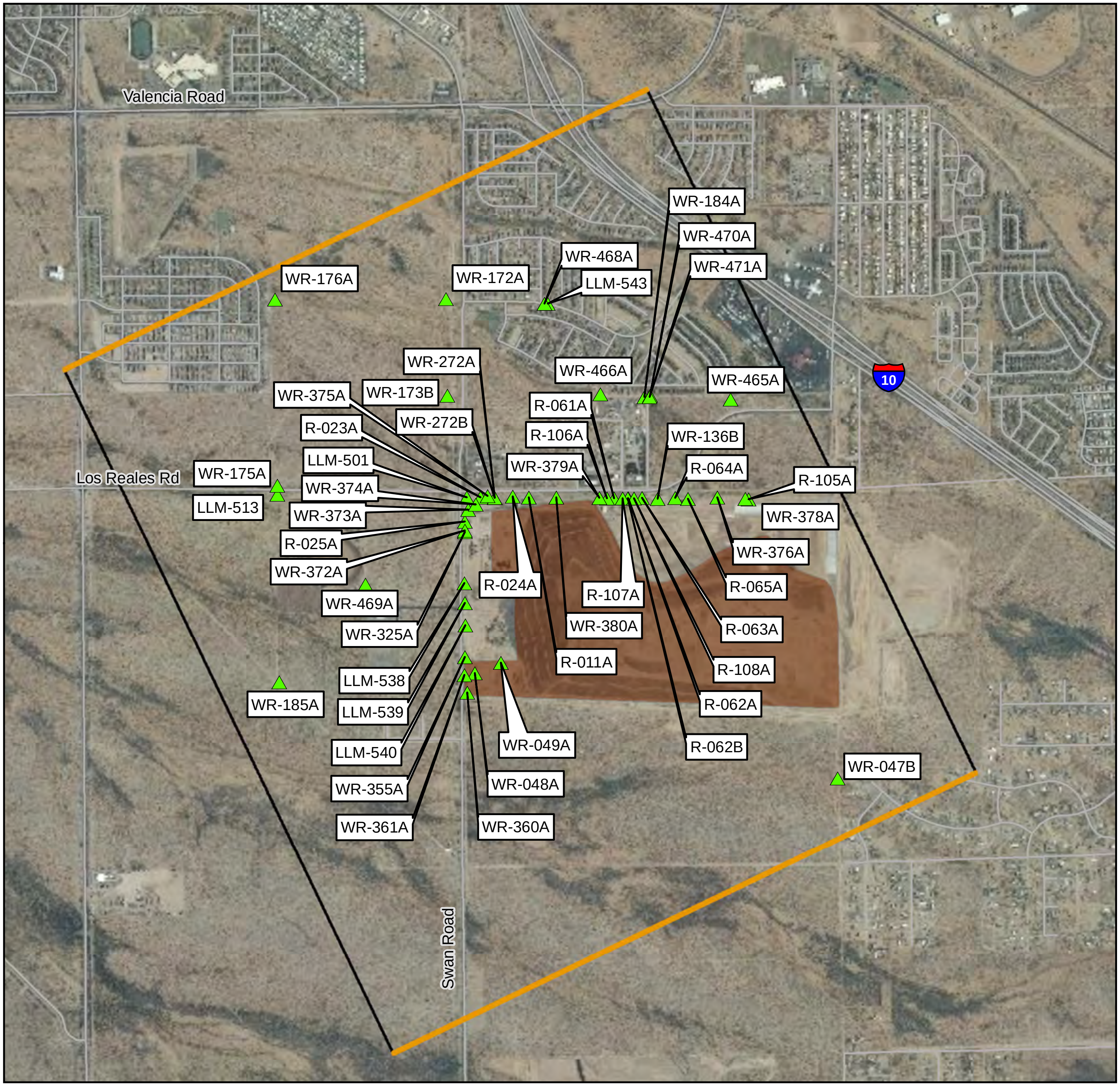
MODEL LITHOLOGY
LAYER 9

MONTGOMERY & ASSOCIATES
Water Resource Consultants

2012

FIGURE B-12

GIS-Tuc\1373.03\LITH_Layer9\23July2012



EXPLANATION

- Monitor Well
- Specified Head Boundary
- No Flow Boundary
- Los Reales Landfill

0 1,200 2,400
Feet

City of Tucson, Environmental Services
Los Reales Landfill

WATER LEVEL TARGETS

MONTGOMERY & ASSOCIATES
Water Resource Consultants

2012

FIGURE B-13

GIS-Tuc\1373.03\WaterLevelTargets\23July2012

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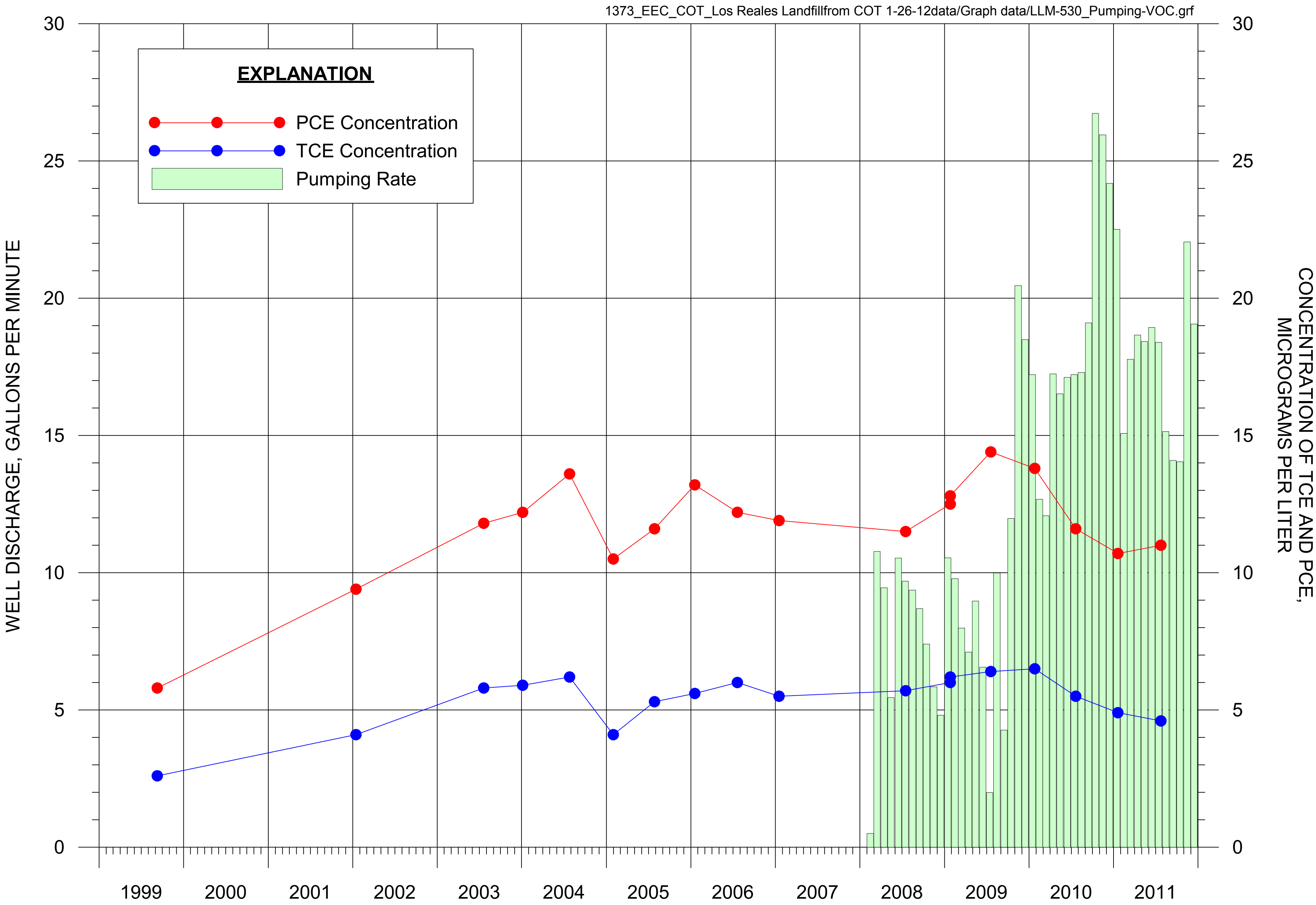
APPENDIX C

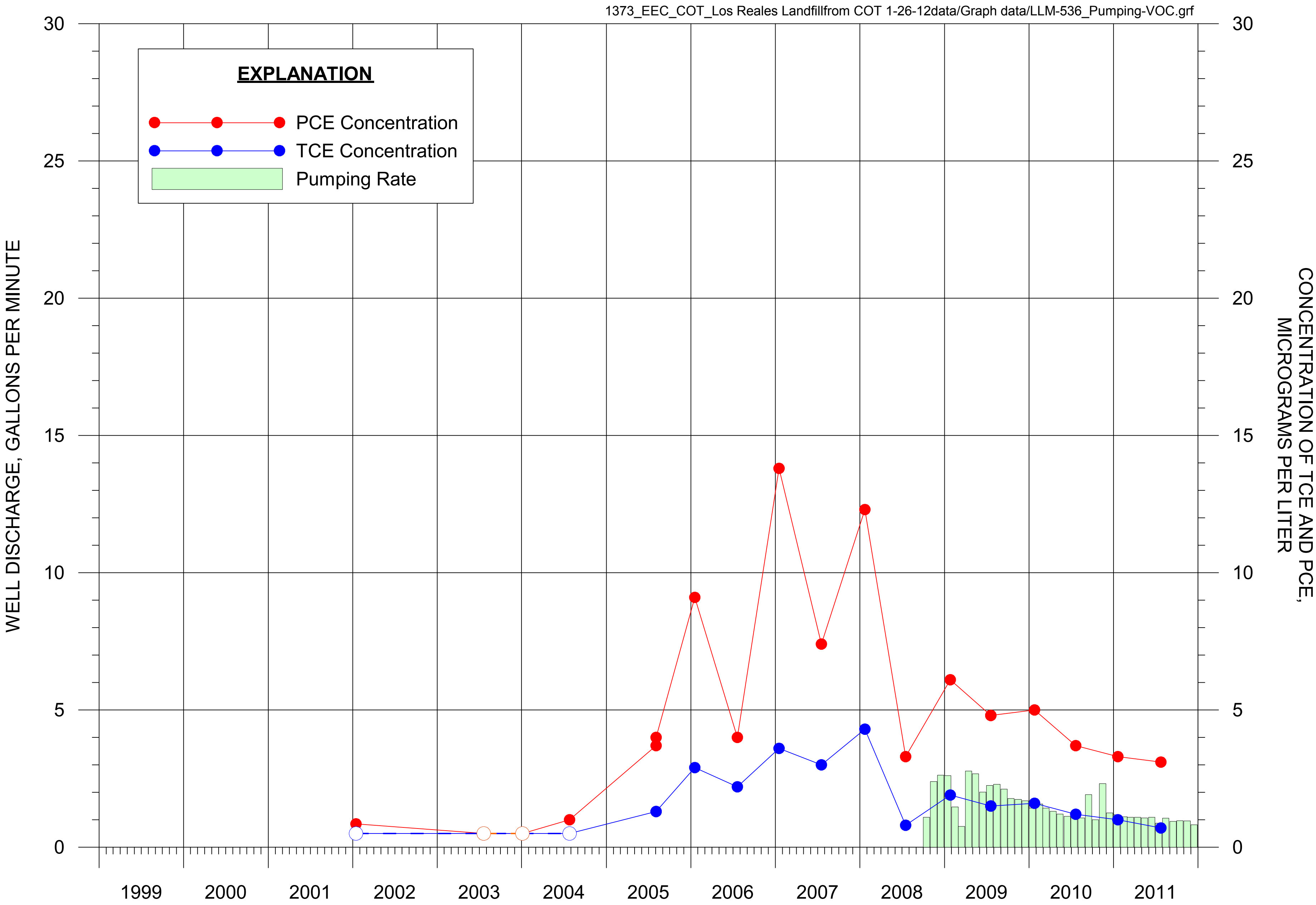
GRAPHS OF REMEDIAL PUMPING VERSUS WATER QUALITY AND WATER LEVELS VERSUS WATER QUALITY LOS REALES LANDFILL CITY OF TUCSON, ENVIRONMENTAL SERVICES



* Open symbols indicate concentration less than detection limit

FIGURE C-1. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL LLM-530
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

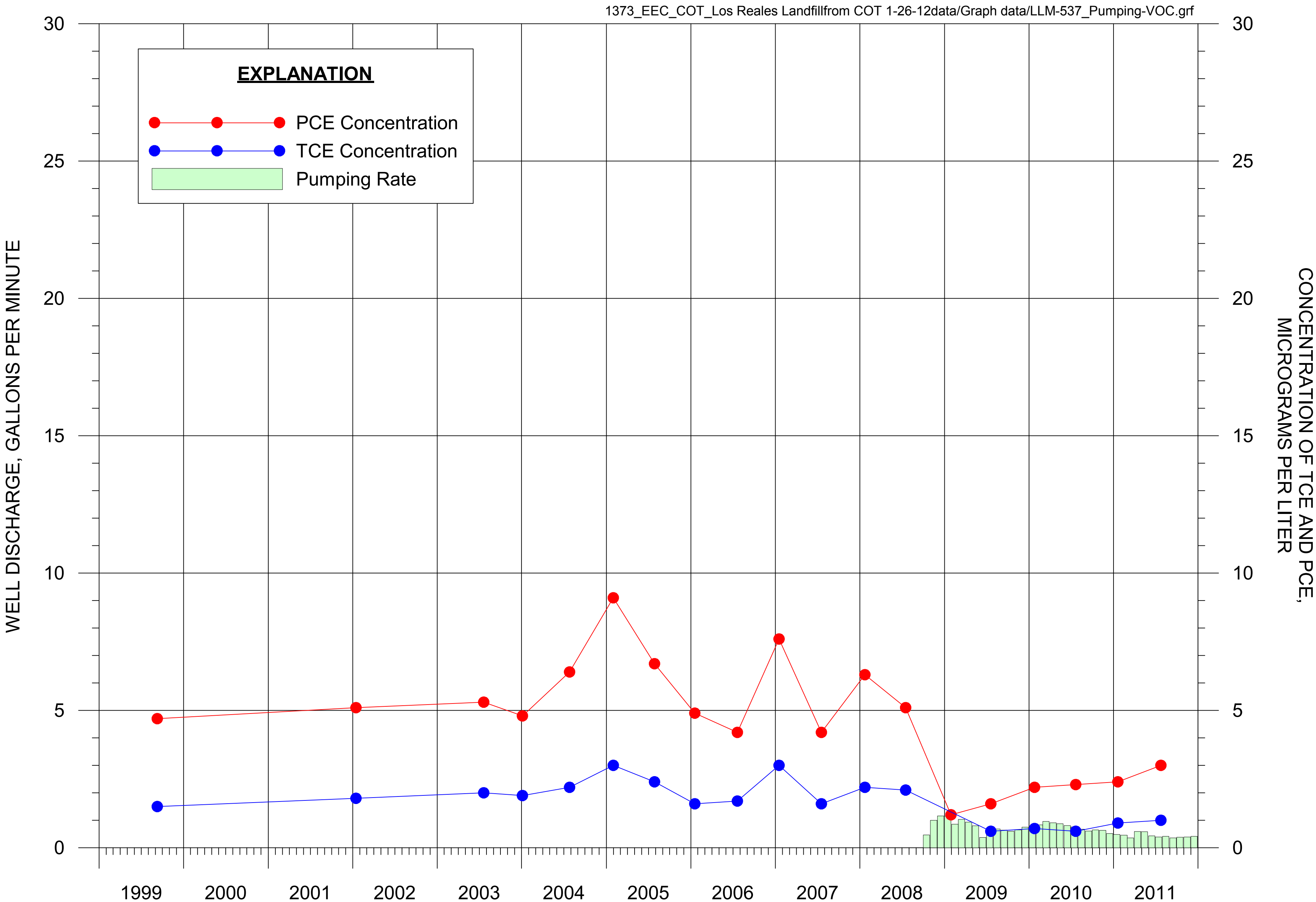
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-2. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL LLM-536
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

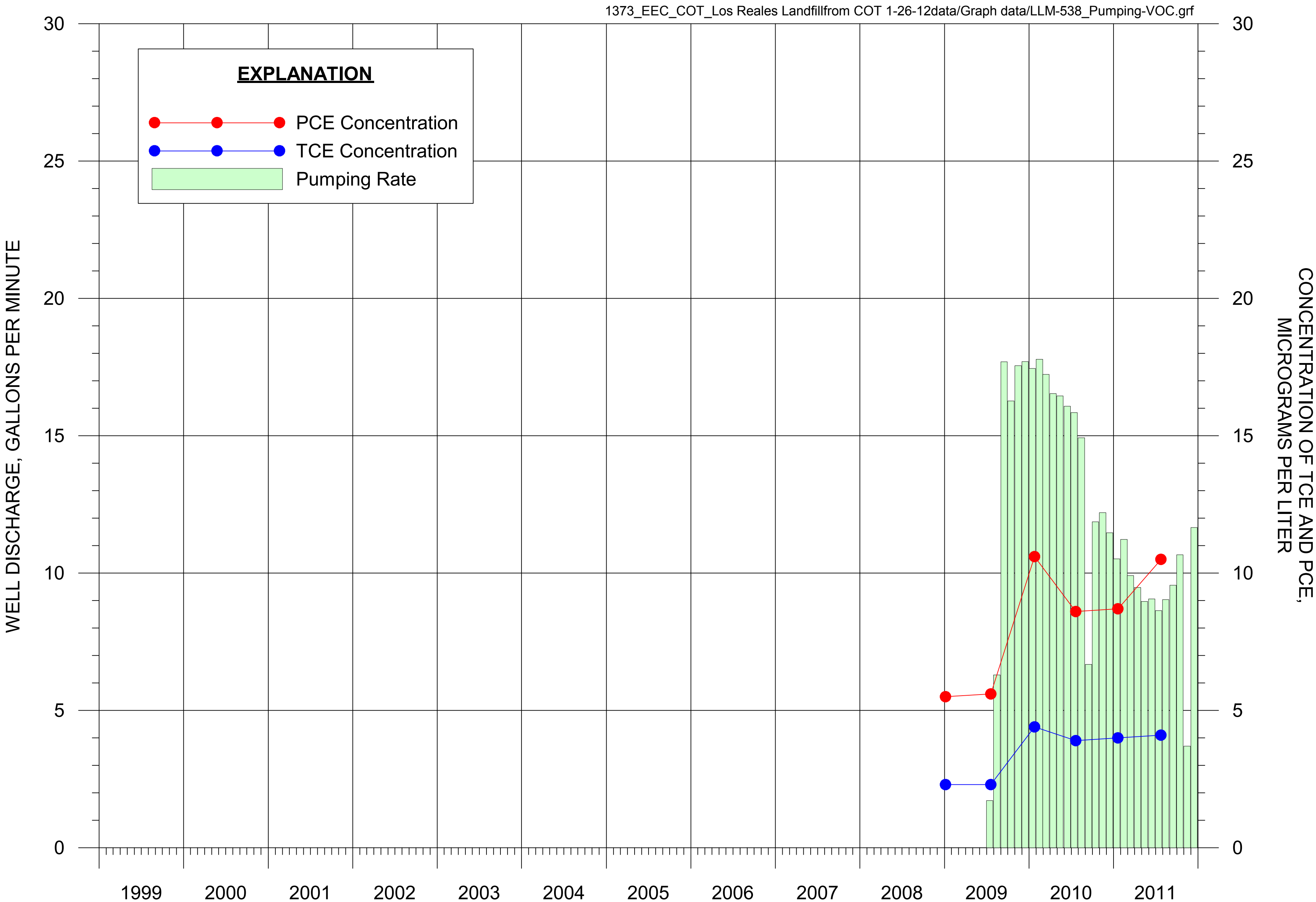


* Open symbols indicate concentration less than detection limit

**FIGURE C-3. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL LLM-537
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA**

DRAFT

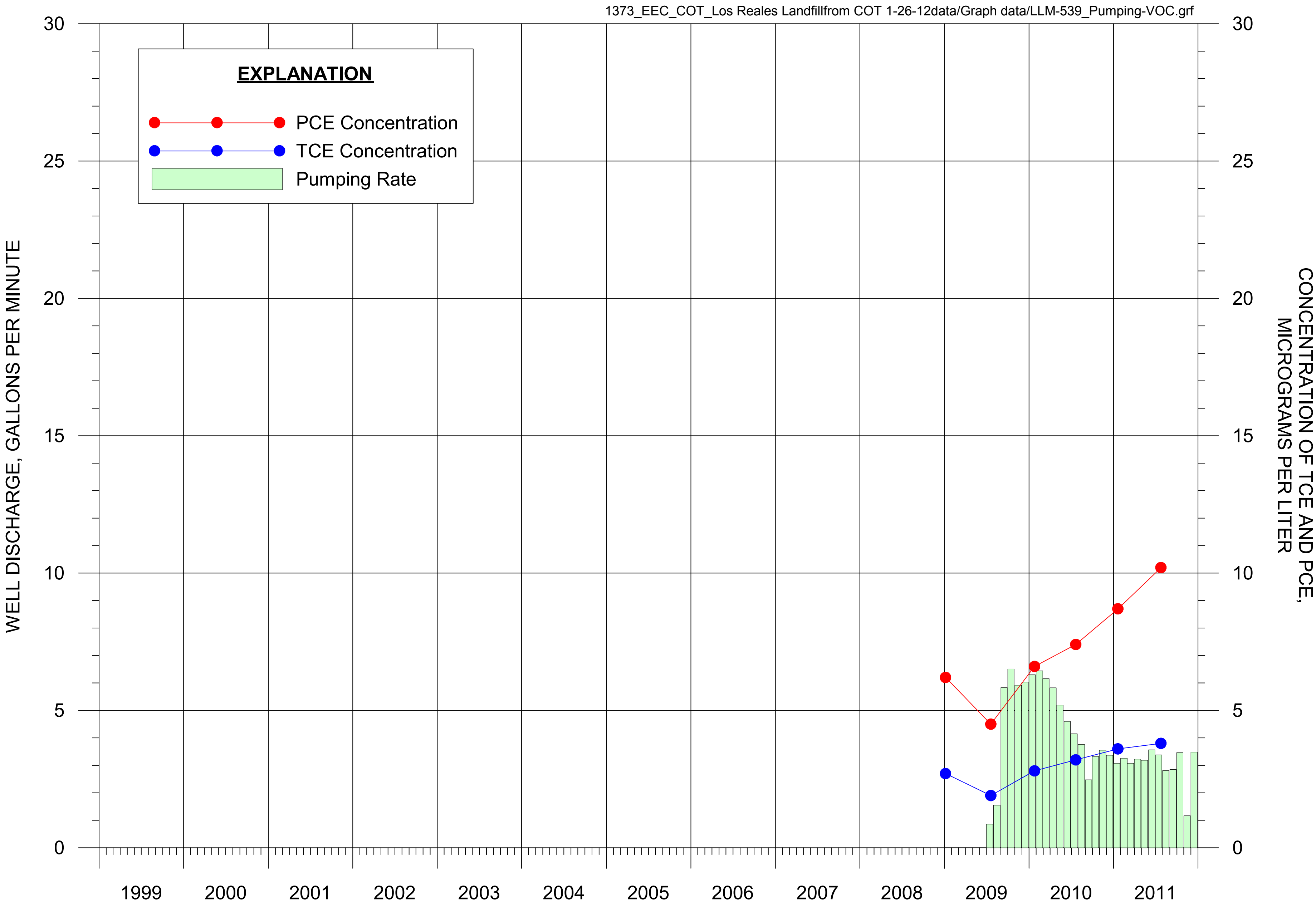
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-4. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL LLM-538
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-5. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL LLM-539
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

