Spring 2014

Performance assessment of capture zones generated by PV-powered pump and treat systems

Yovanna Cortes Di Lena

Department: Geosciences and Geological and Petroleum Engineering

PERFORMANCE ASSESSMENT OF CAPTURE ZONES GENERATED BY PV-POWERED PUMP AND TREAT SYSTEMS

by

YOVANNA CORTES DI LENA

A DISSERTATION

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

in

GEOLOGICAL ENGINEERING

2014

Approved by

A. Curt Elmore, Advisor
Neal Anderson
Mariesa L. Crow
Norbert H. Maerz
J. David Rogers

PUBLICATION DISSERTATION OPTION

This dissertation has been prepared in publication format. Section 1.0, pages 1 to 8, has been added to supply background information for the remainder of the dissertation. Paper 1, pages 9 to 29, is titled "Effectiveness of Capture Zones Generated by Intermittent Pumping of a PV-Powered Pump-and-Treat System Without Energy Storage", and was prepared in the style used by the *Remediation Journal* as published in volume 23, number 3 in 2013. Paper 2, pages 30 to 58, is titled "Performance Evaluation of PV-Powered Pump and Treat Systems Using Typical Meteorological Year Three Data", and was prepared in the style used by the *Journal of Hazardous, Toxic, and Radioactive Waste* as accepted on October 14, 2013. Paper 3, pages 59 to 81, is titled "General Method for Predicting Capture Zone Widths for PV-Powered Pump and Treat Systems Using PVWATTS and Basic Hydrogeologic Data", and was prepared in the style used by the *Journal of Environmental Engineering* as submitted on January 14, 2014.

ABSTRACT

Pump and treat (P&T) is a technology that has been extensively used to remove and/or contain contaminated groundwater. Hydraulic containment of contaminants is accomplished by generating capture zones through pumping of groundwater. An appropriate delineation of capture zones is necessary to design an effective P&T system. P&T systems conventionally operate continuously to achieve steady-state capture zones, which require significant amounts of energy. The use of renewable energies to meet power demands of remedial systems may reduce a project's carbon dioxide emissions. The hydraulic effectiveness of a photovoltaic (PV) powered P&T system without energy storage was characterized using data collected at two different remediation sites, a Dry-cleaning Environmental Response Trust Fund site in Rolla, Missouri and the Former Nebraska Ordnance Plant near Mead, Nebraska. A method to estimate hydraulic containment effectiveness of PV-powered P&T systems without energy storage was developed. The performance of a hypothetical PV-powered P&T system that operates both intermittently by assuming that the system does not include an energy storage component and continuously by assuming that system includes a relatively small capacity energy storage component was analyzed using widely available Typical Meteorological Year 3 data. A methodology to estimate capture zone widths for PV-powered P&T systems without energy storage throughout the continental U.S. as a function of solar insolation data, transmissivity, and hydraulic gradient was developed. Maps depicting predicted capture zone widths for specified transmissivity values and a hydraulic gradient were developed. The applicability of the developed methodology was illustrated with two actual sites where groundwater remediation has taken place.

ACKNOWLEDGMENTS

I would like to express my sincere and deep appreciation to my major advisor Dr. A. Curt Elmore for his guidance, encouragement, and support during the completion of this degree. I would like to thank the members of my committee, Dr. Anderson, Dr. Crow, Dr. Maerz, and Dr. Rogers, as well as Dr. Jeffrey D. Cawlfield, for their guidance, time, and years of hard work at the Missouri University of Science and Technology.

Special thanks to my fellow graduate students Erica Collins, John Conroy, Joe Guggenberger, Lara Hubble, Carlo Salvinelli, and Kayla Speidel for their assistance and friendship over my time at Missouri University of Science and Technology. Also, special thanks to Monica Guggenberger and Elamin Ismail for their help with ArcMap.

Finally, and most importantly, I would like to thank my parents and sister for their continued support, encouragement, inspiration, and love during this process. Without them, none of this would be possible.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOMENCLATURE

Symbol	Description	Page
AFB	Air Force Base	4
α	solar altitude angle	38
a_s	solar azimuth angle	38
a_w	surface azimuth angle	38
β	tilt angle	38
˚C	degrees Celsius	39
CER	capture equivalence ratio	25
cm/s	centimeters per second	22
CO_2	carbon dioxide	2
CPR	capture-zone pumping ratio	27
DC	direct current	5
δ	solar declination angle	37
DERT	Dry-Cleaning Environmental Response Trust Fund	6
EPA	Environmental Protection Agency	1
ESRL	Earth System Research Laboratory	17
ET	equation of time	37
ηc	module electrical efficiency	39
FNOP	Former Nebraska Ordnance Plant, Nebraska	3
GCW	groundwater circulation well	16
GHI	global horizontal irradiance	39
GHGs	green house gases	2

1. PREVIOUS AND PRELIMINARY WORK

1.1. PURPOSE

The purpose of this document is to fulfill the requirements for the Ph.D. degree in Geological Engineering and to present for faculty review the areas of research and subsequent peer reviewed papers.