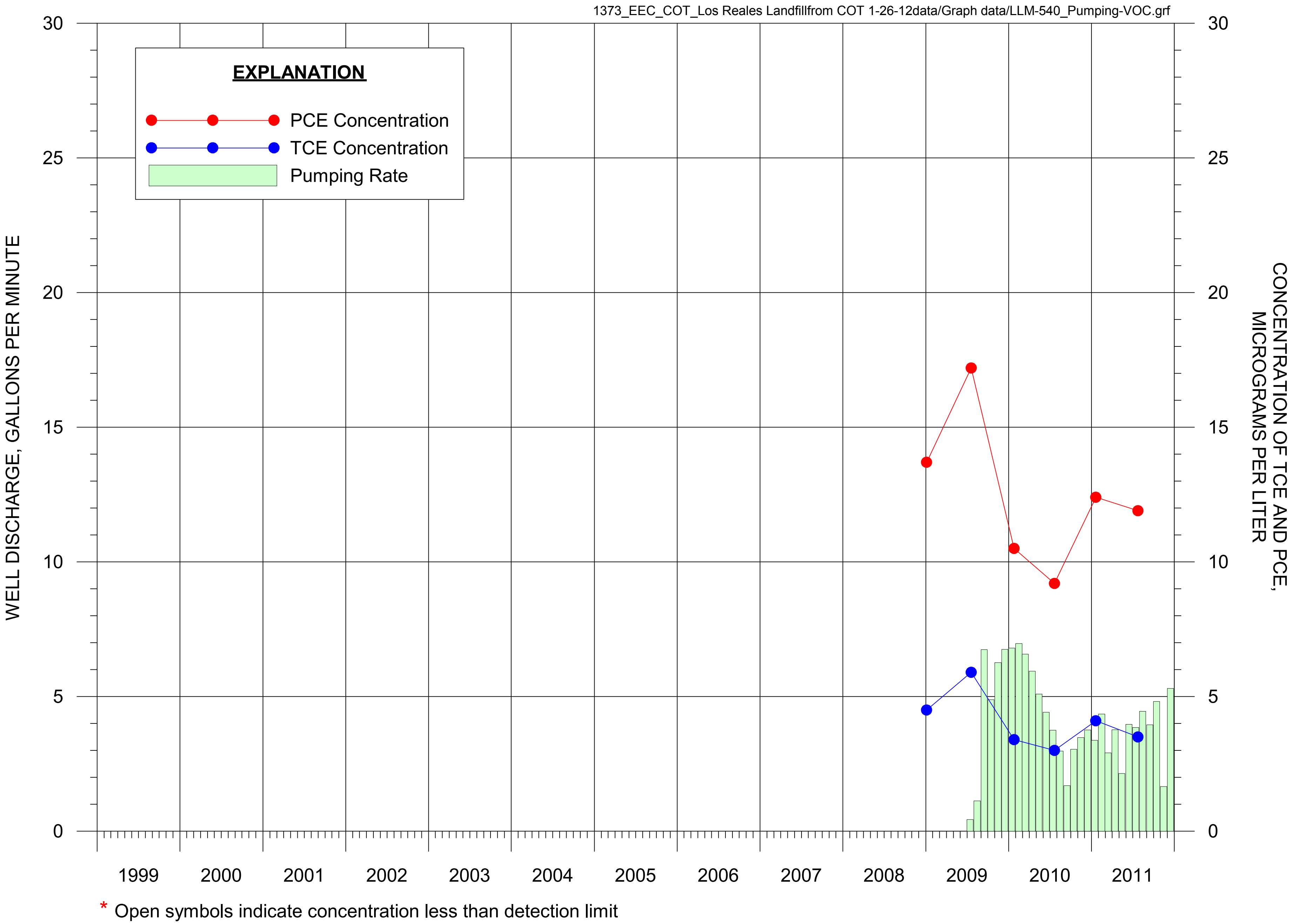


FIGURE C-6. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL LLM-540
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

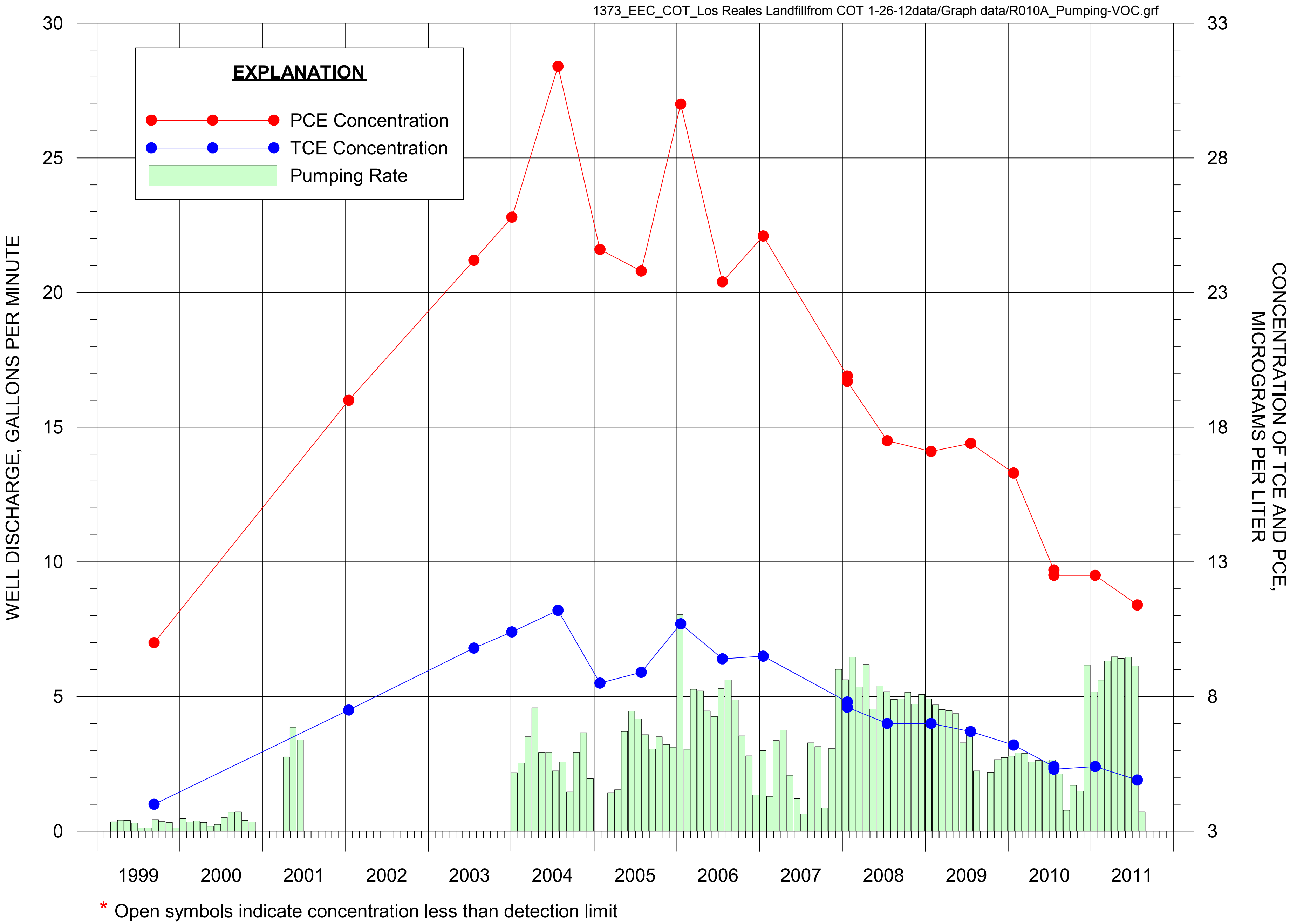


FIGURE C-7. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-010A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

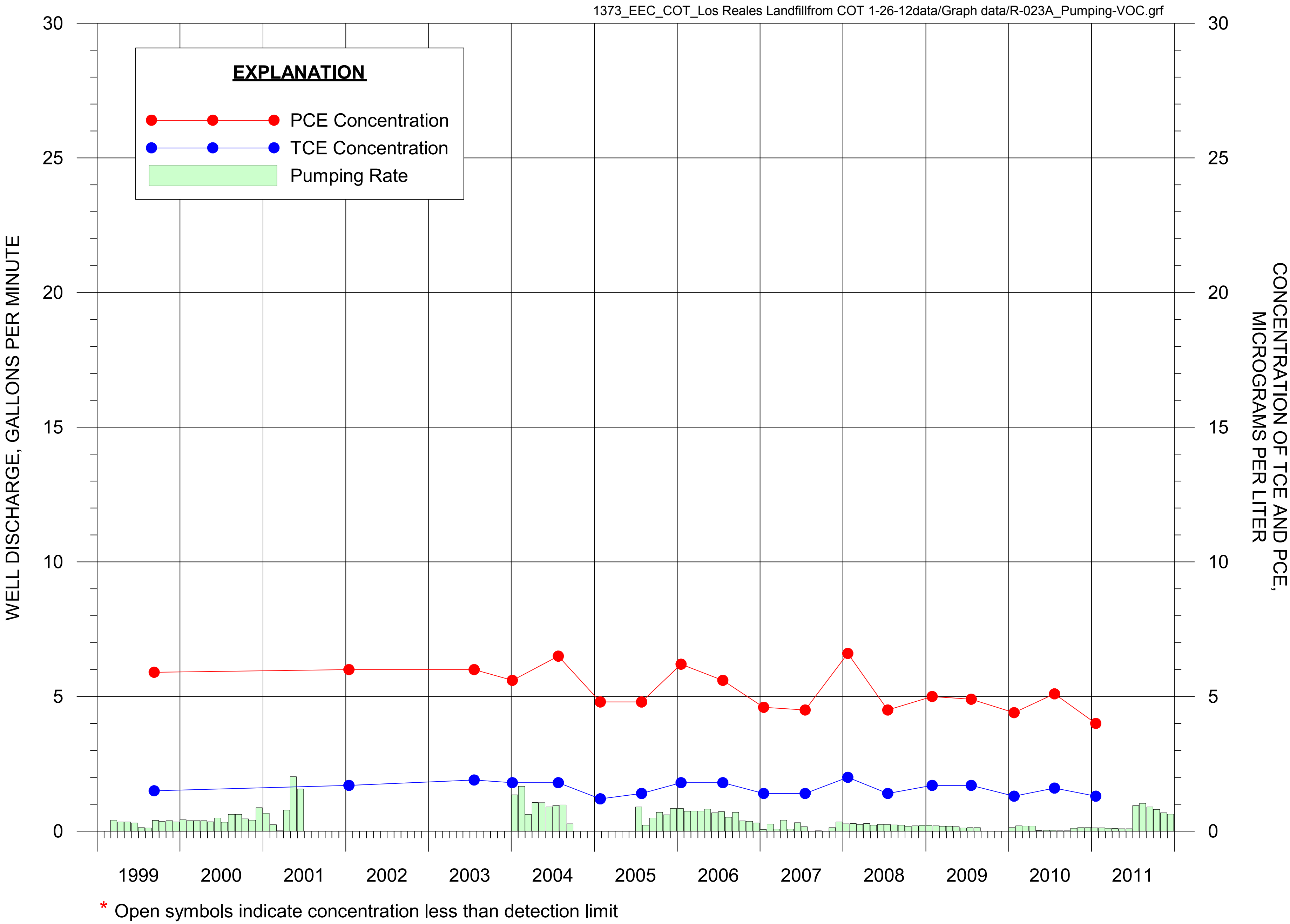
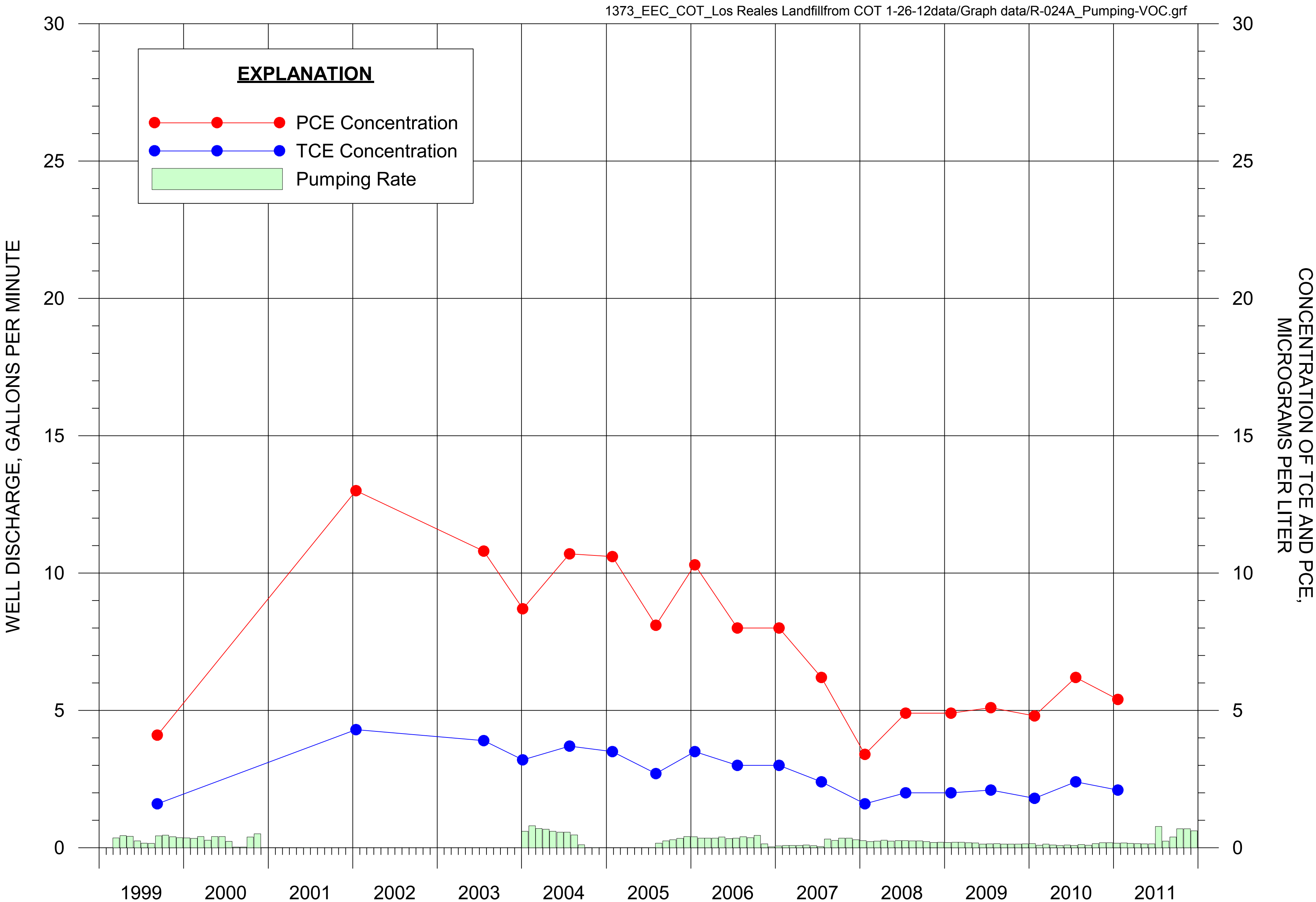


FIGURE C-8. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-023A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-9. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-024A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

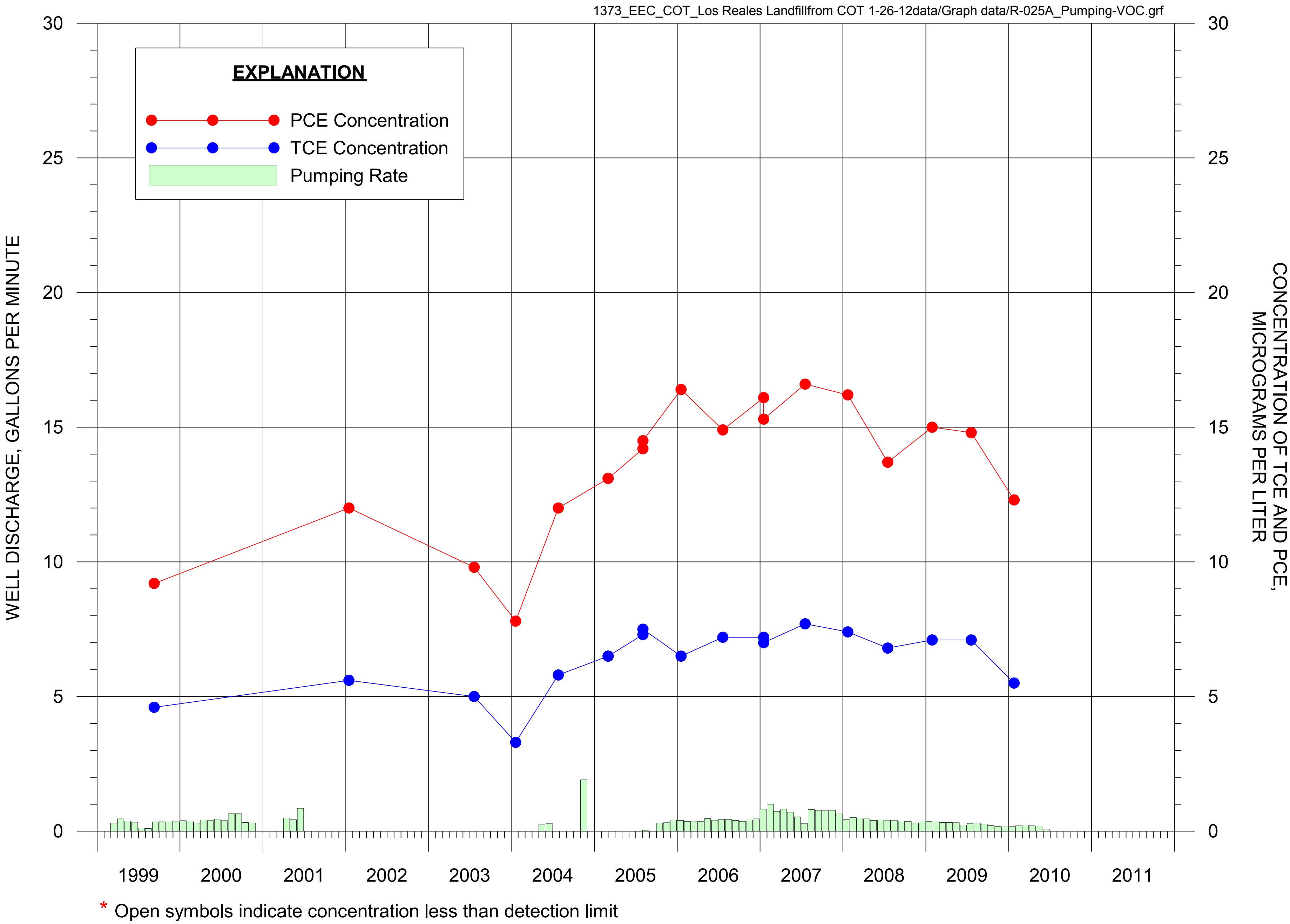
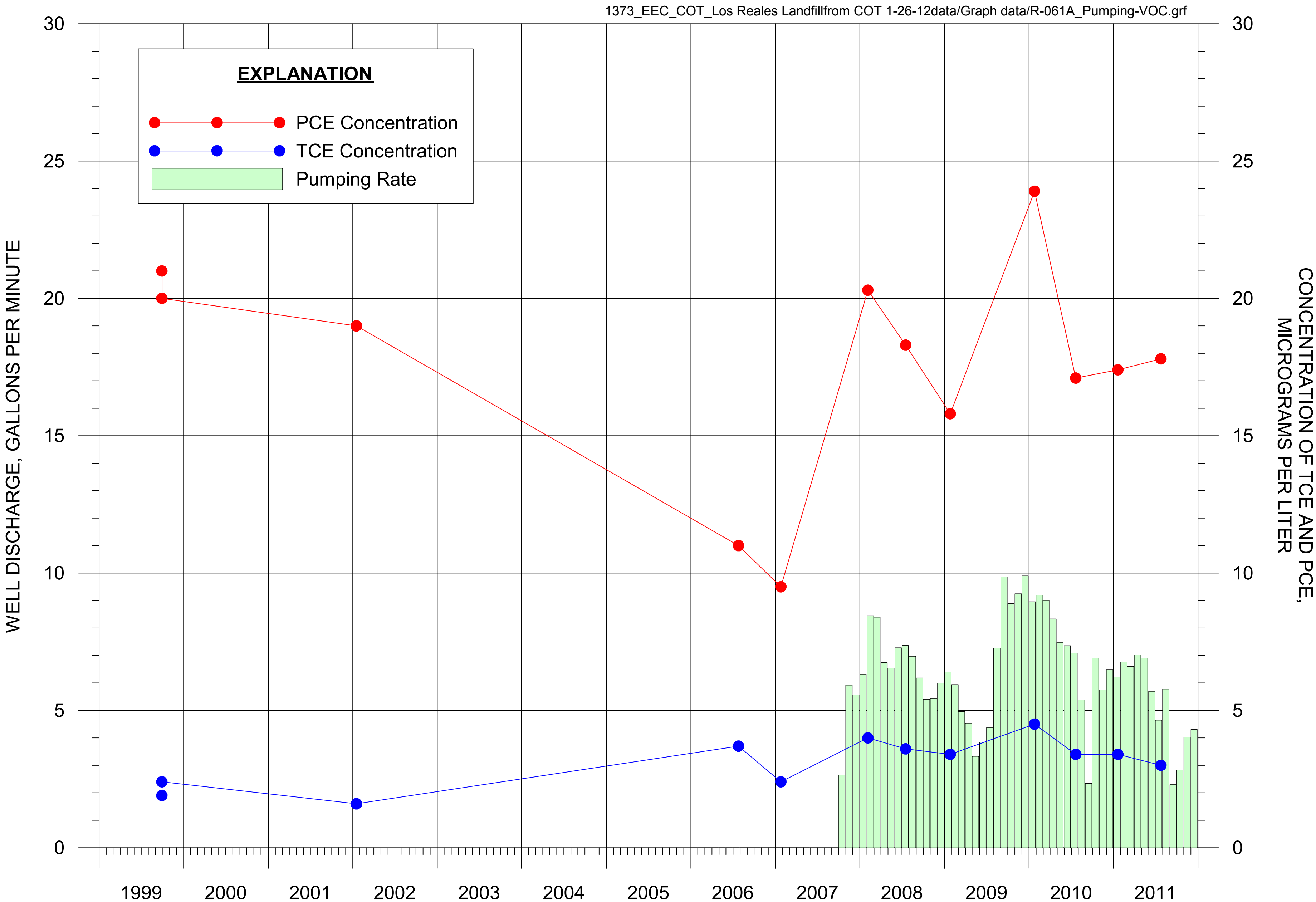


FIGURE C-10. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-025A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-11. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-061A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

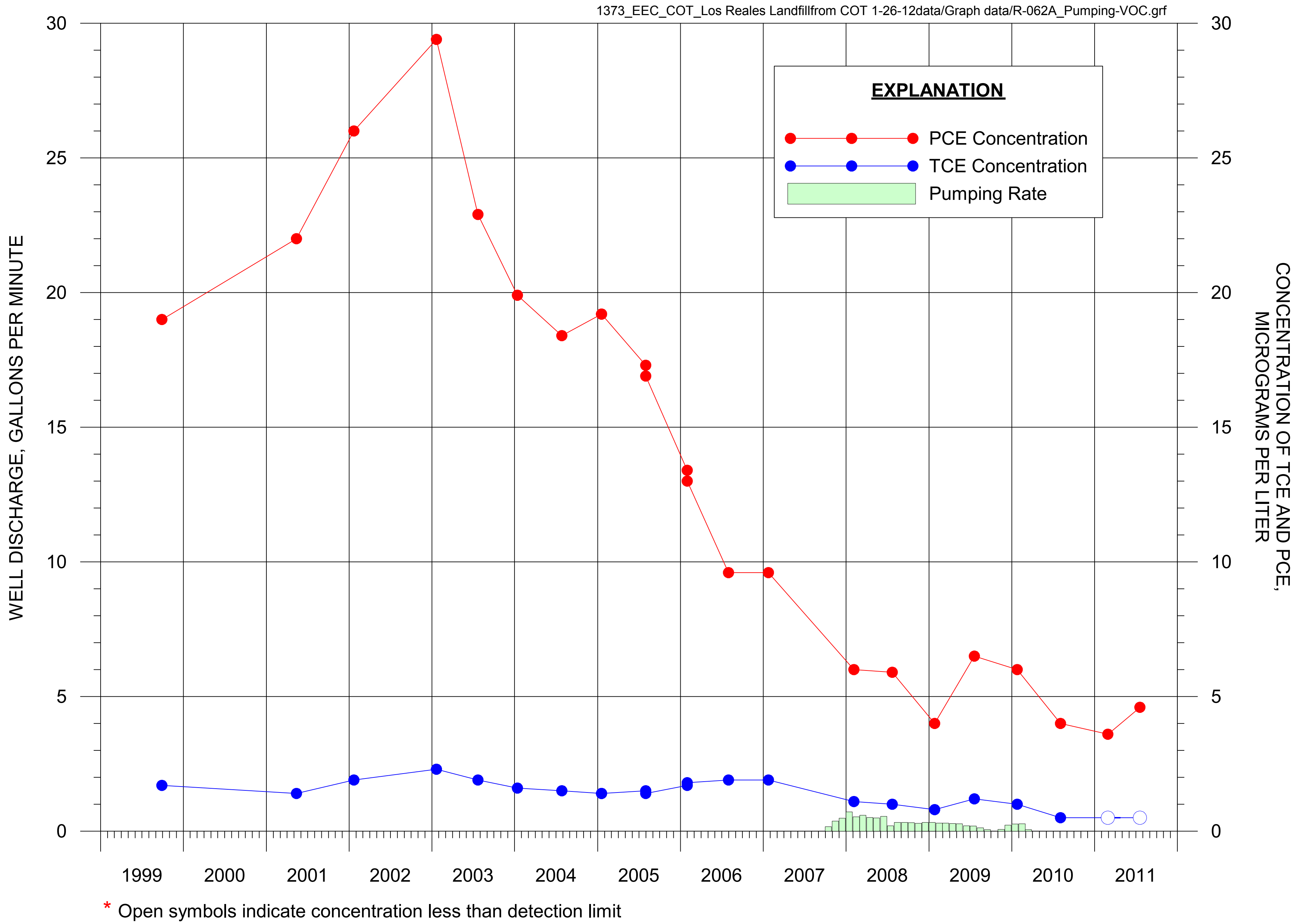


FIGURE C-12. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-062A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

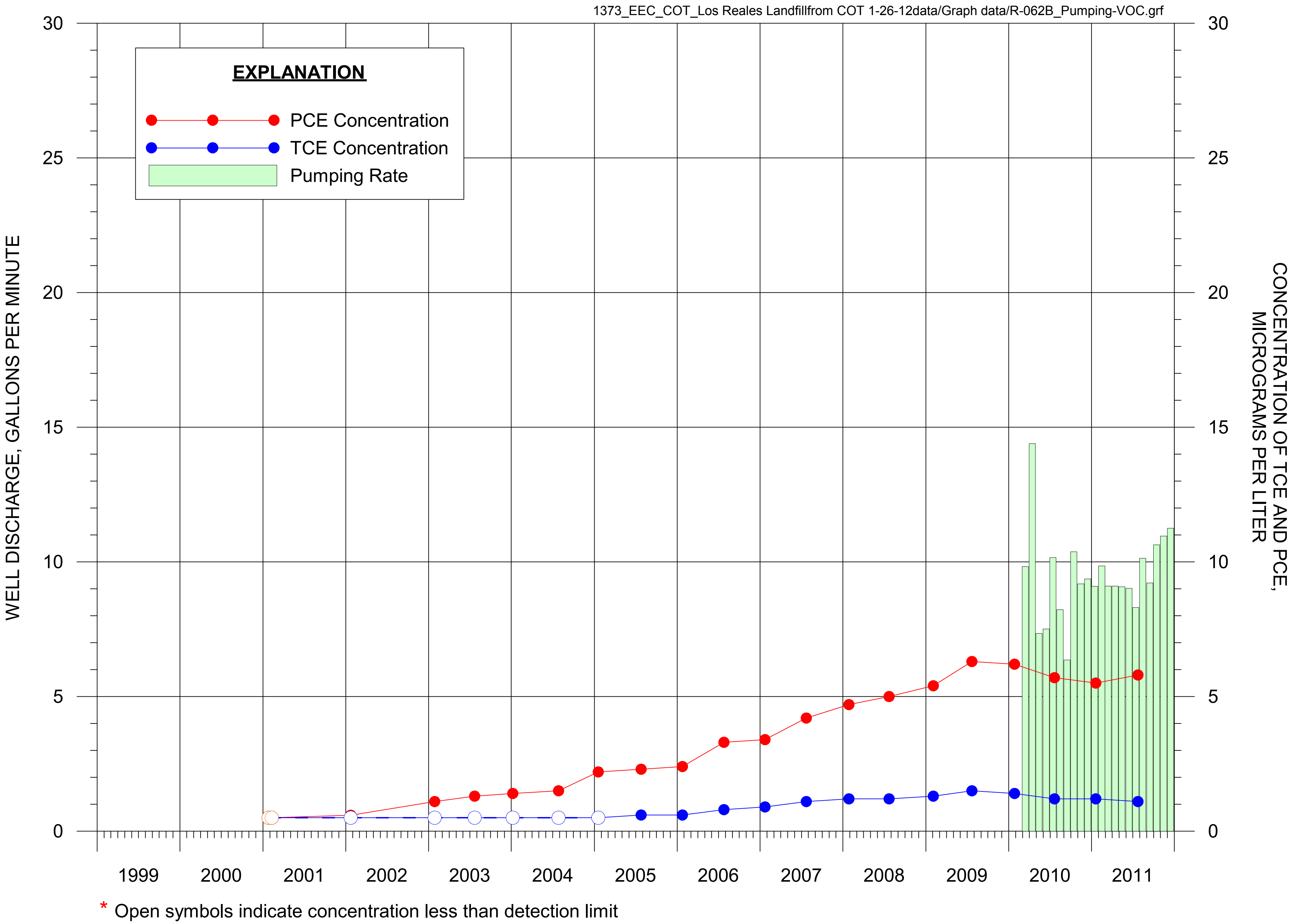
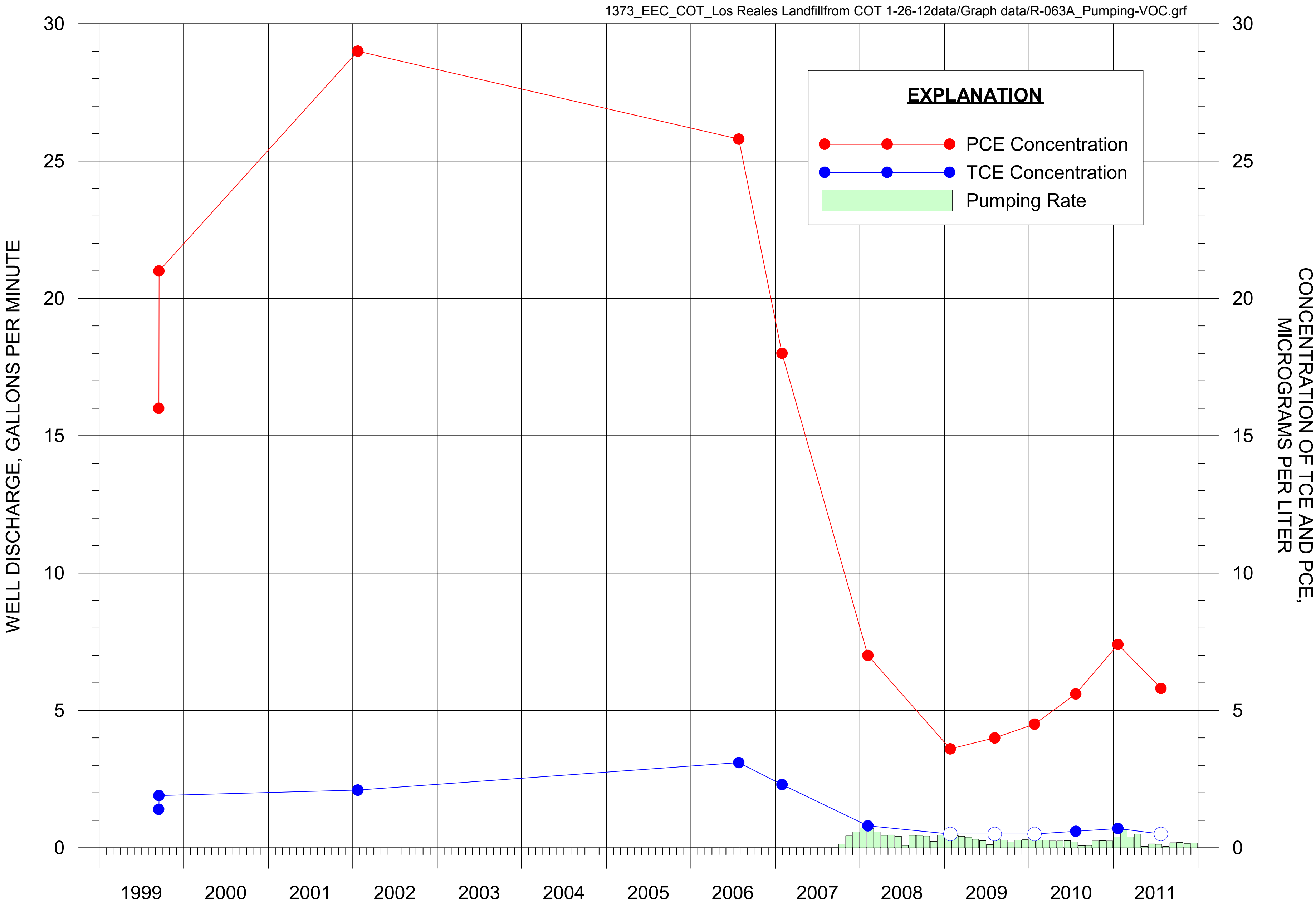


FIGURE C-13. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-062B LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

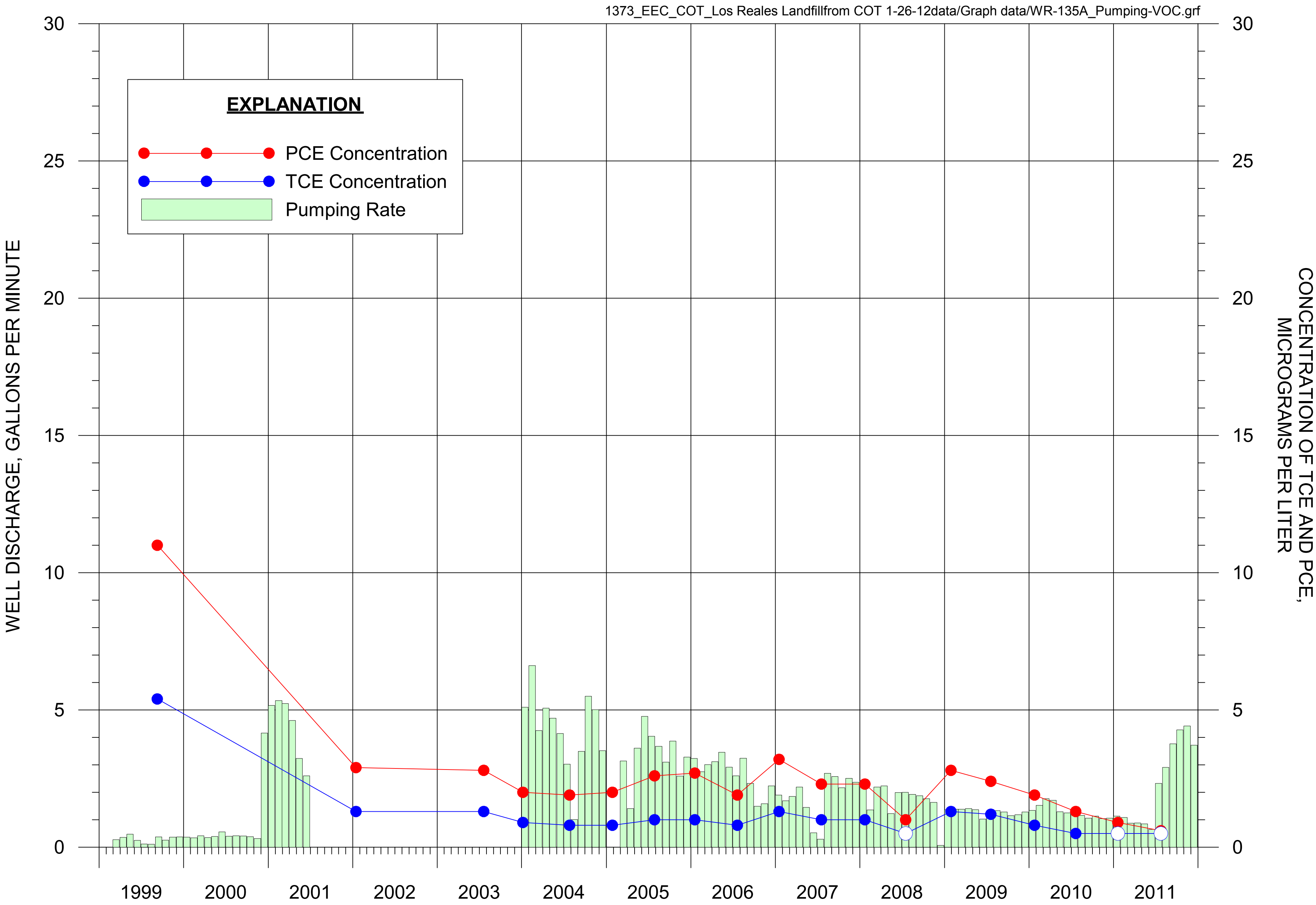
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

**FIGURE C-14. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL R-063A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA**

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-15. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL WR-135A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

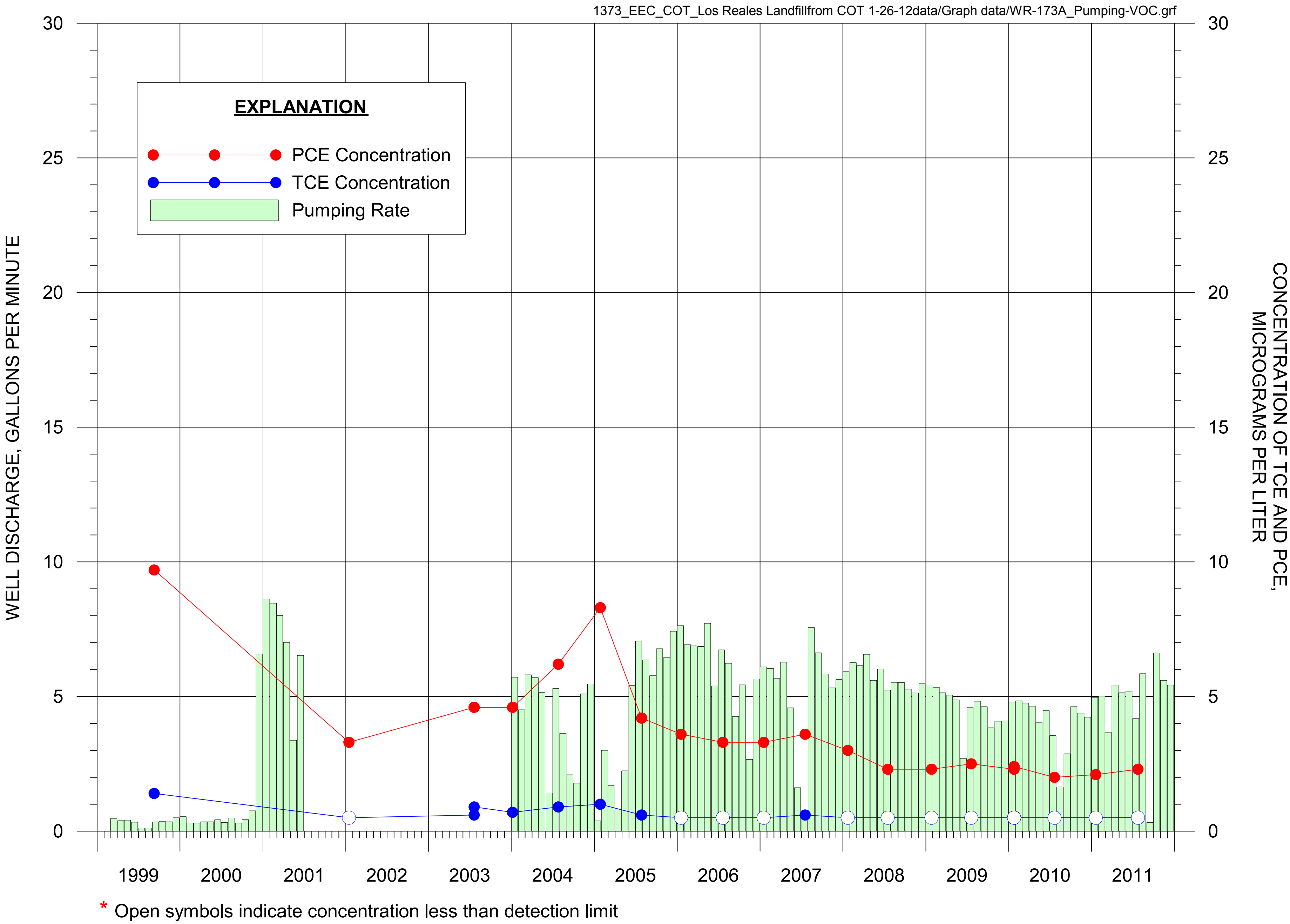


FIGURE C-16. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL WR-173A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

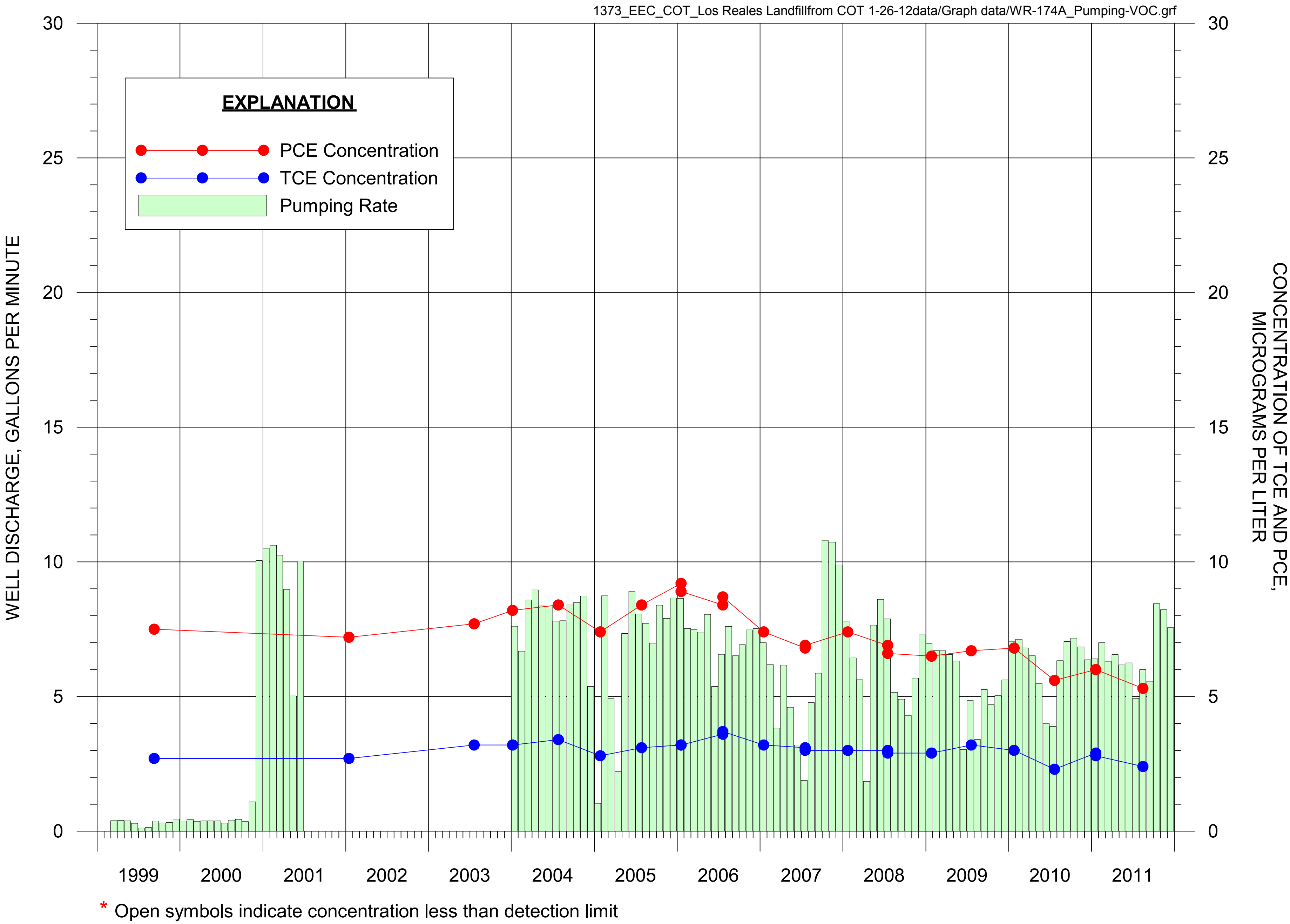
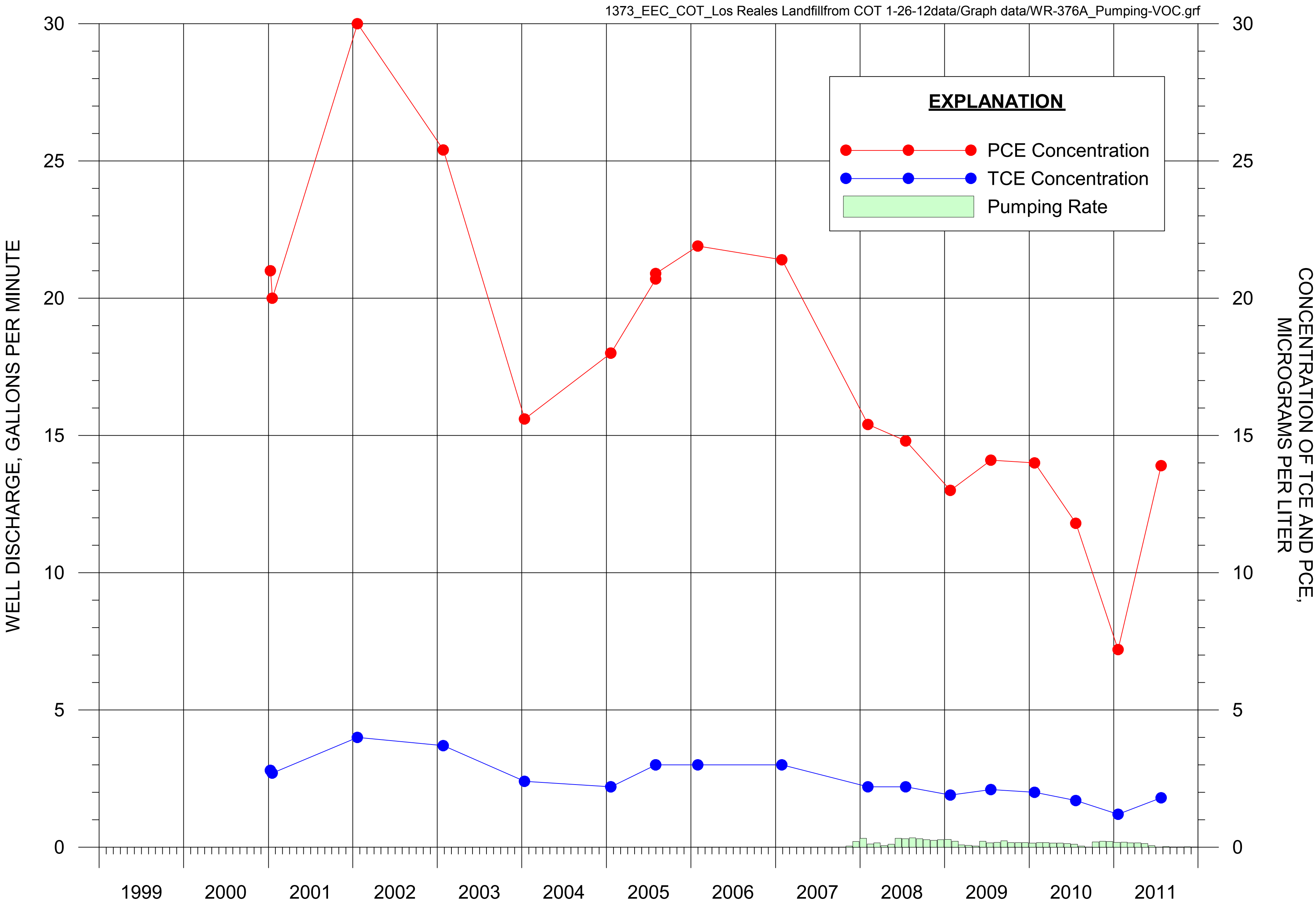