1.2. INTRODUCTION

One of the most commonly used technologies to remediate and/or contain contaminated groundwater is pump and treat remediation (P&T). P&T systems can be designed to prevent the spread of contaminants by hydraulic containment or to restore the quality of the aquifer by removing or reducing the contaminant concentration in groundwater. The United States (U.S.) Environmental Protection Agency (EPA) (1996) indicates that P&T groundwater remediation efforts include elements of both hydraulic containment and restoration through mass removal. Hydraulic containment of contaminants is achieved by generating a capture zone through aquifer pumping. Therefore, an appropriate delineation of capture zones is necessary to design an effective P&T system. Capture zone evaluations are performed in the designing phase of P&T systems as a tool to determine both the location of the extraction wells and pumping rates necessary to achieve hydraulic containment of the contaminant plume.

P&T systems conventionally operate continuously until the contaminant concentrations in groundwater are reduced to acceptable levels, thus achieving steady state capture zones. As with many other remediation technologies, P&T systems require large amounts of energy to operate continuously. The U.S. EPA (2008a) indicates that in

2007 approximately 70 percent of the U.S. electricity supply was generated by fossil fuel power plants and that for each kilowatt-hour (kWh) of electricity generated, 1.37 pounds of carbon dioxide (CO_2) were emitted into the air. Furthermore, it states that the estimated energy annual average consumed by P&T systems is 490 x 10^6 kWh, resulting in an estimated CO_2 emission annual average of 323 x 10^3 metric tons.

Green and sustainable remediation (GSR) is emerging as a viable method to minimize the adverse effects of remediation on the environment and to maximize the environmental benefit of cleanup activities. One way in which GSR practices attempt to reduce the footprint of remediation activities is by reducing the energy consumption and emission of green house gasses (GHGs). The U.S. EPA (2008a) suggests that the use of renewable energies, such as wind and solar energy, to meet power demands of remedial systems and/or auxiliary equipment may reduce a project's carbon footprint. Additionally, it states that using renewable energies to power P&T systems provides significant opportunities at sites that are located in remote areas where extension of utility lines might be cost prohibited or infeasible due to difficult access.

Continuous operation of P&T systems powered by renewable energy may be cost-prohibitive given the need to offset the inherent intermittency of renewable energy sources. Therefore, one of the challenges associated with photovoltaic (PV) powered P&T systems is the assessment of their performance given the intermittent nature of the power availability. This is especially true for systems that attempt to lower costs by eliminating or significantly reducing energy storage.

This dissertation focuses on the assessment of capture zones, in terms of width, generated by PV-powered P&T system without energy storage or with a relatively small capacity energy storage component as a function of solar radiation and hydrogeologic data.

1.3. REVIEW OF RELEVANT LITERATURE

1.3.1. P&T Systems. P&T systems can be designed to prevent the spread of contaminants by hydraulic containment or to restore the quality of the aquifer by removing or reducing the contaminant concentration in groundwater. The U.S. EPA (1996) indicates that P&T groundwater remediation efforts include elements of both hydraulic containment and restoration through mass removal. Hydraulic containment of contaminants is achieved by generating a capture zone through aquifer pumping. The U.S. EPA (2008a) defines a capture zone as the three-dimensional region that contributes the groundwater extracted by one or more wells. Traditionally, P&T systems have been designed to operate continually to achieve steady-state capture zones. Capture zone analysis are included in the designing phase of P&T systems to determine the appropriate number of the extraction wells and pumping rates to achieve hydraulic containment of the contaminant plume. A disadvantage associated with P&T remediation is the long time periods required to achieve aquifer restoration due to tailing and rebound of contaminant concentration as identified in the U.S. EPA (1996).

1.3.2. Green Remediation. The U.S. EPA (2008a) discusses several projects in which renewable energies has been used to power P&T systems including the BP Paulsboro site in New Jersey, the former Nebraska Ordnance Plant (FNOP) site near Mead, Nebraska, and the former St. Croix Alumina Plant in the U.S. Virgin Islands. At BP Paulsboro, petroleum products and chlorinated compounds are being removed from groundwater using solar energy to power a P&T system composed of six recovery wells and a biologically activated carbon treatment system. At the FNOP, groundwater contaminated with trichloroethene (TCE) is being removed from the subsurface using circulation wells powered by a wind turbine for air stripping and ultraviolet (UV) treatment. A hybrid system powered by solar and wind energy is being used at the Former St. Croix Alumina Plant to recover hydrocarbons from groundwater.