FIGURE C-17. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL WR-174A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

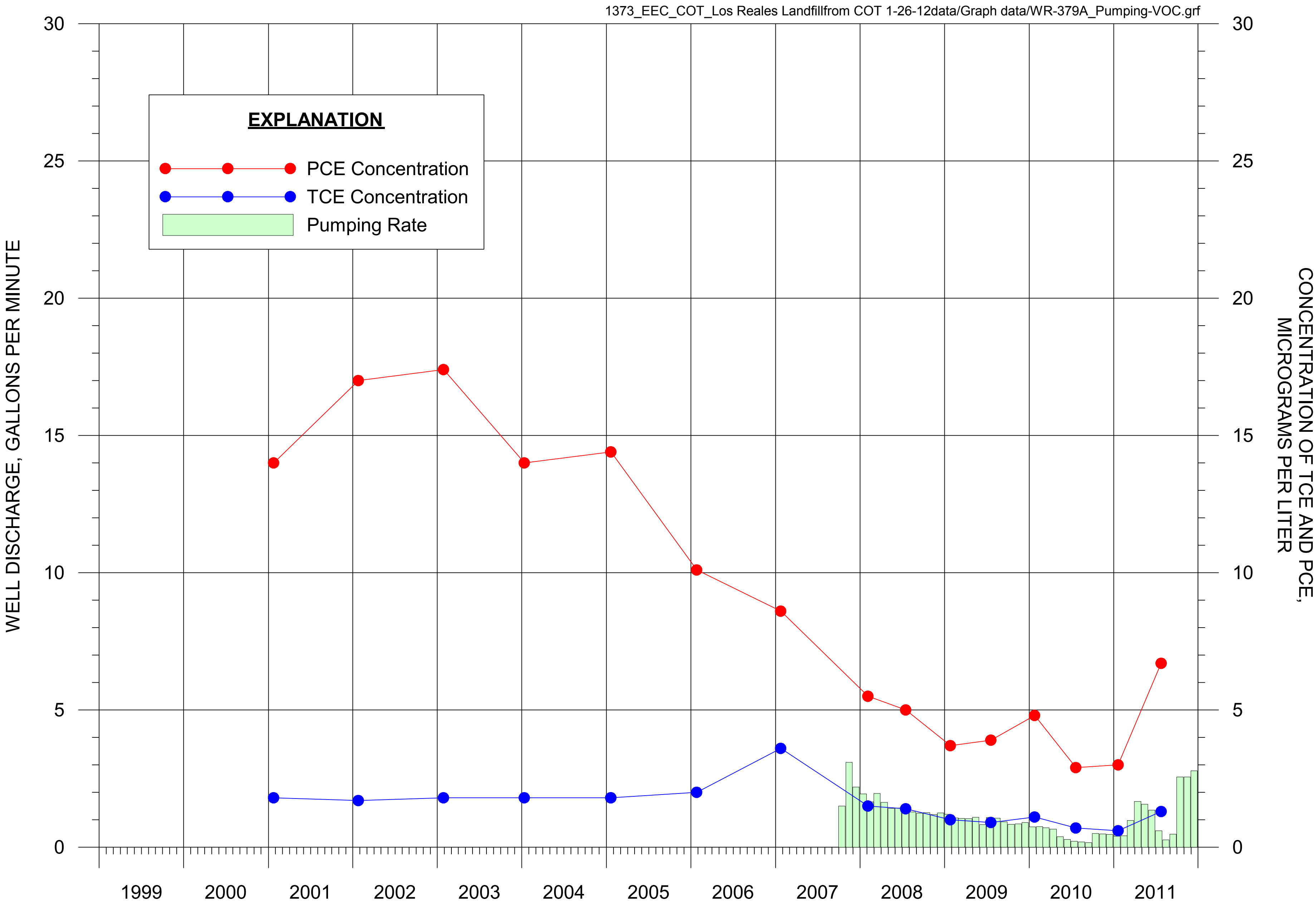
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-18. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL WR-376A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

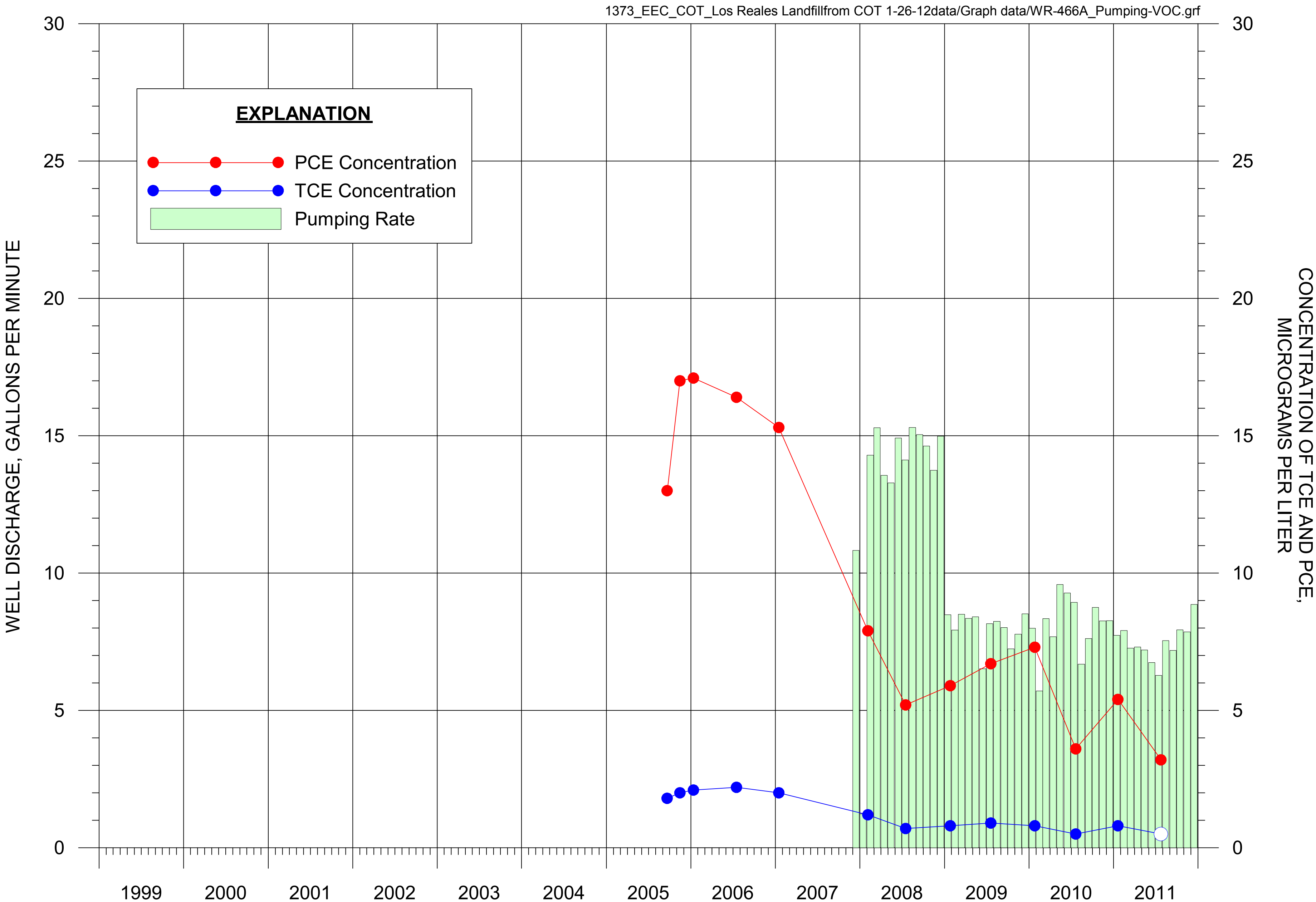
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-19. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL WR-379A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

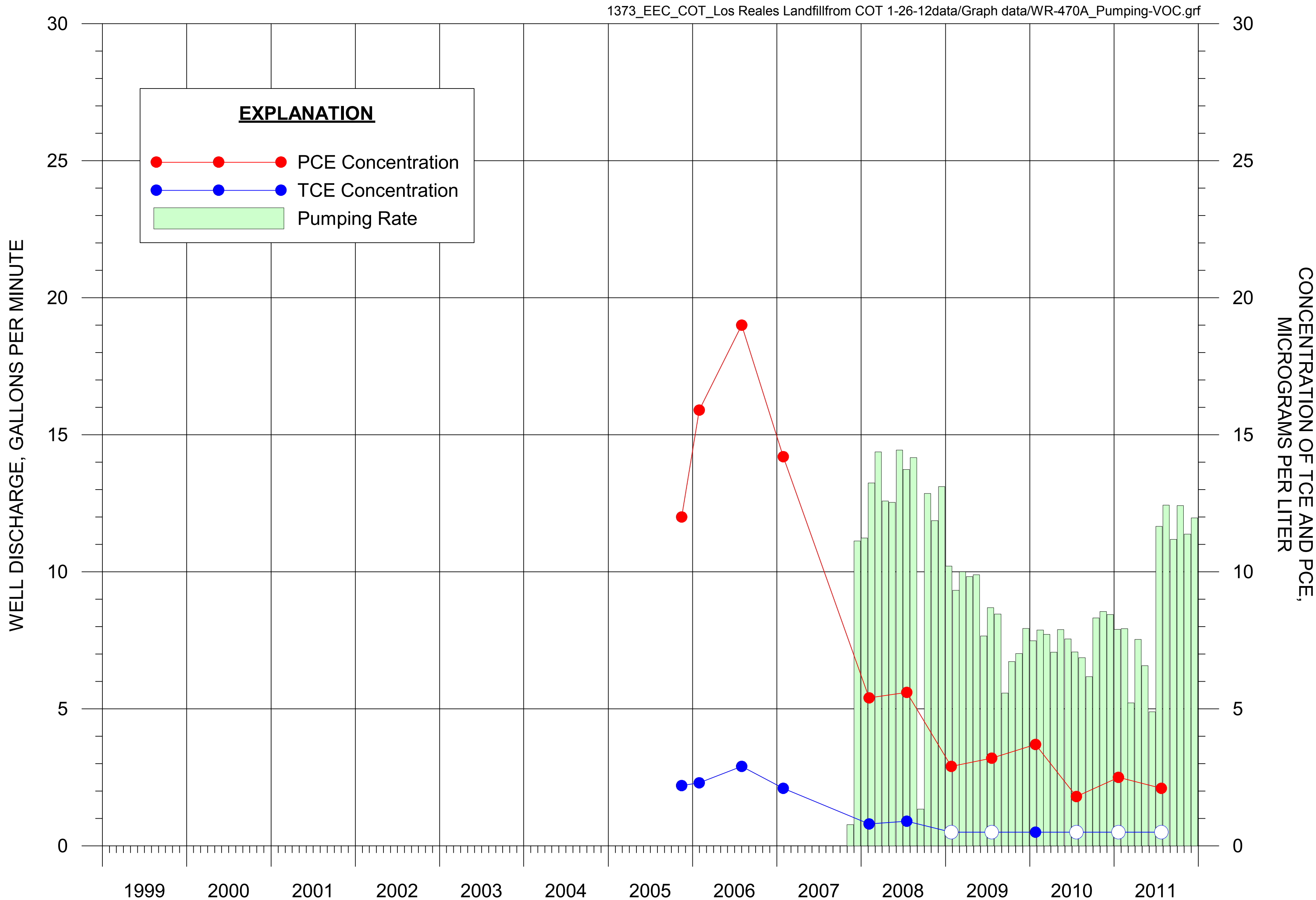
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-20. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL WR-466A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-21. GRAPH OF WELL DISCHARGE, TCE AND PCE FOR WELL WR-470A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

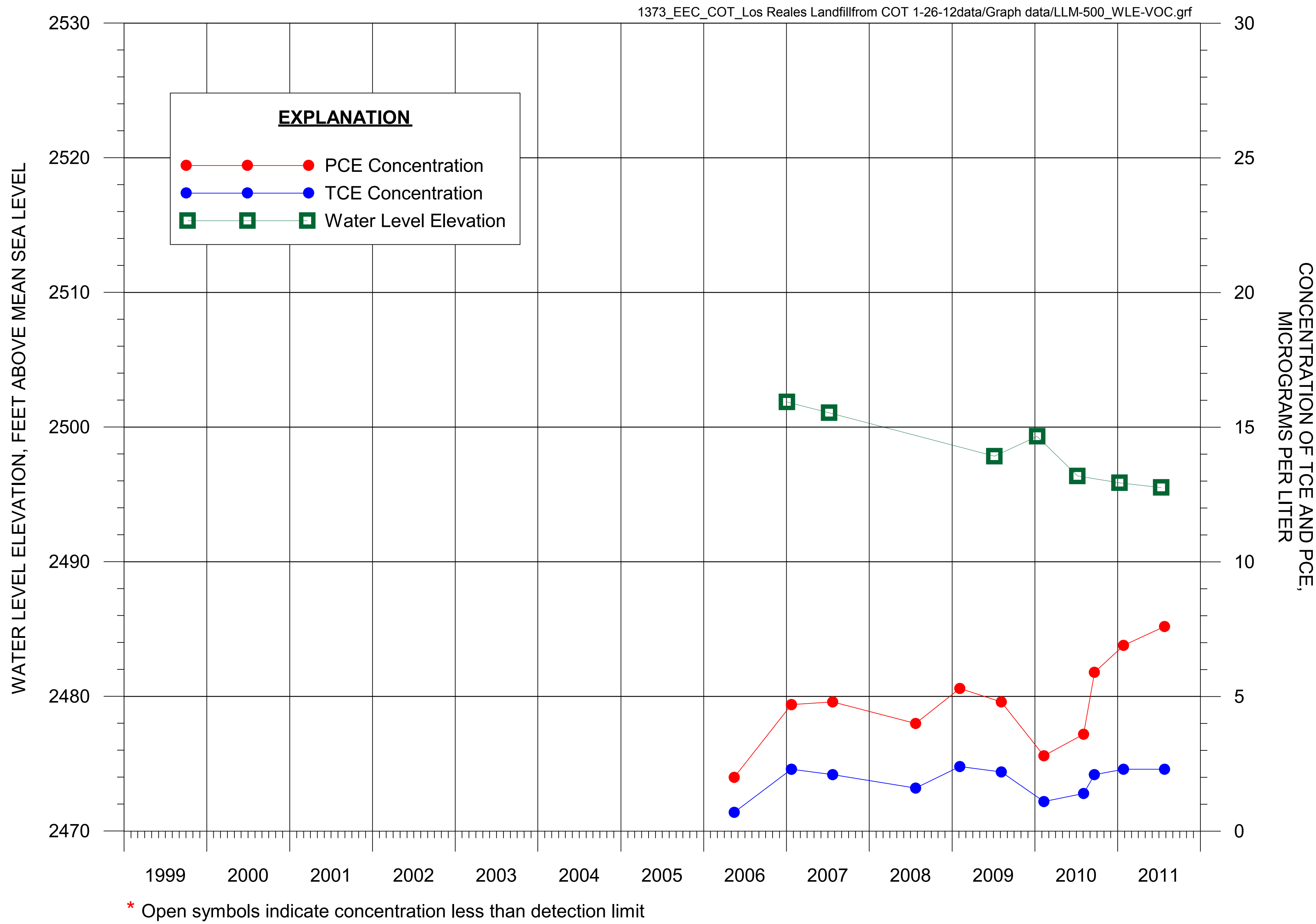
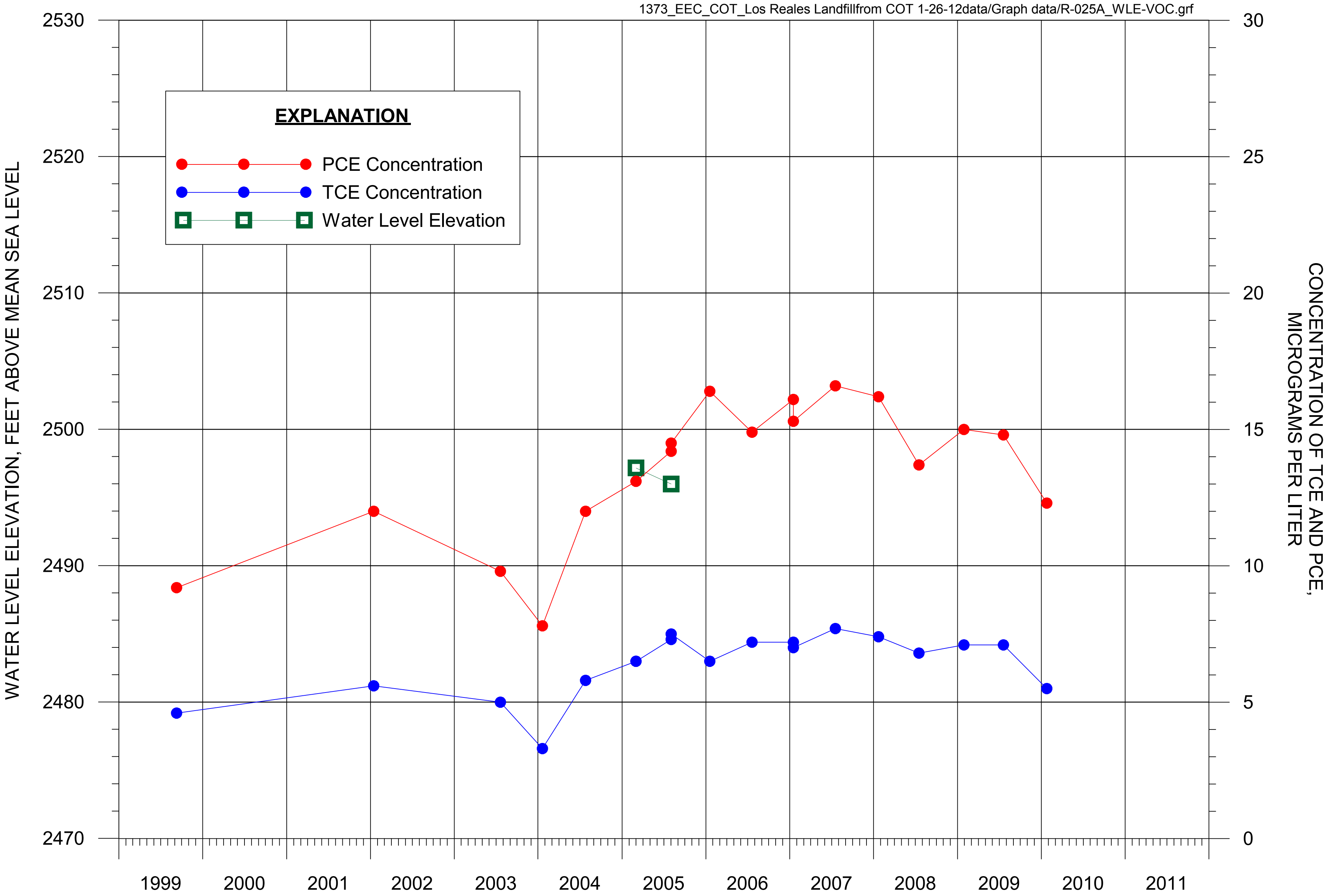


FIGURE C-22. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL LLM-500
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

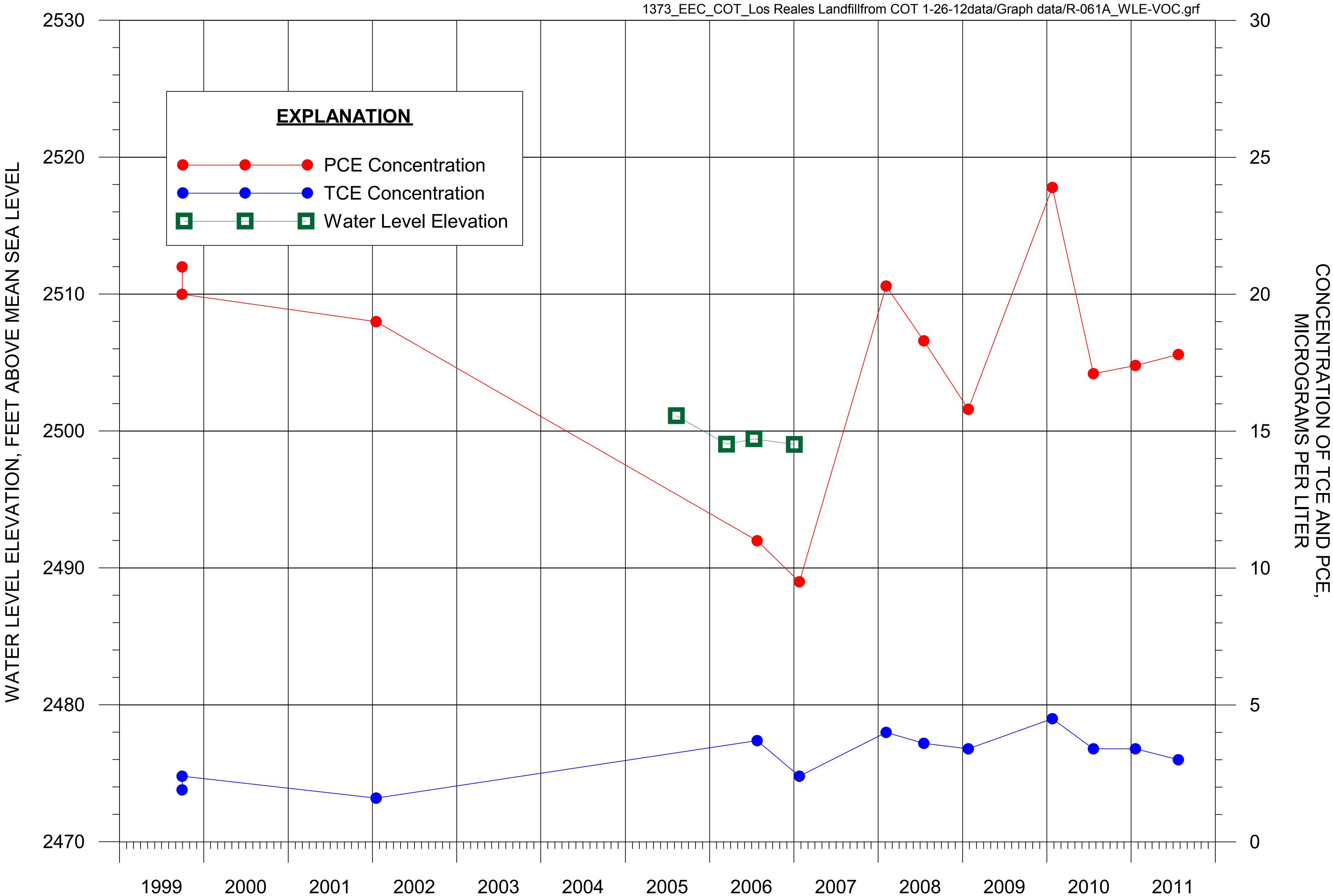
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-23. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL R-025A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

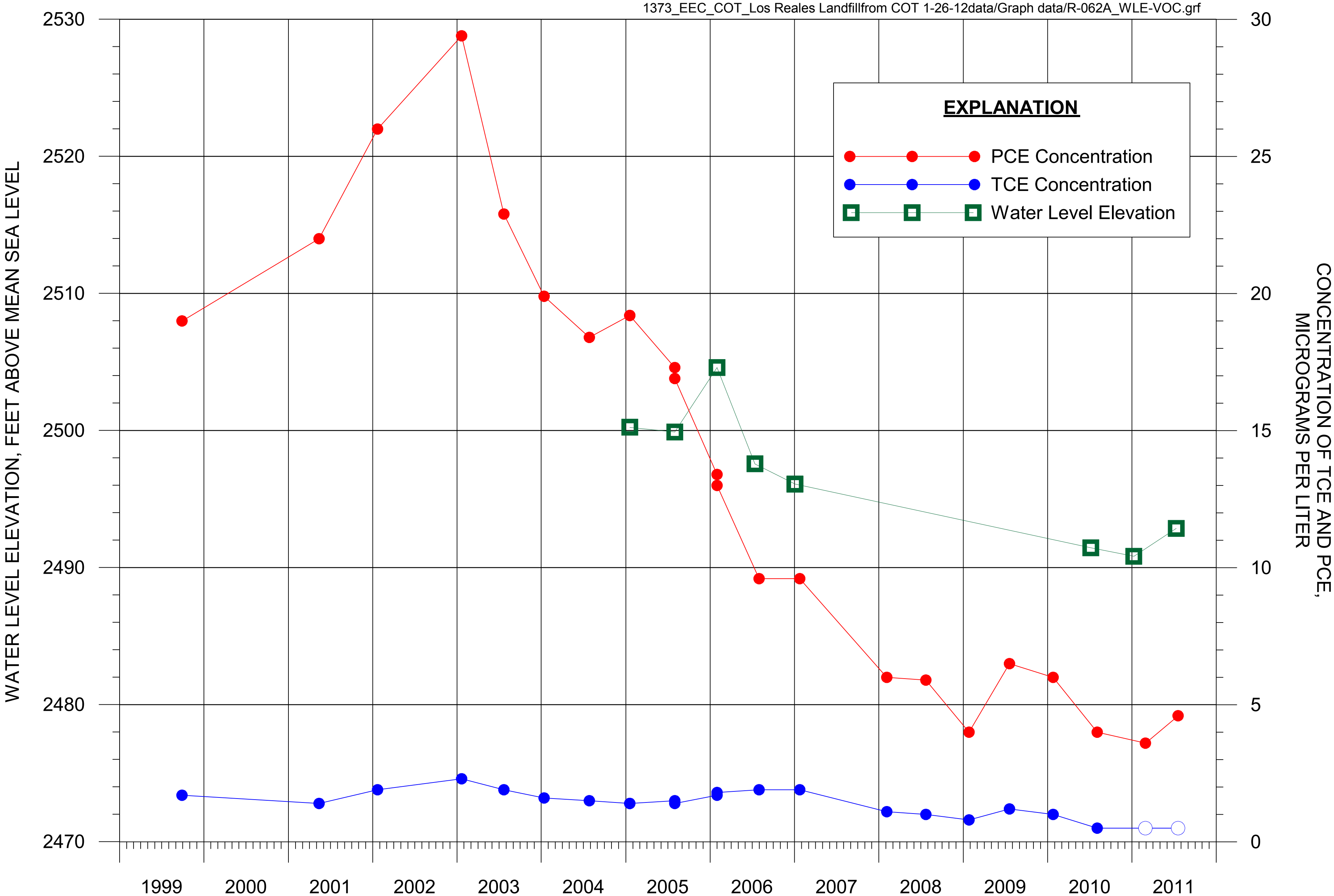
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-24. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL R-061A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-25. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL R-062A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

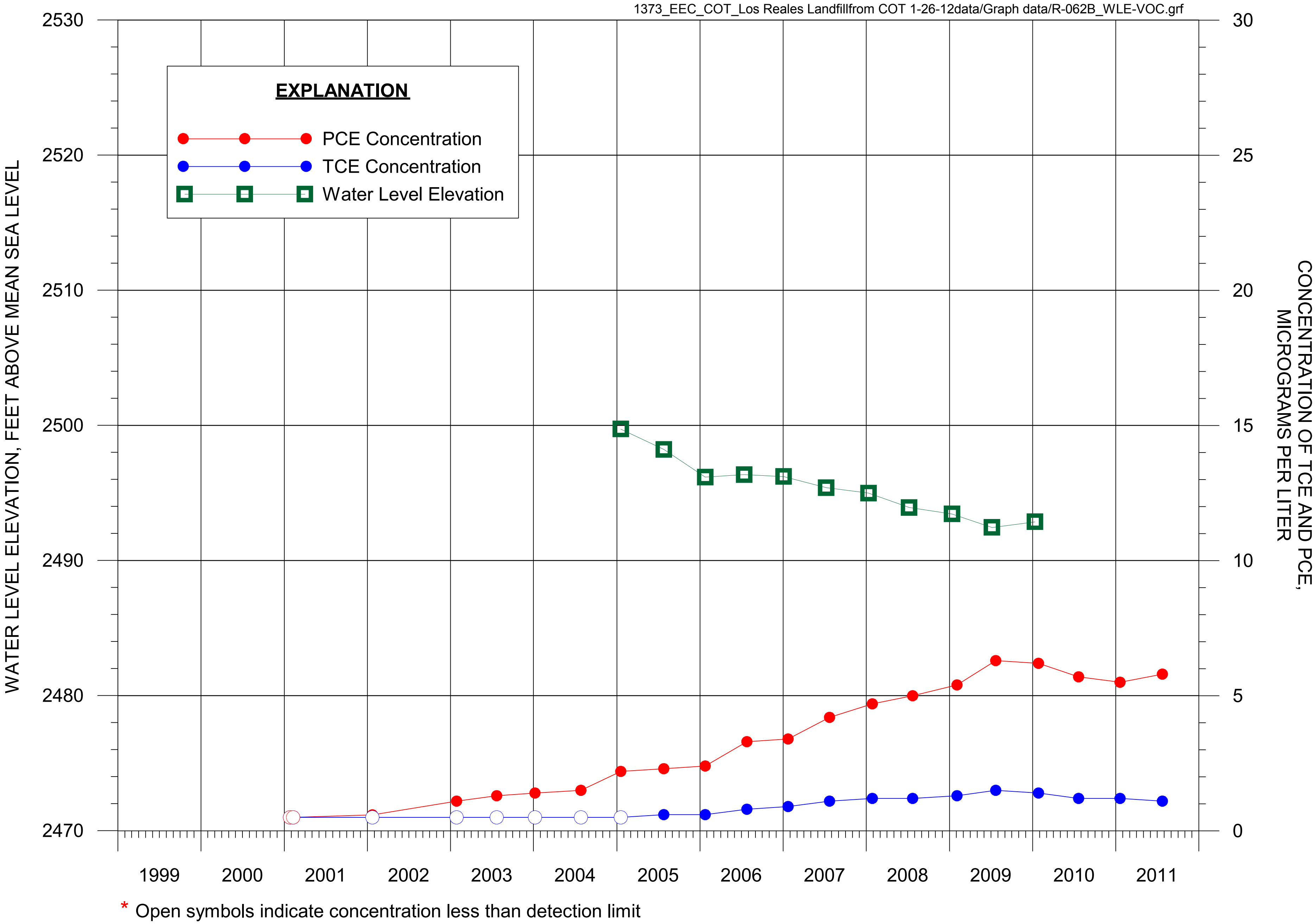


FIGURE C-26. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL R-062B LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

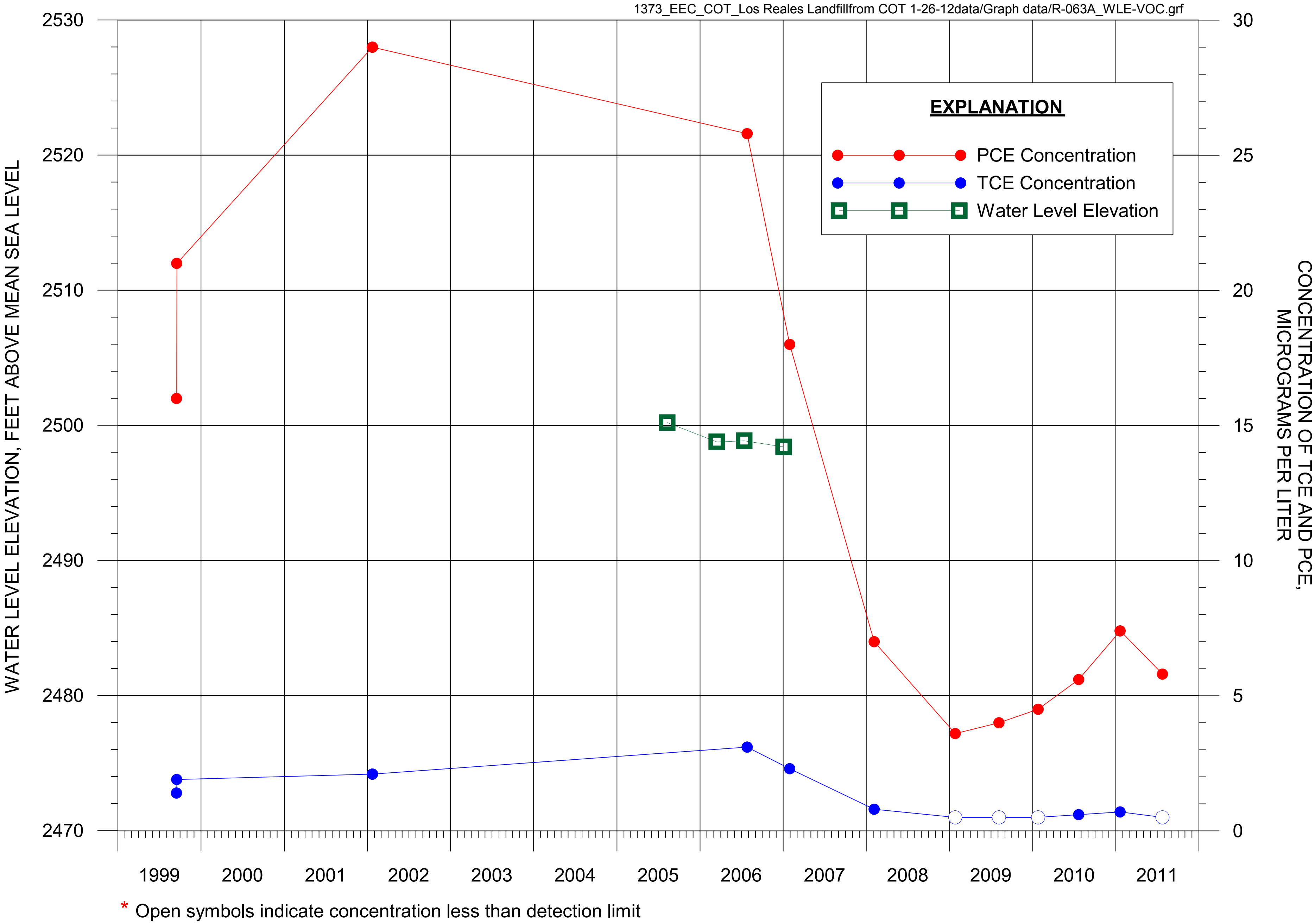
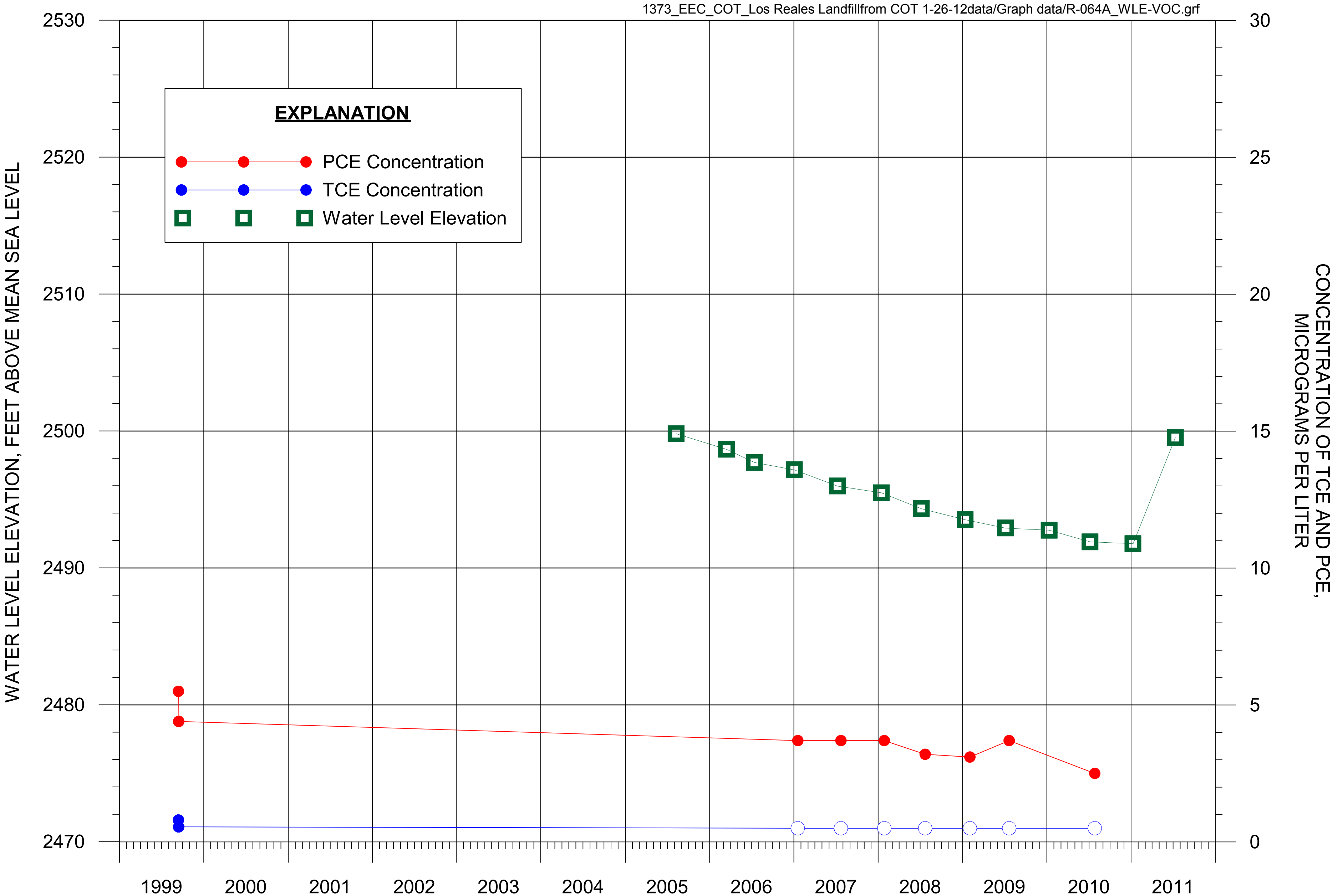


FIGURE C-27. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL R-063A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

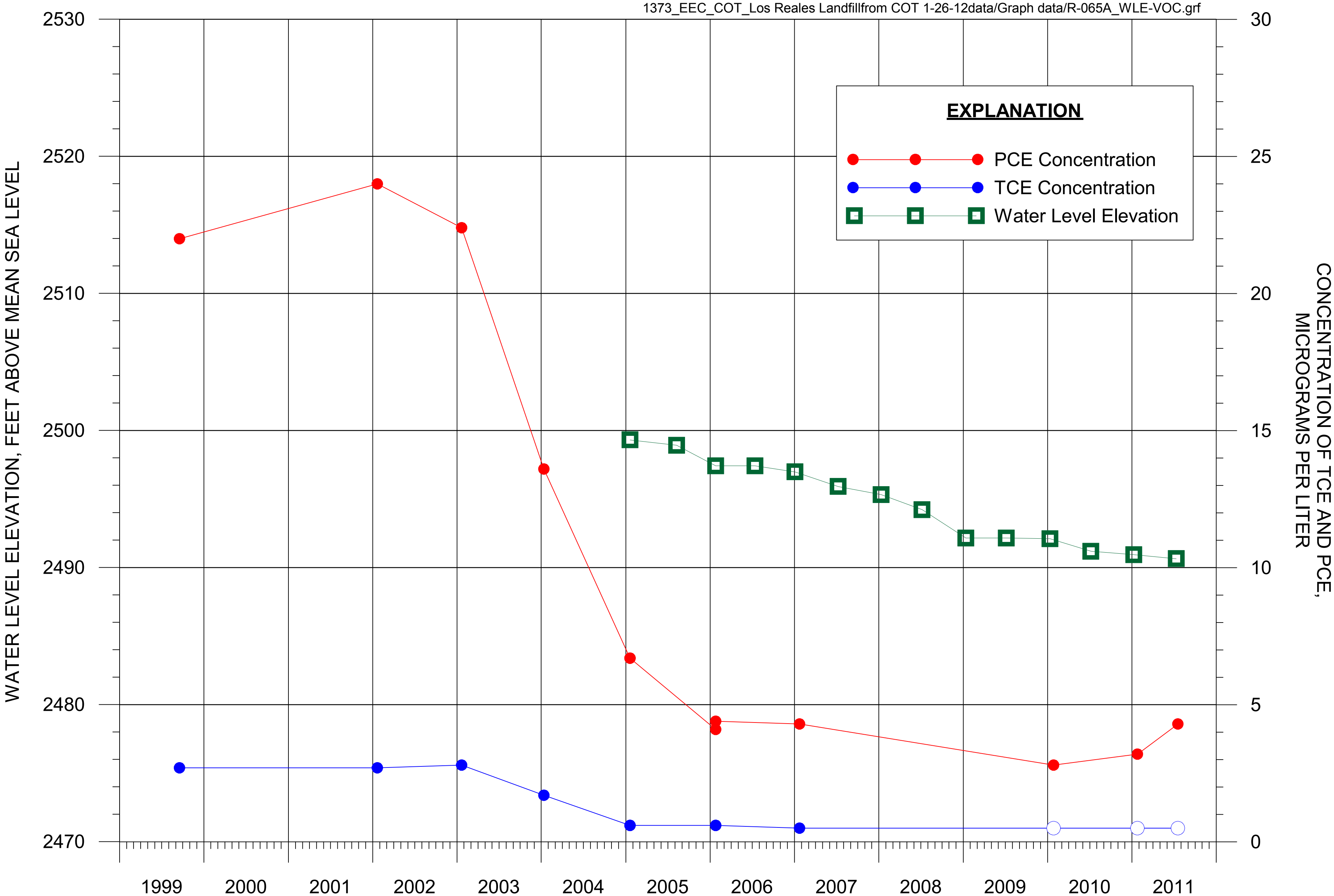
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-28. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL R-064A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

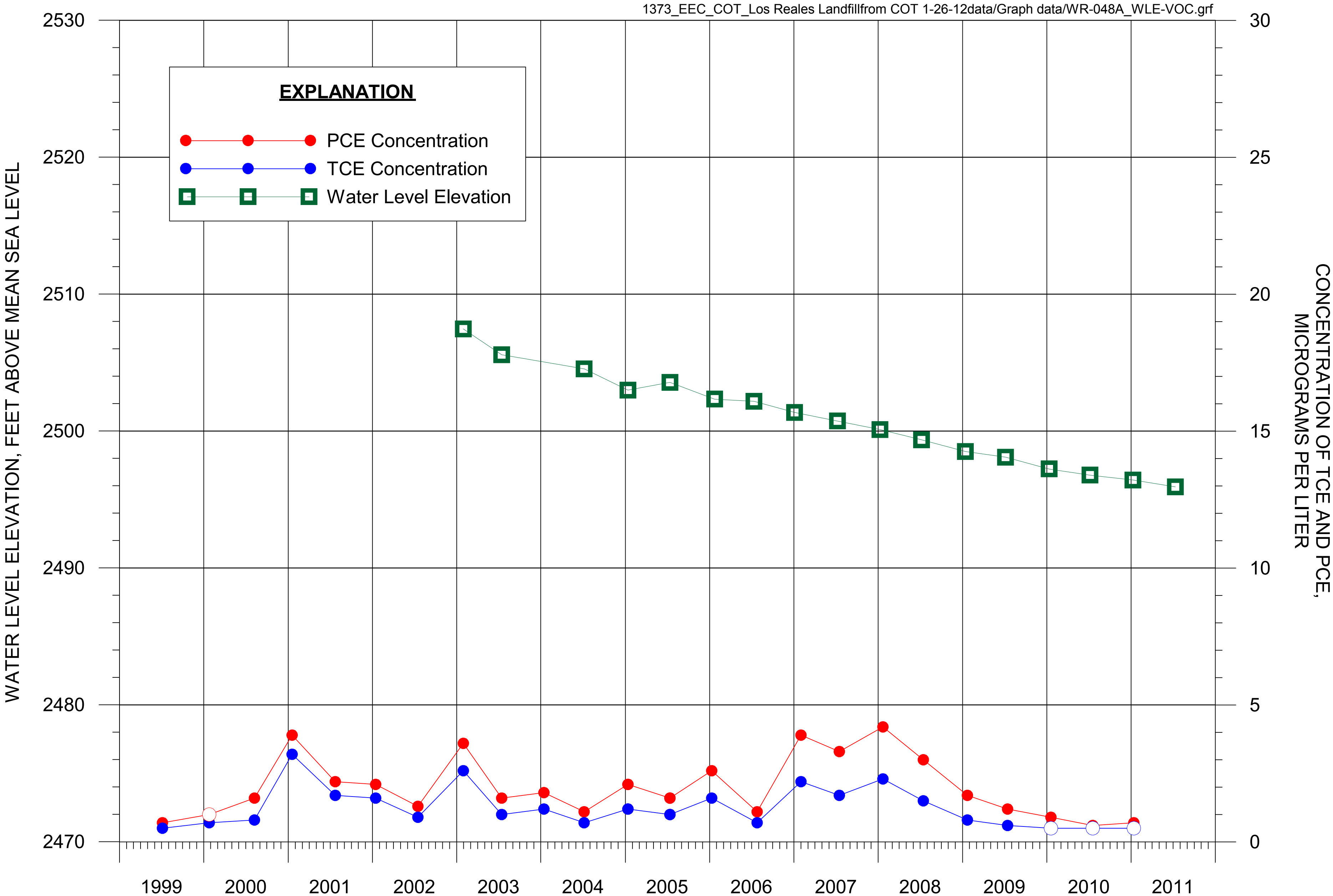
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-29. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL R-065A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