Additional projects in which solar and/or wind energy is being used as power sources for P&T systems include the Altus Air Force Base (AFB) in Oklahoma, the Apache Powder Company in Arizona, and the Lawrence Livermore National Laboratory (LLNL) in California as discussed in Dellens (2007). At the Altus AFB, solar energy is used to extract and circulate groundwater through a bioreactor to remove TCE. Solar energy is being used at the Apache Powder Company to power a pump to recirculate water through constructed wetlands when the system is unable to discharge water back to the aquifer. At the LLNL, volatile organic compounds (VOCs) are being removed from groundwater by a P&T system powered by solar energy.

1.3.3. Intermittent Pumping of P&T Systems. Intermittent pumping of P&T systems (not powered by renewable energies) has been considered as a method of improving the system performance by increasing contaminant removal effectiveness and reducing costs. Keely (1989) indicates that the resting phase of the intermittent pumping can allow time for contaminant concentrations to increase in groundwater where mass transfer limitations exit. In Liu et al. (2000), an optimal intermittent pumping schedule was developed for a P&T system to minimize total costs and health risks and to maximize the quantity of contaminant removal from an aquifer with known hydraulic limitations and water miscible contaminant. In Mackay et al. (2000), field experiments were conducted at a site where contamination by VOCs was present to compare the efficiencies of intermittent pumping and continuous pumping. Aksoy and Culver (2004) analyzed the cost-effectiveness and performance of intermittent pumping schemes with respect to continuous pumping for a mass transfer-limited aquifer. Mackay et al. (2000) and Aksoy and Culver (2004) found that intermittent pumping powered by traditional sources may be competitive with constant pumping depending on the intermittent pumping scheme, contaminant's initial mass, and site characteristics.

Intermittent pumping schemes due to the inherent variability of renewable energy as a power source were studied by Chandrasekaran and Thyagarajah (2011), Collins et al. (2013), and Conroy et al. (2013). Chandrasekaran and Thyagarajah (2011) developed a model to evaluate the performance of a water pump using a permanent magnet direct current (DC) motor (PMDC) powered by a PV array. Collins et al. (2013) assessed the performance of a PV-powered P&T without energy storage using the volume of groundwater extracted from a contaminated aquifer and, monthly predictions and measured values of solar insolation. Conroy et al. (2013) compared transient capture zones generated by a hypothetical PV-powered P&T system that included a relatively high capacity energy storage component. The study showed that capture zones generated by PV-powered systems that include a high capacity energy storage component can be 90 percent as effective as those generated by utility powered systems.

1.4. RESEARCH OBJECTIVES AND OUTLINE

This dissertation was separated into three distinct papers which were submitted separately to peer-reviewed journals. The first paper, titled "Effectiveness of Capture Zones generated by Intermittent Pumping of a PV-Powered Pump-and-Treat System Without Energy Storage", was published in the Remediation Journal in volume 23, number 3 in 2013. The objectives of this paper were to:

- Characterize the hydraulic containment effectiveness of a PV-powered P&T system without energy storage using data collected at two different remediation sites, a Dry-cleaning Environmental Response Trust (DERT) Fund site in Rolla, Missouri and the FNOP near Mead, Nebraska. This included the following:
  - Development of intermittent pumping schedules.
  - Development of a continuous pumping schedule.
  - Modeling of the pumping schedules.
  - Comparison between the modeled capture zones.
- Develop a method to estimate hydraulic containment effectiveness of PV-powered P&T systems without energy storage.

The second paper, titled "Performance Evaluation of PV-Powered Pump and Treat Systems Using Typical Meteorological Year 3 Data", was published in the Journal of Hazardous, Toxic, and Radioactive Waste on January 8, 2014. The objectives of this paper were to:

- Analyze the performance of a hypothetical PV-powered P&T system that operates both intermittently by assuming that the system does not include an energy storage component and continuously by assuming that system includes a relatively small capacity energy storage component using two metrics, volume of groundwater removed and capture zone width. This included the following:

- Development of variable intermittent pumping schedules using Typical Meteorological Year (TMY) 3 data.
- Development of a continuous pumping schedule.
- Estimation of volume of groundwater extracted.
- Modeling of the pumping schedules.
- Comparison between the modeled capture zones and volume of extracted groundwater.

The third paper, titled "General Method for Predicting Capture Zone Widths for PV-Powered Pump and Treat Systems Using PVWATTS and Basic Hydrogeologic Data", was submitted to the Journal of Environmental Engineering on January 14, 2014. The objectives of this paper were to:

- Develop a methodology to estimate capture zone widths for PV-powered P&T systems without energy storage throughout the continental U.S. as a function of solar insolation data, transmissivity, and hydraulic gradient. This included the following:
    - Selection of TMY2 stations using the National Renewable Energy Laboratory (NREL) (2013) Annual Average Daily Solar Radiation per Month map.

  - Development of variable intermittent pumping schedules for each of the selected stations using PVWATTS.
  - Modeling of the pumping schedules.
  - Performance of spline analysis to interpolate capture zone widths between each of the selected stations.
  - Development of maps depicting predicted capture zone widths for specified transmissivity values.
- Illustrate the applicability of the methodology with two actual sites where groundwater remediation has taken place.

1.5. ORIGINAL CONTRIBUTION

The research presented in this dissertation analyzes the performance of P&T systems that operate intermittently due to the inherent variability of solar energy as the power source using two metrics: capture zone width and volume of groundwater extracted. Some of the original aspects of this research include:

- Consideration PV-powered P&T system that operates intermittently with variable flow rates when solar radiation is available by assuming that the system does not include energy storage (no batteries).
- Consideration PV-powered P&T system that operates continuously with variable flow rates by assuming that the system includes a relatively small capacity energy storage component (limited batteries) that could provide sufficient power for a specific minimum flow rate when solar insolation is not available.

- Characterization of the hydraulic containment effectiveness of a PV-powered P&T system without energy storage for a site using real data collected at two different remediation sites.
- Development of a new variable to define hydraulic containment effectiveness of PV-powered P&T systems without energy storage.
- Development of a methodology to estimate the effectiveness of the hydraulic containment of PV-powered P&T systems without energy storage as a function of total volume of groundwater expected to be extracted.
- Development of equations to estimate pump discharges of PV-powered P&T systems without and with a relatively small capacity energy storage component as a function of solar radiation and PV cell temperature.
- Use of hourly values of solar insolation and ambient temperature that are widely available to develop pumping schedules for PV-powered P&T systems without and with a relatively small capacity energy storage component.
- Evaluation of the effect of seasonality on the performance of the PV-powered P&T systems without and with a relatively small capacity energy storage system.
- Comparison of the approximate costs when the rated flow rate of a PV-powered P&T system without energy storage is increased and when a relatively small capacity energy storage component is included.
- Analysis of the variability of the capture zones generated by PV-powered P&T systems without and with a relatively small capacity energy storage system.

- Assessment of the relationship between the PV-powered P&T system without and with a relatively small capacity energy storage component time of operation and, generated capture zone width and estimated volume of extracted groundwater.
- Use of daily average values of solar insolation that are widely available to develop pumping schedules for PV-powered P&T systems without energy storage.
- Development of maps for the continental U.S. depicting predicted capture zone widths for a PV-powered P&T system without energy storage as a function of solar insolation for specified transmissivity values and a hydraulic gradient.
- Development of a feasibility-level methodology to estimate the width of capture zones generated by PV-powered P&T systems without energy storage using maps depicting the predicted capture zone widths for the continental U.S., transmissivity, and hydraulic gradient.

PAPER

I. EFFECTIVENESS OF CAPTURE ZONES GENERATED BY INTERMITTENT PUMPING OF A PV-POWERED PUMP-AND-TREAT SYSTEM WITHOUT ENERGY STORAGE

Yovanna Cortes Di Lena, E.I; Andrew Curtis Elmore, Ph.D., P.E.; John Conroy, E.I.

ABSTRACT

A common technology to remediate and/or contain contaminated groundwater is pump and treat remediation (P&T). Traditionally, P&T systems have been designed to operate continuously to achieve steady state capture zones, for which large amounts of energy are required. Green and sustainable remediation (GSR) is emerging as a viable method to minimize the adverse effects of remediation on the environment. One of the challenges associated with photovoltaic (PV) powered P&T systems is the assessment of their performance given the intermittent nature of the power availability. This paper characterizes the hydraulic containment effectiveness of a PV powered P&T system without energy storage using data collected at two different remediation sites, a Dry-cleaning Environmental Response Trust Fund site in Rolla, Missouri and the Former Nebraska Ordnance Plant near Mead, Nebraska. Additionally, a method to estimate the effectiveness of the hydraulic containment as a function of the total volume of groundwater expected to be extracted is being proposed. Two transient and a continuously pumped capture zones were modeled using Visual MODFLOW® 2012.1 along with MODPATH and compared. The study shows that smaller capture zones will be generated from intermittent pumping when compared to continuous pumping.