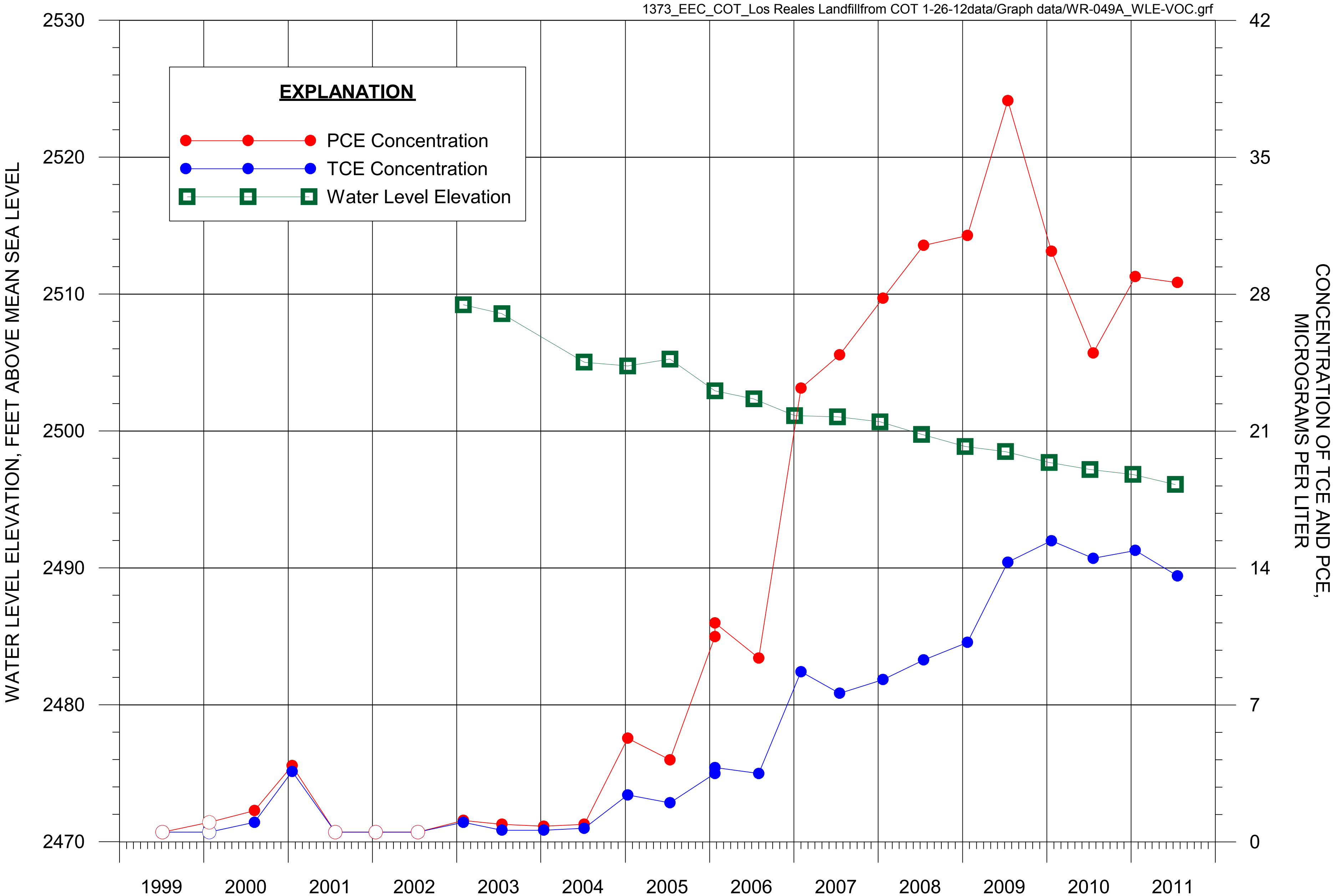
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-30. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-048A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-31. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-049A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

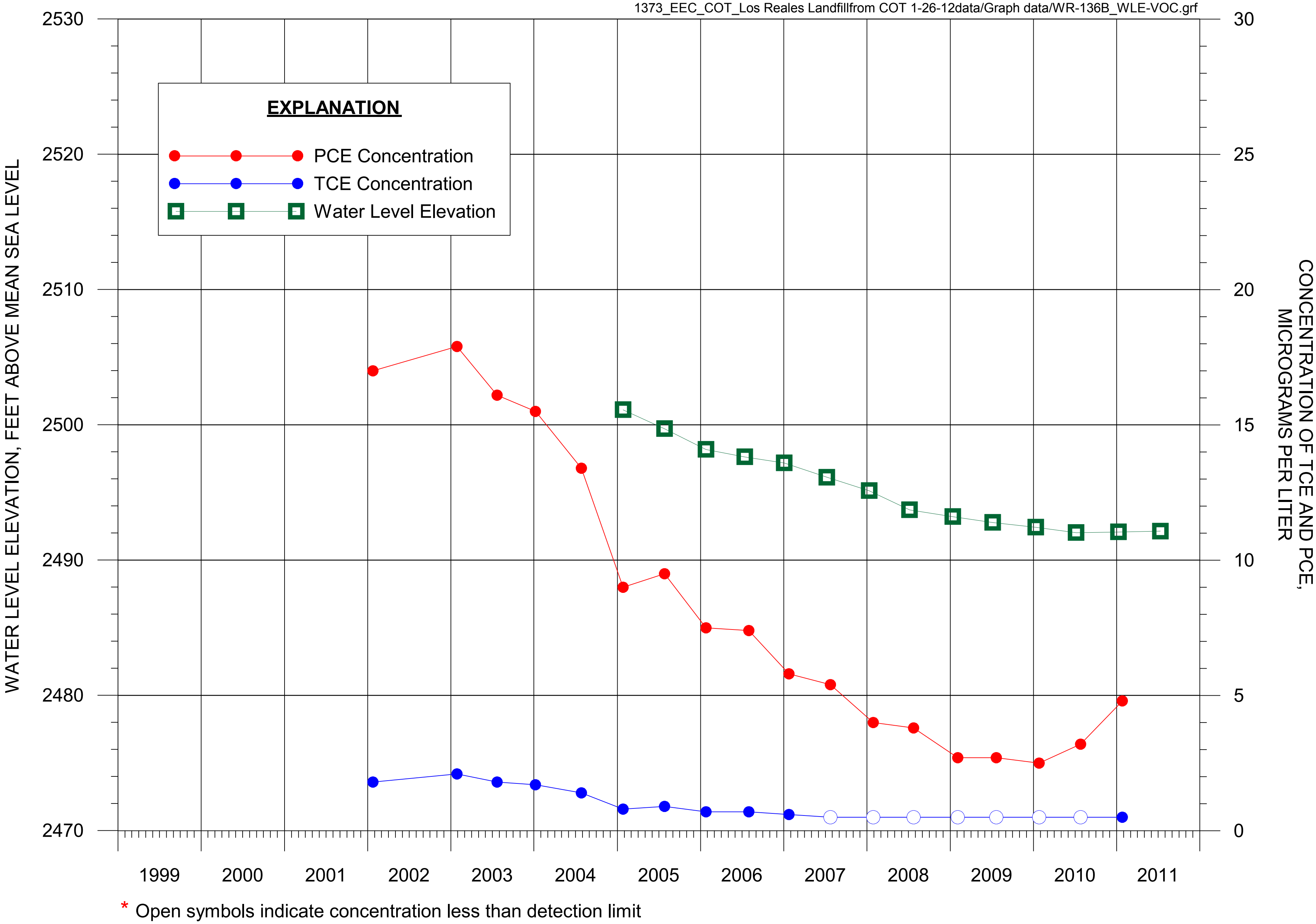
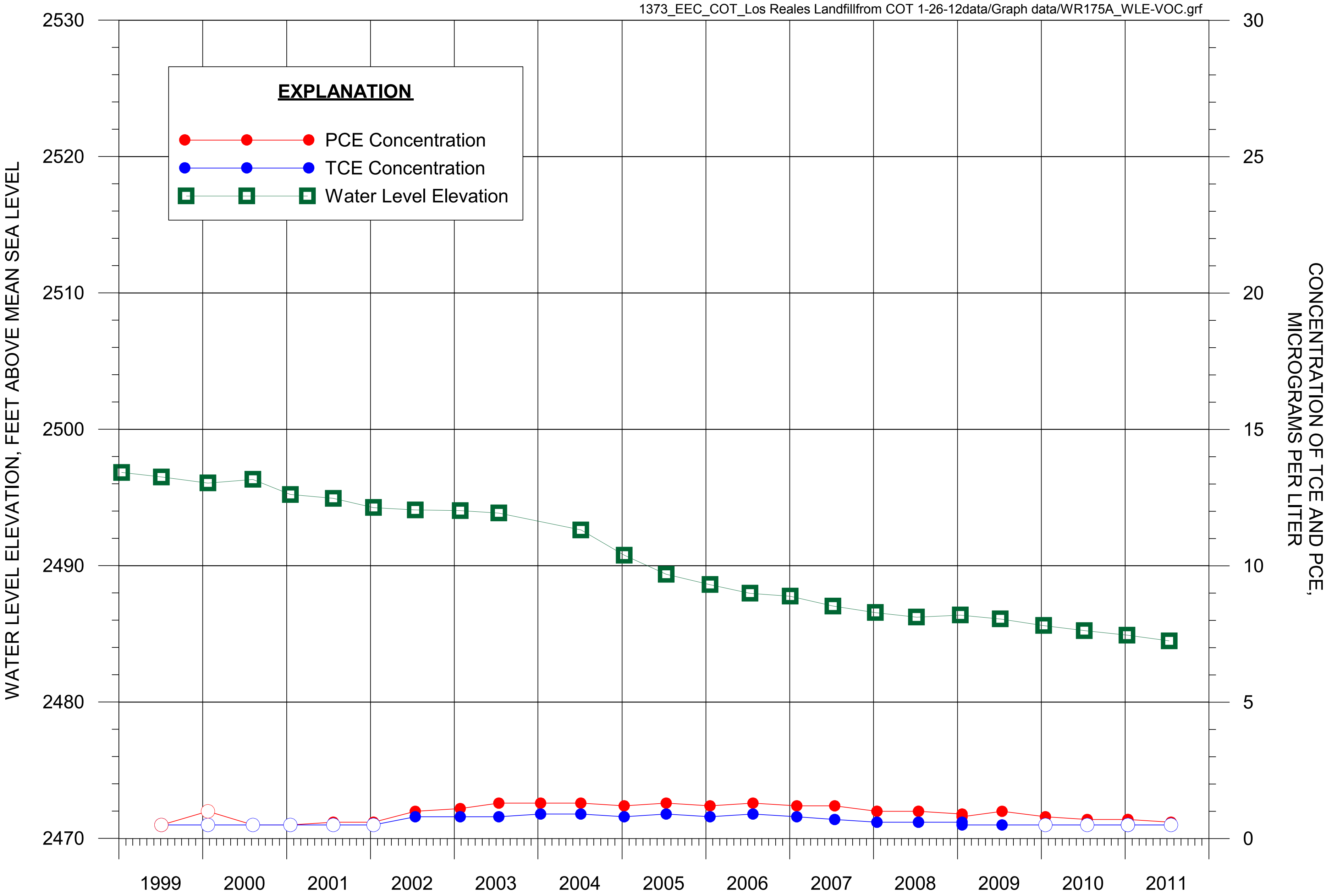


FIGURE C-32. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-136B LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

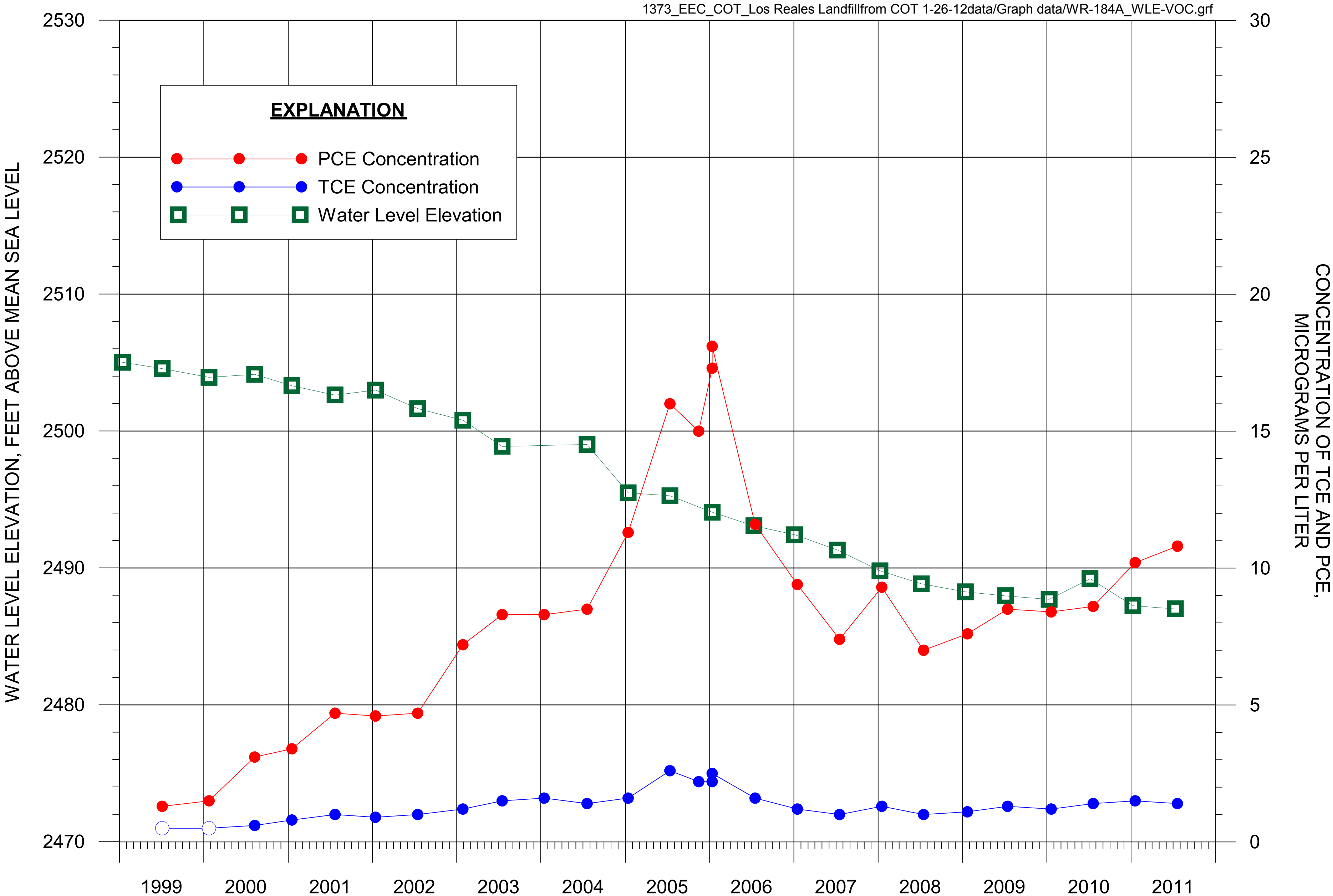
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-33. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-175A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

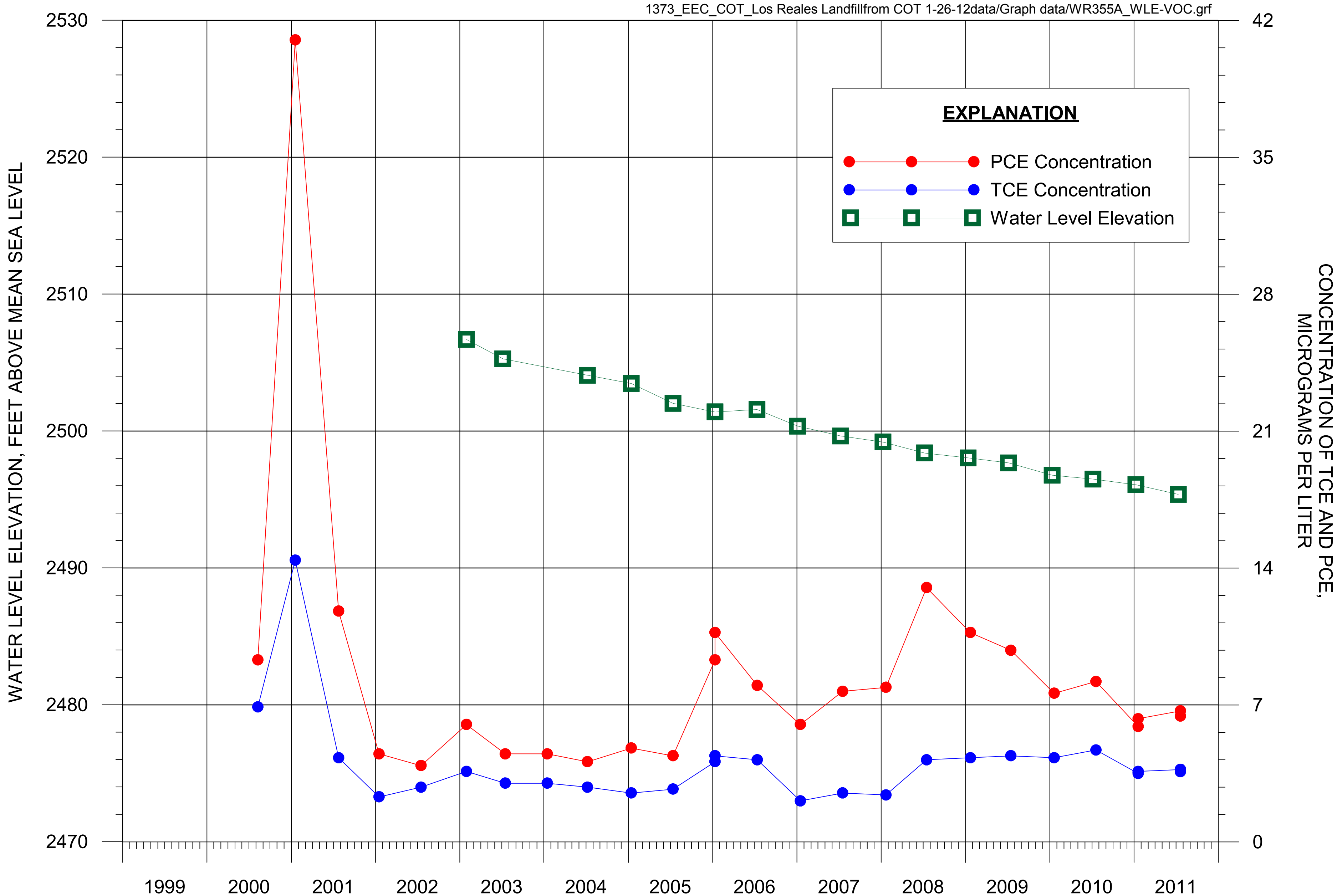
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-34. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-184A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

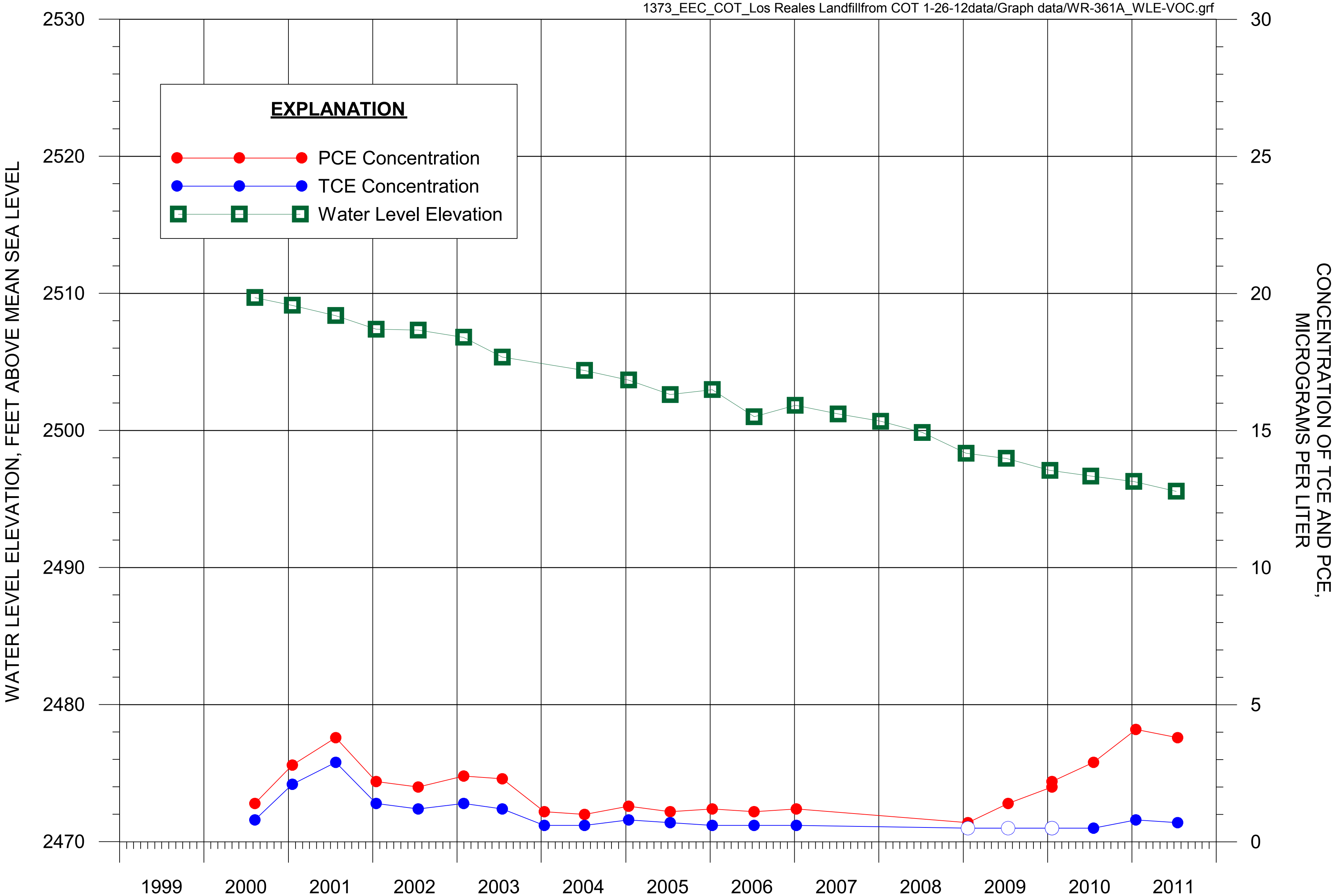
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-35. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-355A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-36. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-361A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