INTRODUCTION

There are different technologies to remediate and/or contain contaminated groundwater. One of the most commonly used is pump and treat remediation (P&T). P&T involves extracting contaminated groundwater and treating it prior to disposal. Typically, continuous operation of P&T systems is performed until the contaminant concentrations in groundwater are reduced to acceptable levels. P&T systems, as with many other remediation technologies, require large amounts of energy to operate continuously. The United States (U.S.) Environmental Protection Agency (EPA) indicates that in 2007 approximately 70 percent of the U.S. electricity supply was generated by fossil fuel power plants and that for each kilowatt-hour (kWh) of electricity generated, 1.37 pounds of carbon dioxide (CO_2) were emitted into the air (EPA, 2008a). Furthermore, it states that the estimated energy annual average consumed by P&T systems is 490 x 10^6 kWh, resulting in an estimated CO_2 emission annual average of 323 x 10^3 metric tons.

Green and sustainable remediation (GSR) is emerging as a viable method to minimize the adverse effects of remediation on the environment and to maximize environmental benefit of cleanup activities. One aspect of GSR practices is the reduction of the carbon footprint of remediation activities by reducing the energy consumption and emission of green house gasses. The U.S. EPA suggests that the use of renewable energies, such as wind and solar energy, to meet power demands of remedial systems and/or auxiliary equipment may reduce a project's CO_2 emissions (EPA, 2008a).

The U.S. EPA discusses several projects that are currently implementing sustainable remediation practices (EPA, 2008a). Projects which use renewable energy systems to power P&T systems include the BP Paulsboro site in New Jersey, the Former Nebraska Ordnance Plant (NOP) site near Mead, Nebraska, and the Former St. Croix Alumina Plant in the U.S. Virgin Islands. At BP Paulsboro, petroleum products and chlorinated compounds are being removed from groundwater using solar energy to power a P&T system composed of six recovery wells and a biologically activated carbon treatment system. At the Former NOP, groundwater contaminated with trichloroethene (TCE) is being removed from the subsurface using circulation wells powered by a wind turbine for air stripping and ultraviolet (UV) treatment. A hybrid system powered by solar and wind energy is being used at the Former St. Croix Alumina Plant to recover hydrocarbons from groundwater. Additional projects in which solar and/or wind energy is being used as power sources for P&T systems are discussed in Dellens (2007). These projects include the Altus Air Force Base (AFB) in Oklahoma, the Apache Powder Company in Arizona, and the Lawrence Livermore National Laboratory (LLNL) in California. At the Altus AFB, solar energy is used to extract and circulate groundwater through a bioreactor to remove TCE. Solar energy is being used at the Apache Powder Company to power a pump to recirculate water through constructed wetlands when the system is unable to discharge water back to the aquifer. At the LLNL, volatile organic compounds (VOCs) are being removed from groundwater by a P&T system powered by solar energy.

The main objective of P&T systems is to prevent the spread of contaminants by hydraulic containment. Hydraulic containment of contaminants is achieved by generating a capture zone via the P&T system. The U.S. EPA (2008b) defines a capture zone as the three-dimensional region that contributes the groundwater extracted by one or more wells. Traditionally, P&T systems have been designed to operate continuously to achieve steady state capture zones. However, continuous operation of P&T systems powered by renewable energy may be cost-prohibitive given the need to offset the inherent intermittency of renewable energy sources.

Intermittent pumping of P&T systems (not powered by renewable energies) has been considered as a method of improving the system performance by increasing contaminant removal effectiveness and reducing costs. Keely (1989) indicates that the resting phase of the intermittent pumping can allow time for contaminant concentrations to increase in groundwater where mass transfer limitations exit. In Liu et al. (2000), an optimal intermittent pumping schedule was developed for a P&T system to minimize total costs and health risks and to maximize the quantity of contaminant removal from an aquifer with known hydraulic limitations and water miscible contaminant. In Mackay et al. (2000), field experiments were conducted at a site where contamination by VOCs was present to compare the efficiencies of intermittent pumping and continuous pumping. Aksoy and Culver (2004) analyzed the cost-effectiveness and performance of intermittent pumping schemes with respect to continuous pumping for a mass transfer-limited aquifer. Mackay et al. (2000) and Aksoy and Culver (2004) found that intermittent pumping powered by traditional energy sources may be competitive with constant pumping depending on the intermittent pumping scheme, contaminant's initial mass, and site characteristics.

Intermittent pumping schemes due to the inherent variability of renewable energy as a power source were studied by Chandrasekaran and Thyagarajah (2011). Chandrasekaran and Thyagarajah (2011) developed a model to evaluate the performance of a water pump using a permanent magnet direct current (DC) motor (PMDC) powered by a photovoltaic (PV) array.

One of the challenges associated with PV powered P&T systems is the assessment of their performance given the intermittent nature of the power availability, especially for systems that attempt to lower costs by eliminating, or significantly reducing, energy storage. This paper characterizes the hydraulic containment effectiveness of a PV powered P&T system without energy storage using data collected at two different remediation sites. Additionally, a method to estimate the effectiveness of the hydraulic containment as a function of the total volume of groundwater expected to be extracted (pumped) is proposed.

MODELED SITE

Collins et al. (2013) describes the use of a PV-powered P&T system to remediate contaminated groundwater at a Missouri Dry-cleaning Environmental Response Trust Fund (DERT) site in Rolla, Missouri located at longitude 37˚57'20.19"N and latitude 91˚46'8.47"W. Two limitations of the study included the poorly characterized hydrogeologic properties of the site and the lack of data describing the aquifer response to pumping. The study generated data on weekly average volumes of extracted water that can be used to describe the intermittent nature of the PV powered P&T system. Hydrogeologic conditions and aquifer response to remedial pumping have been relatively well characterized at the former NOP site located near Mead, Nebraska (Elmore and Graff, 2002; Elmore and DeAngelis, 2004; Miller and Elmore, 2005). Efforts at the former NOP have included GSR practices of using a wind turbine and beneficial reuse of treated groundwater as indicated in Elmore and Graff (2002), Elmore and DeAngelis (2004), and the U. S. EPA (2008b). PV powered pumping has not been used at this site at present.

The study presented in this paper is based on a hypothetical site. This site has been synthesized using time schedule data from the Rolla, Missouri site and hydrogeologic/aquifer response data from the former NOP. Another way to describe the hypothetical site is that the solar irradiation characteristics at the former NOP site were the same as those observed at the Rolla, Missouri site.

PUMP AND TREAT SYSTEM DESCRIPTION

Collins et al. (2013) indicates that the P&T system in the Missouri site included a single-axis, south-facing passive tracking PV array horizontally inclined at 35 degrees sized to directly power a DC pump without the use of energy storage devices. The no-storage system had several advantages over an energy-storage system, including lower costs, simpler design, and a smaller carbon footprint. However, without energy storage capabilities, the system only operated during daylight hours.

The groundwater circulation well (GCW) system at the former NOP site, which was operated at 3.16 liters per second (L/s), included a casing diameter of 0.30 meters (m) with the 3.05 m extraction interval located at approximately 18.3 m below ground surface (bgs) as indicated in Elmore and Graff (2002), Elmore and DeAngelis (2004), and Miller and Elmore (2005).

PUMPING SCHEDULES

To predict the capture zone at the hypothetical site, an intermittent pumping schedule was developed. Daily average flow rates were estimated using the weekly average volumes of groundwater extracted and the available daylight hours at the Rolla, Missouri site. The weekly average volumes of groundwater extracted, which were tabulated for 245 days from February to October, 2011 (subject time period), ranged from 111 to 8,833 L and are presented in Exhibit 1. As a result, the developed intermittent pumping schedule consists of variable flow rates. Collins et al. (2013) indicates that the variability in the average volumes may have been the result of competing remedial activities at the site and a well design based on inadequate well yield data. Daylight hours were calculated using the apparent sunrise and sunset for each day obtained from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), Earth System Research Laboratory (ESRL) website (www.esrl.noaa.gov/gmd/grad/solcalc/). The calculated daylight hours ranged from 10.7 to 15.0. The estimated daily average flow rates were normalized by the maximum estimated daily average flow rate (2.40×10^{-2} L/s) and subsequently scaled up using the pumping rate at which the GCW system was operated at the former NOP site (3.16 L/s) given by Elmore and DeAngelis (2004). Exhibit 2 shows the daily average flow rates used in the variable flow rate simulation. Exhibit 3 summarizes the statistical characteristics of the variable flow rates and pumping periods. Exhibit 4 is a subset of the flow rate data presented in Exhibit 2 that includes the number of daylight hours (pumping time) each day for the month of May 2011.