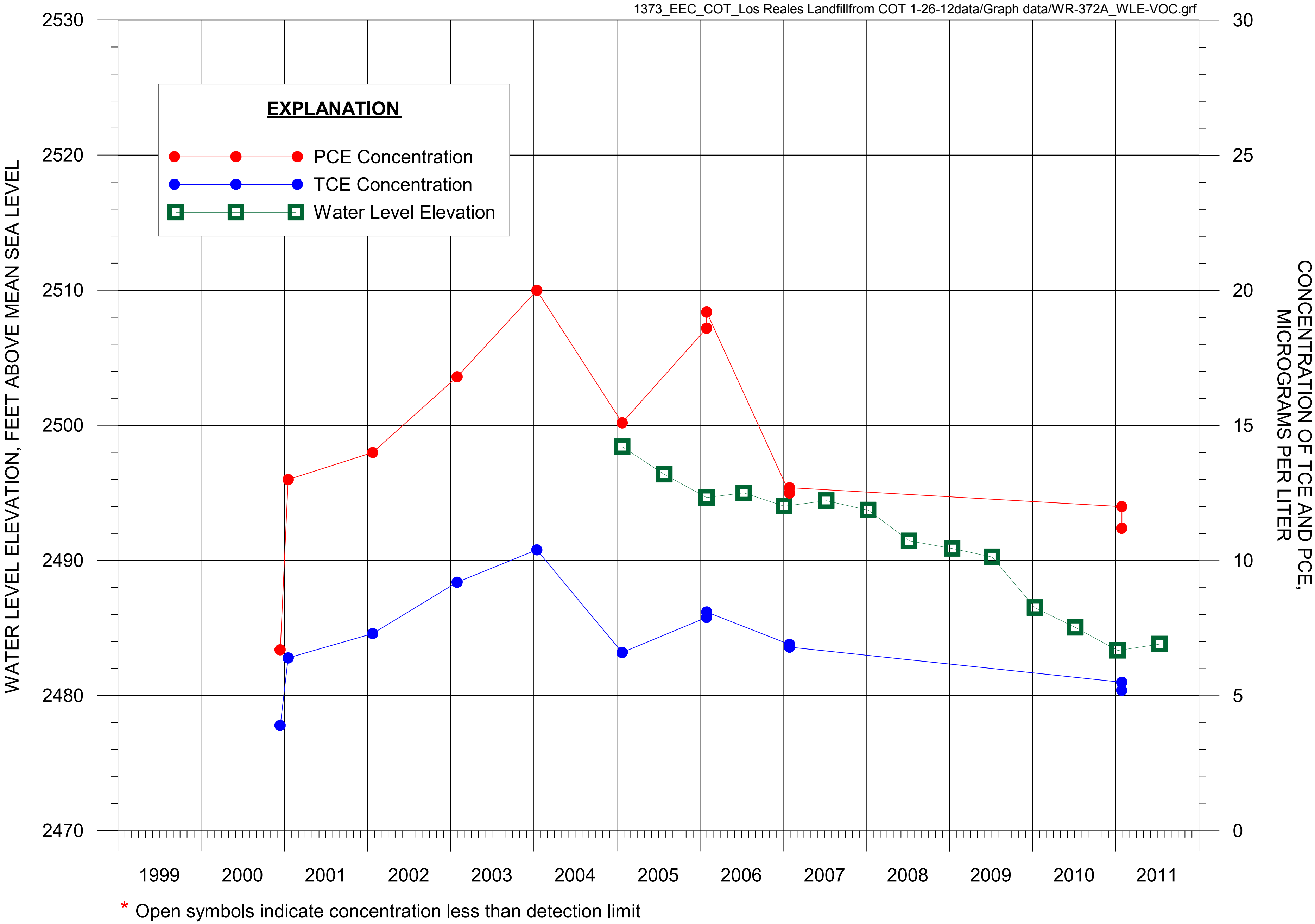
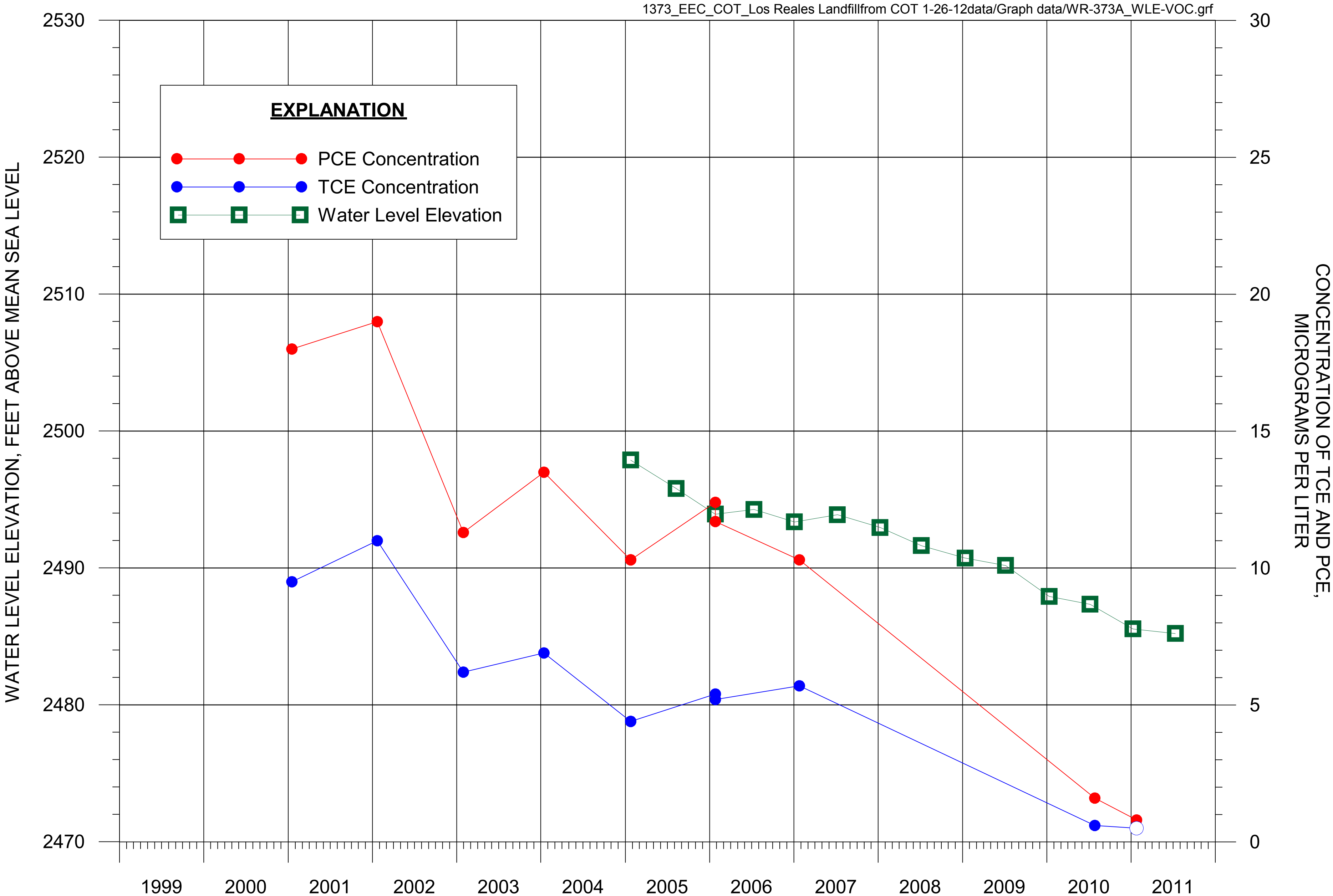


FIGURE C-37. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-372A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

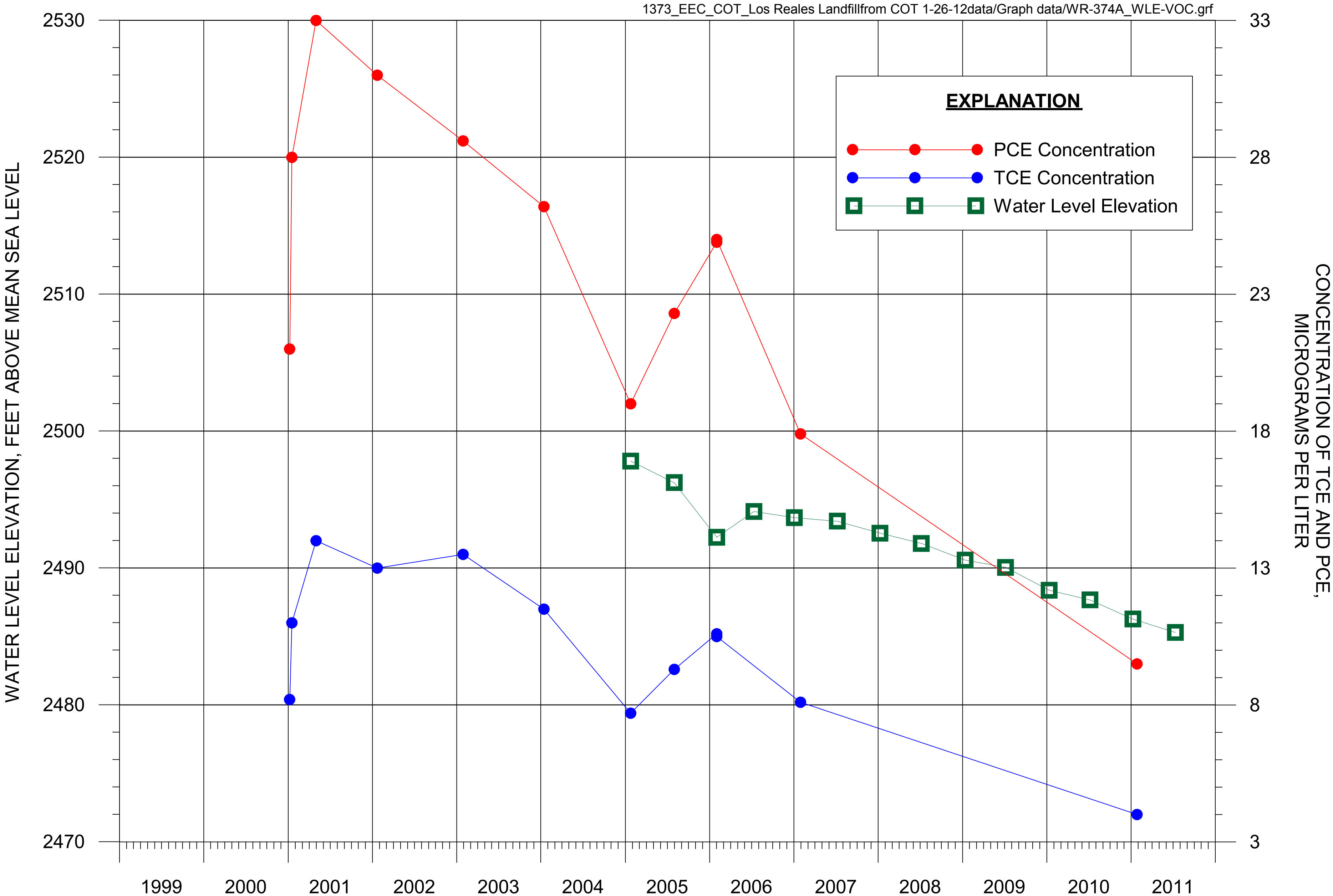
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-38. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-373A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

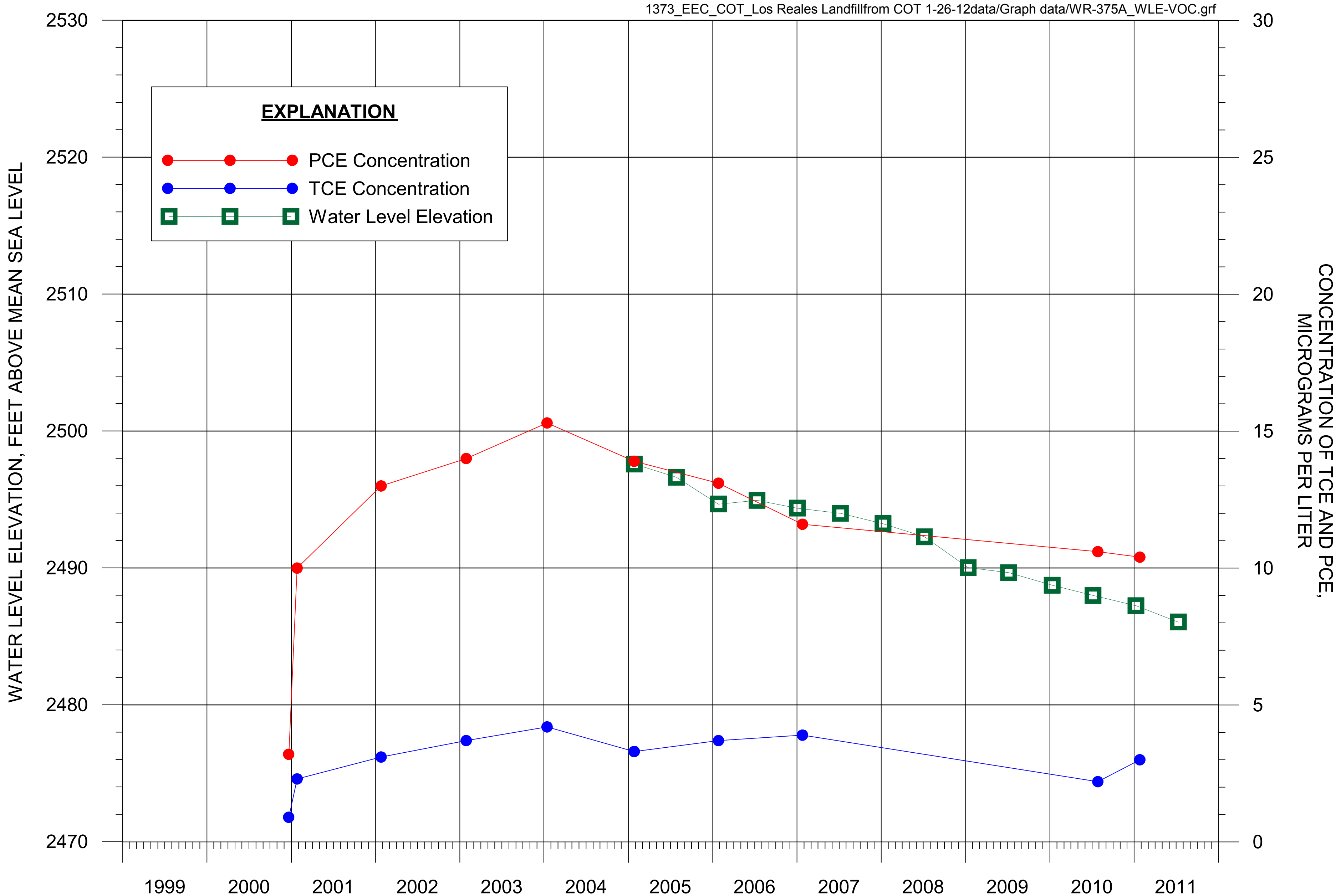
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-39. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-374A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

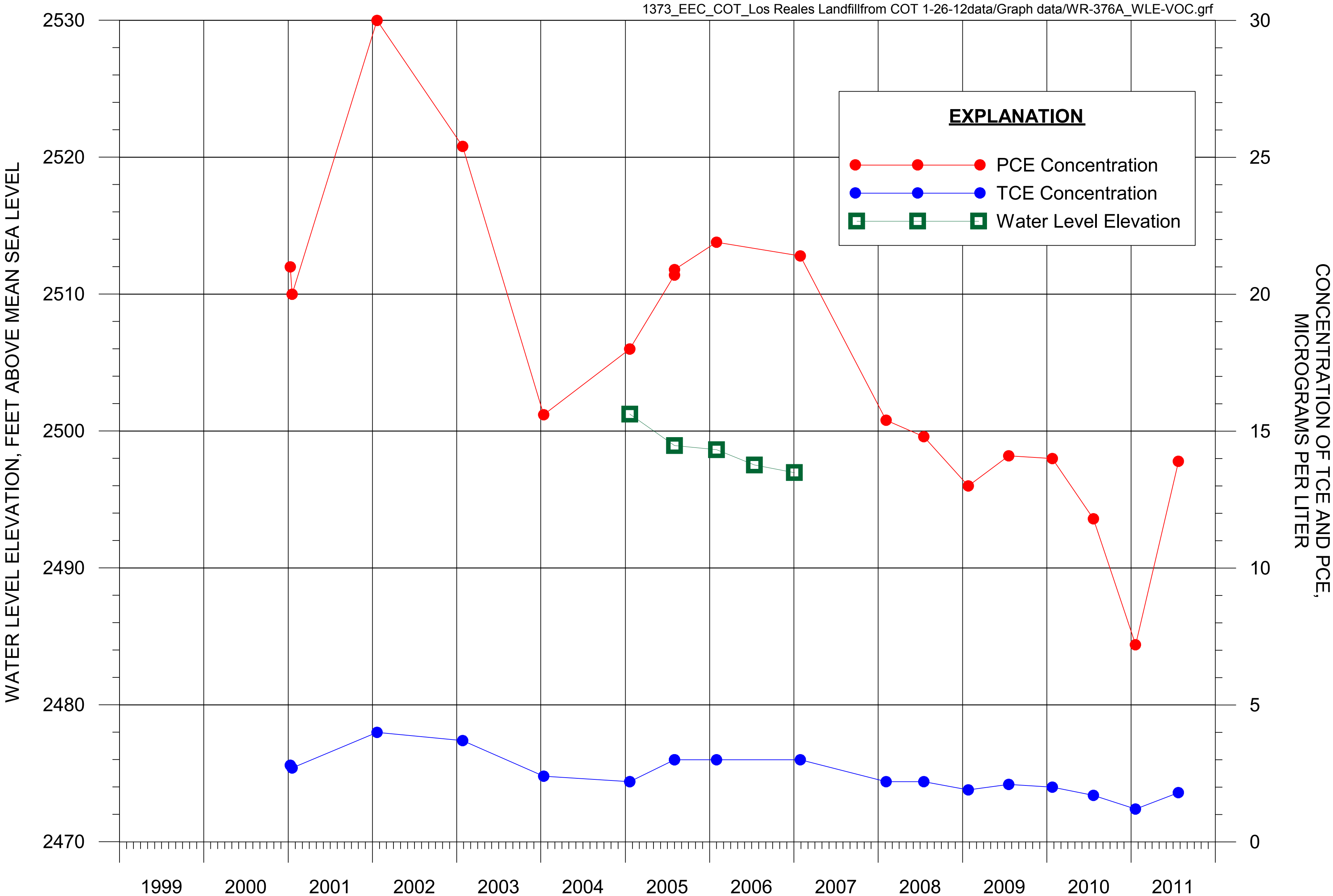
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-40. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-375A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

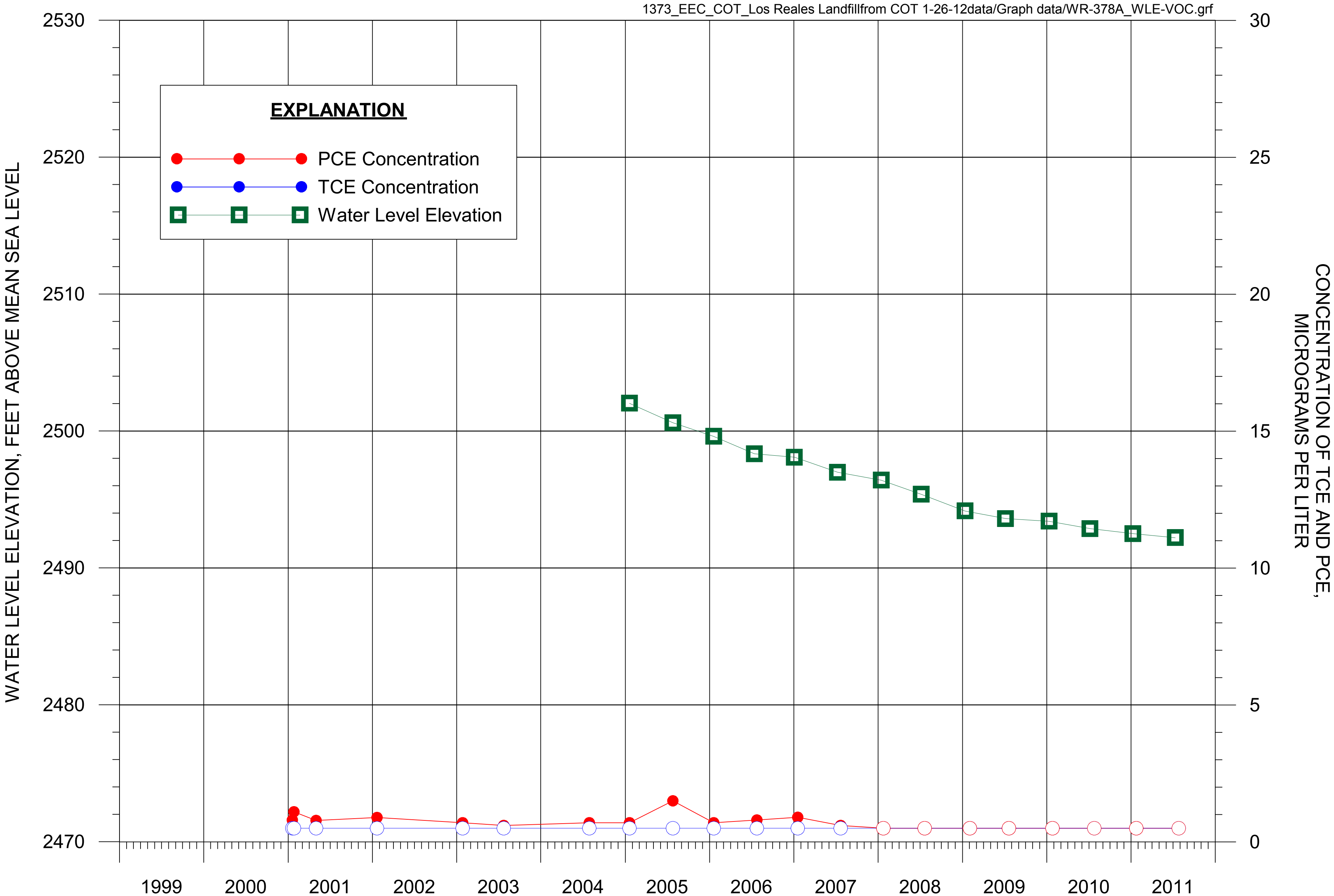
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-41. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-376A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

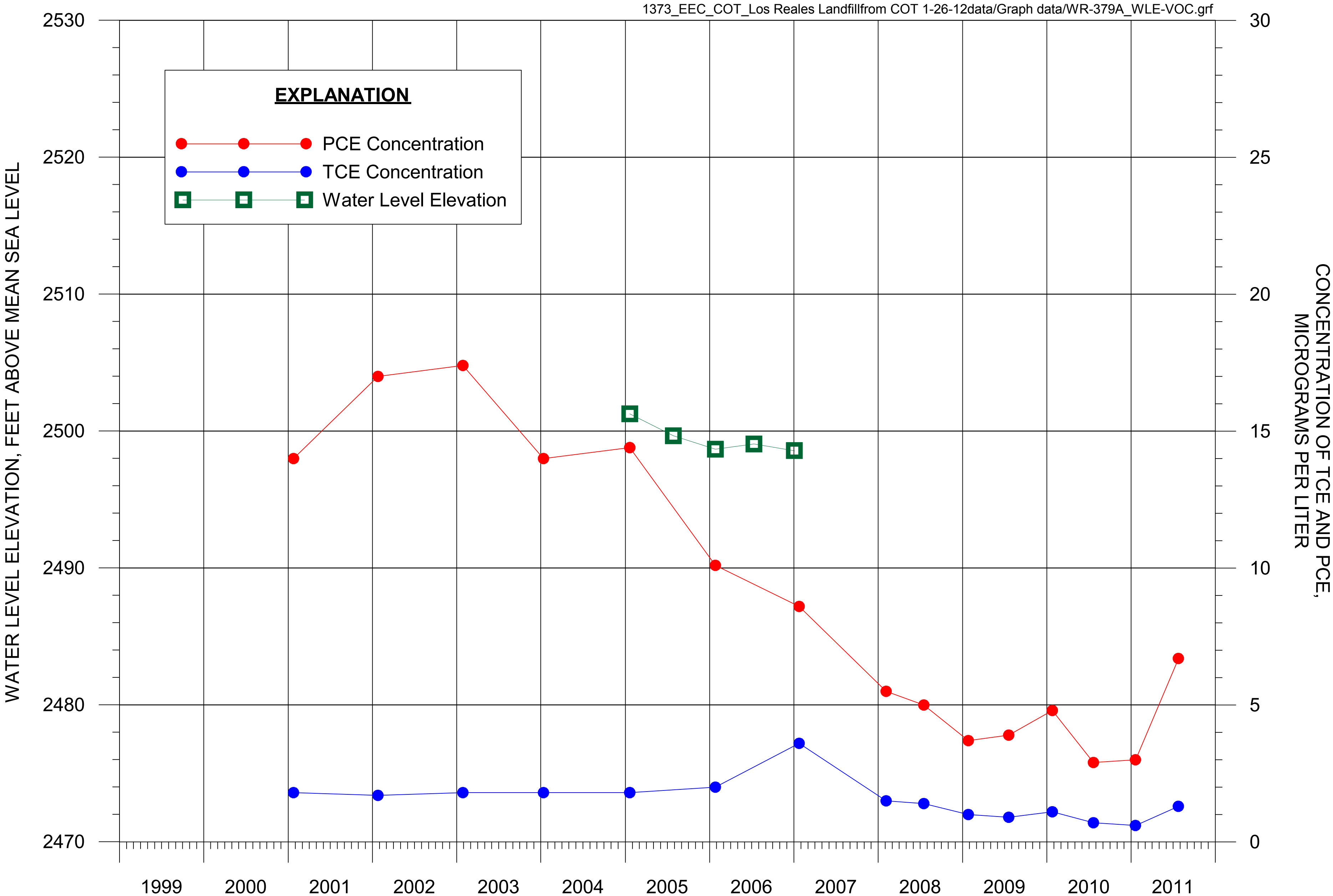
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-42. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-378A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