Exhibit 1. Weekly average volumes of groundwater extracted at the Rolla, Missouri site (Collins et al., 2013)

Week	**Average Volume (L)**	**Week**	**Average Volume (L)**	**Week**	**Average Volume (L)**	**Week**	**Average Volume (L)**	**Week**	**Average Volume (L)**
1	1500	8	5000	15	8833	22	111	29	4111
2	1500	9	6111	16	8667	23	2444	30	4111
3	2444	10	6111	17	8167	24	3222	31	4444
4	3111	11	6778	18	8444	25	4111	32	4333
5	6111	12	7222	19	4333	26	4000	33	3779
6	5167	13	4889	20	3656	27	4444	34	4000
7	3222	14	7111	21	3444	28	4222	35	1889

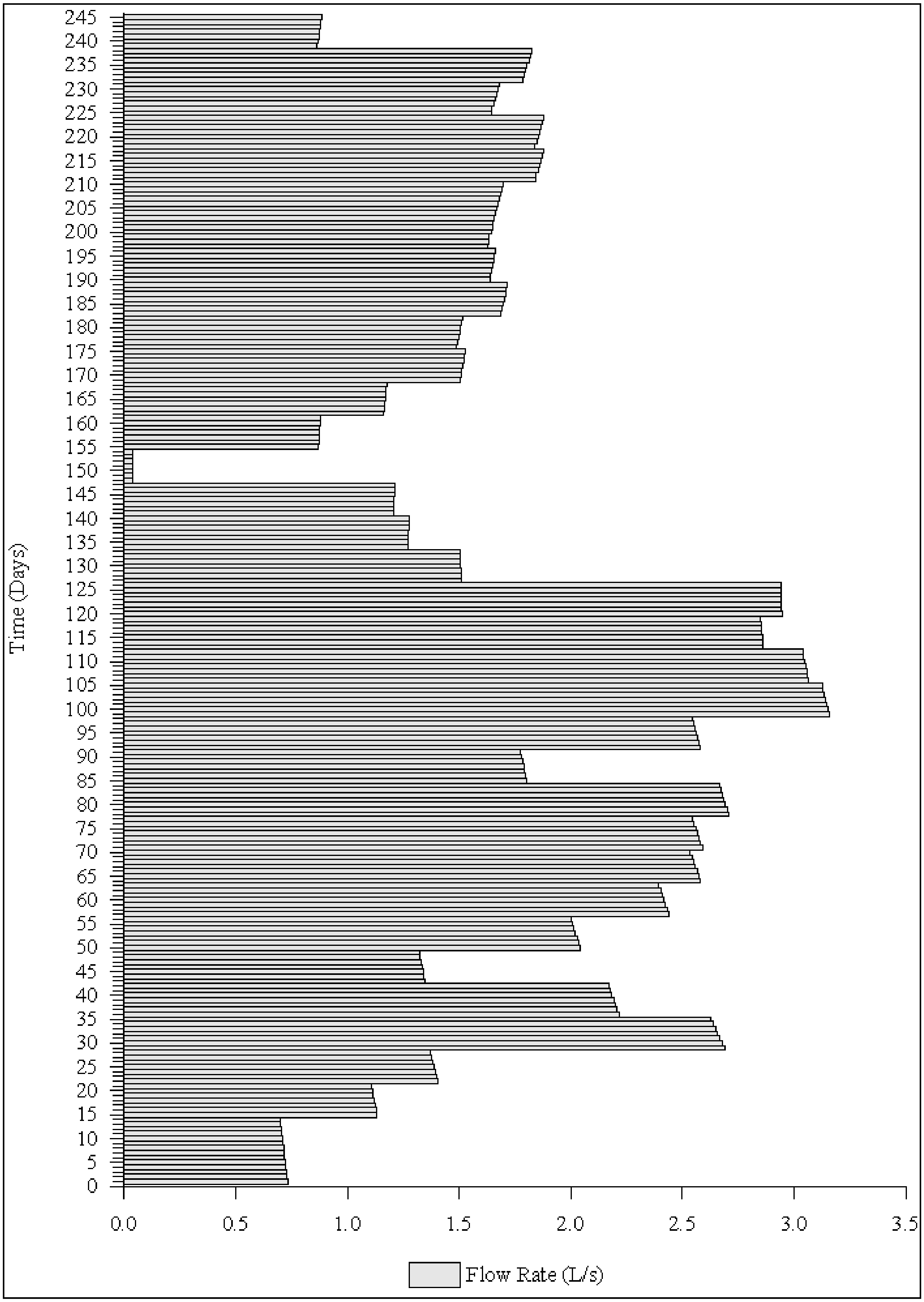

Exhibit 2. Daily variable flow rates for the subject time period

Exhibit 3. Statistical characteristics of the variable flow rates and pumping periods