**FIGURE C-43. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-379A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA**

MONTGOMERY & ASSOCIATES

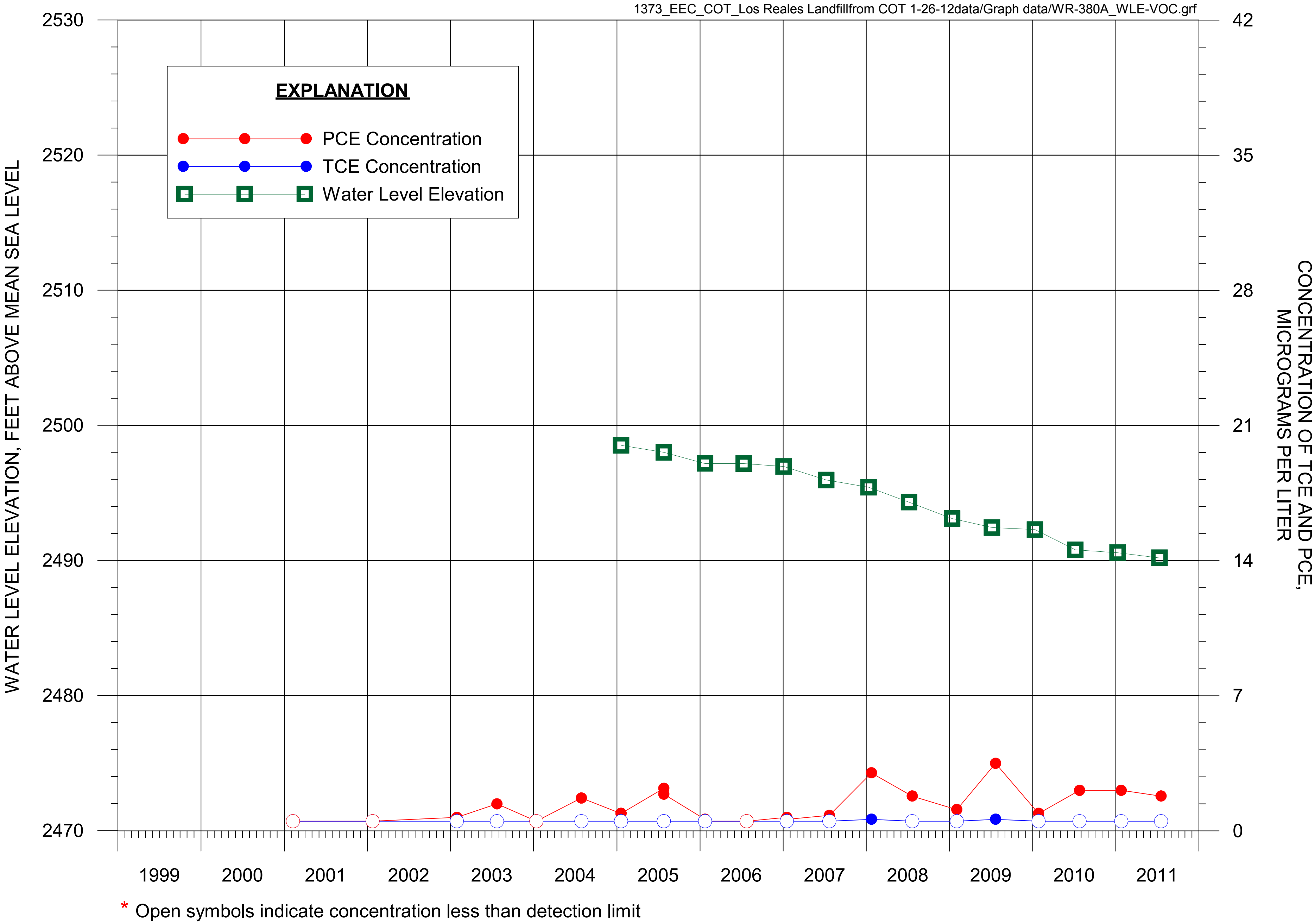
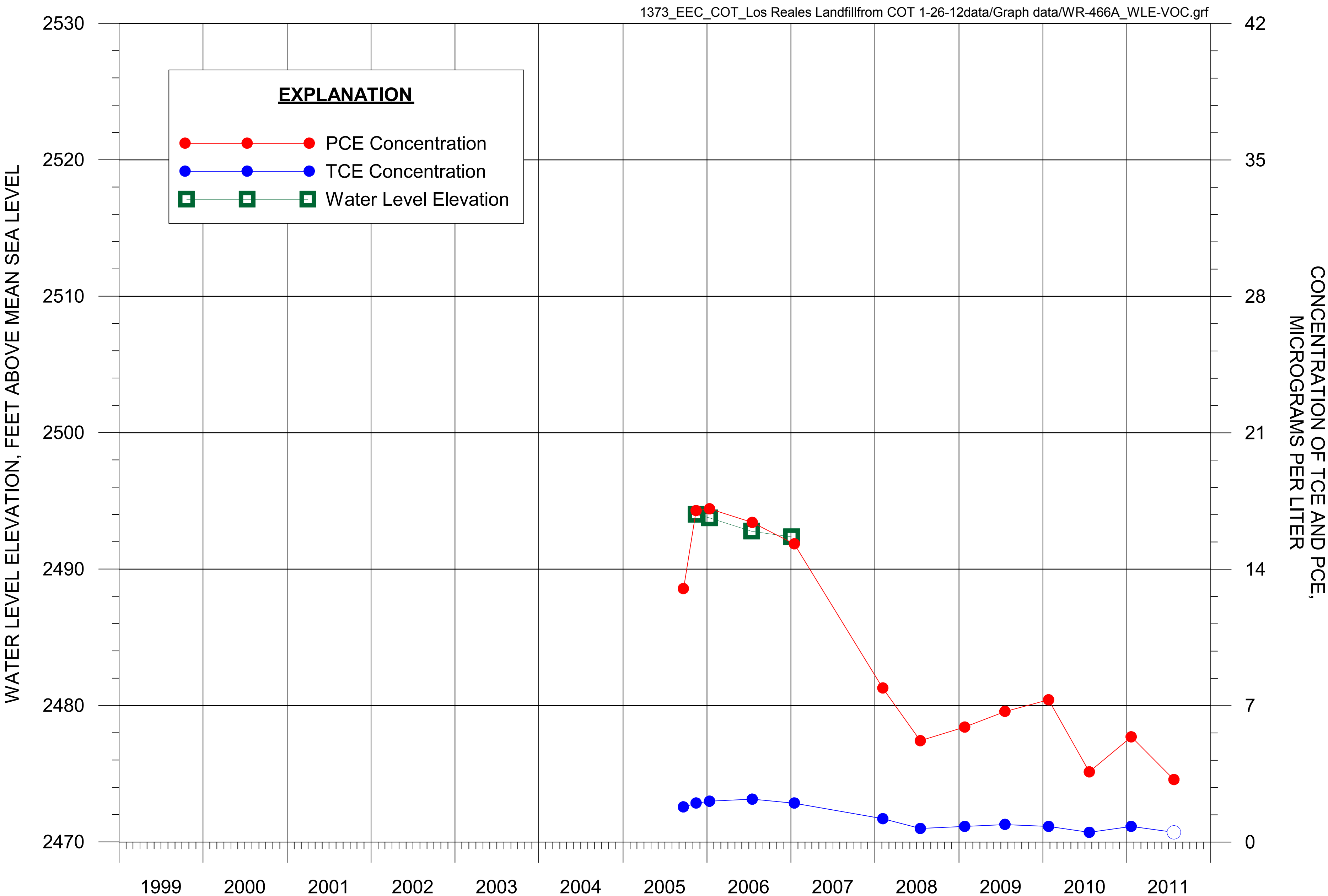


FIGURE C-44. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-380A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-45. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-466A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES

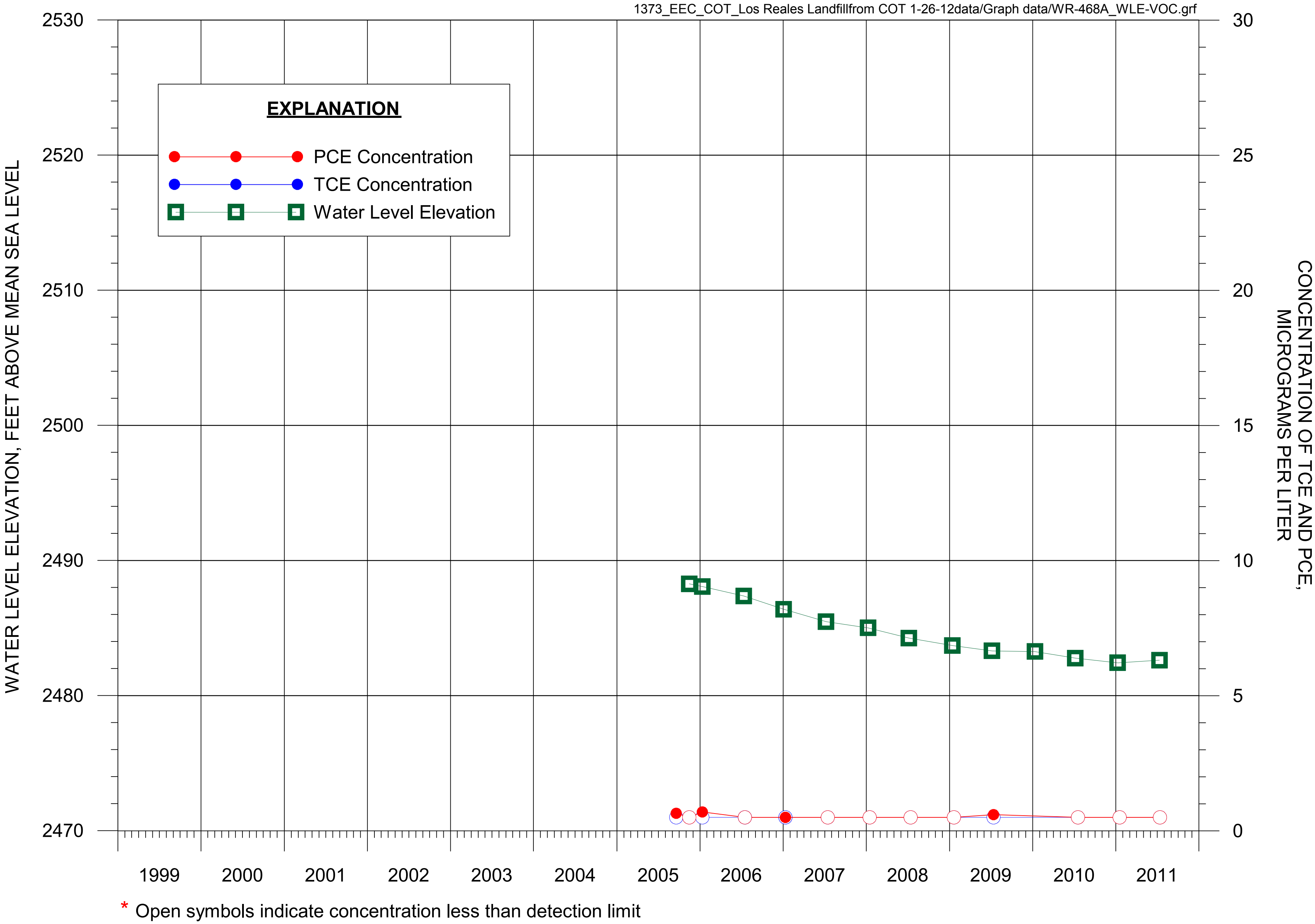
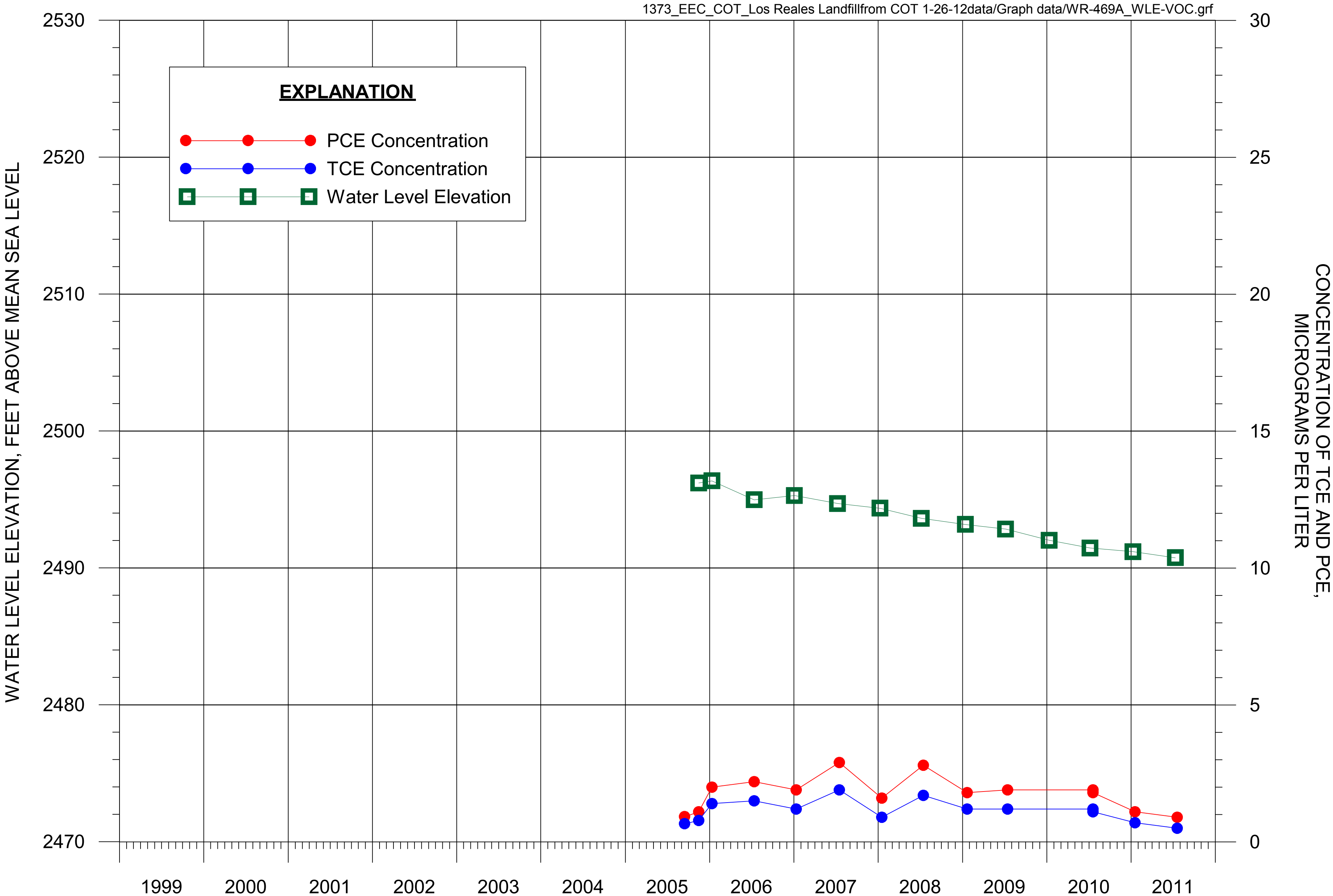


FIGURE C-46. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-468A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

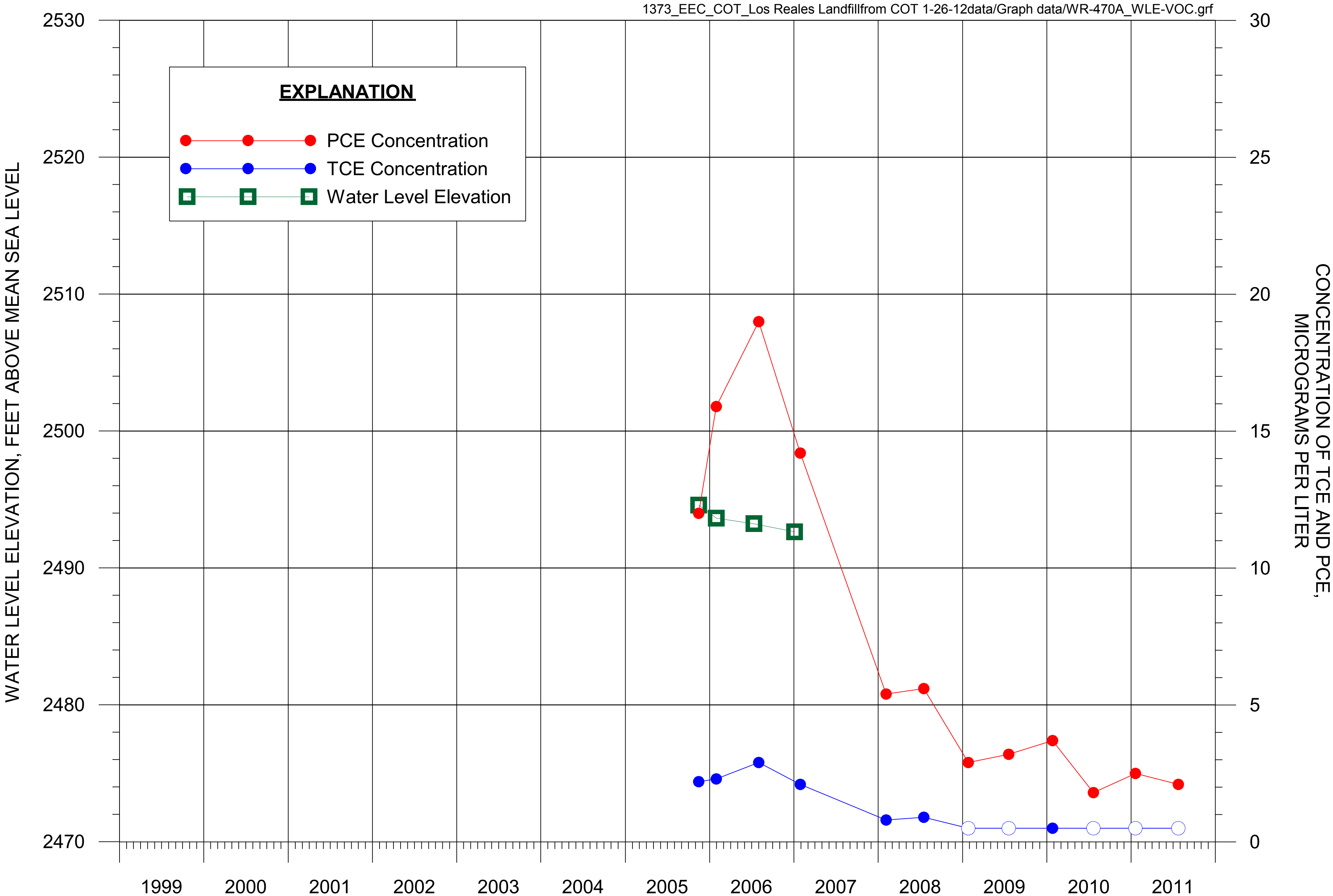
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-47. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-469A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

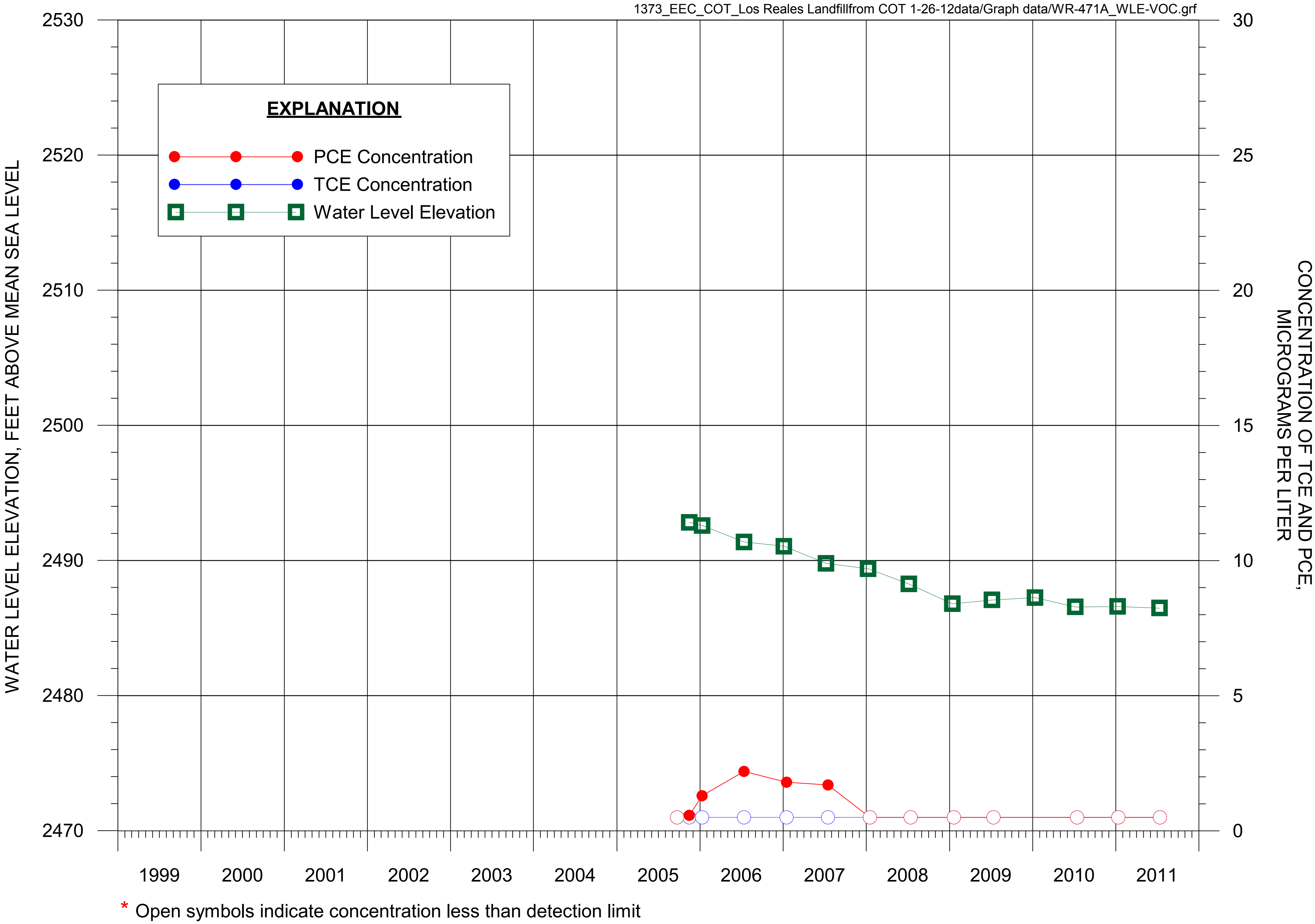
MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

**FIGURE C-48. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-470A
LOS REALES LANDFILL, PIMA COUNTY, ARIZONA**

MONTGOMERY & ASSOCIATES



* Open symbols indicate concentration less than detection limit

FIGURE C-49. GRAPH OF WATER LEVEL ELEVATION, TCE AND PCE FOR WELL WR-471A LOS REALES LANDFILL, PIMA COUNTY, ARIZONA

MONTGOMERY & ASSOCIATES