	Maximum	Minimum	Median	Mean	Standard Deviation
Flow Rate (L/s):	3.16	0.039	1.68	1.79	0.739
Pump On (hr):	15.0	10.7	13.5	13.3	1.31
Pump Off (hr):	13.3	8.97	10.5	10.7	1.31

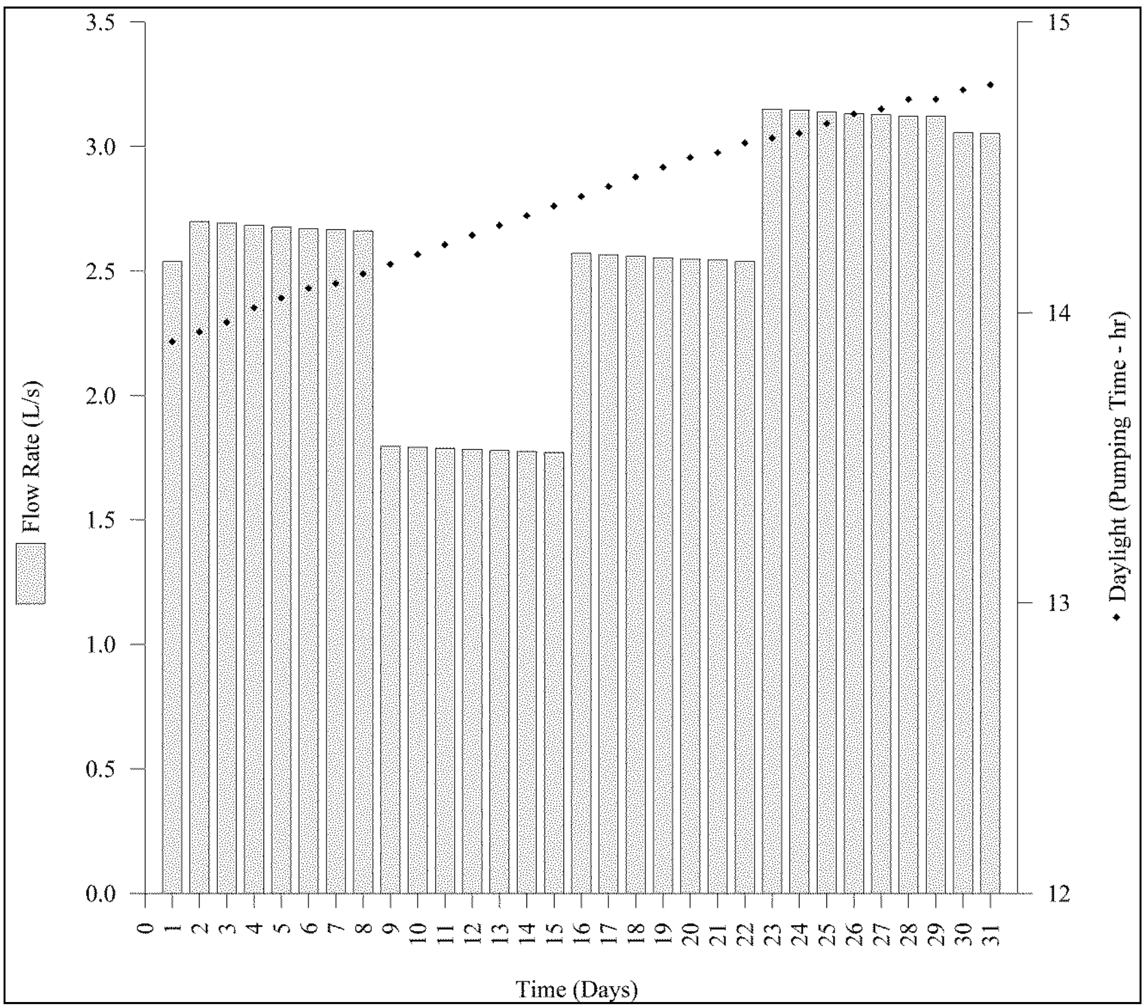

Exhibit 4. Daily variable flow rates and daylight hours for May 2011

It is reasonable to assume that given an adequate well design and absence of other remedial activities, the pumping rate at the Rolla, Missouri site would have been constant. Therefore, a second intermittent pumping schedule for the same time period was developed with a constant flow rate equal to the former NOP's GCWs pumping rate. Exhibit 5 presents a graphical representation of the constant flow rates and the number of daylight hours (pumping time) each day for the month of May 2011.

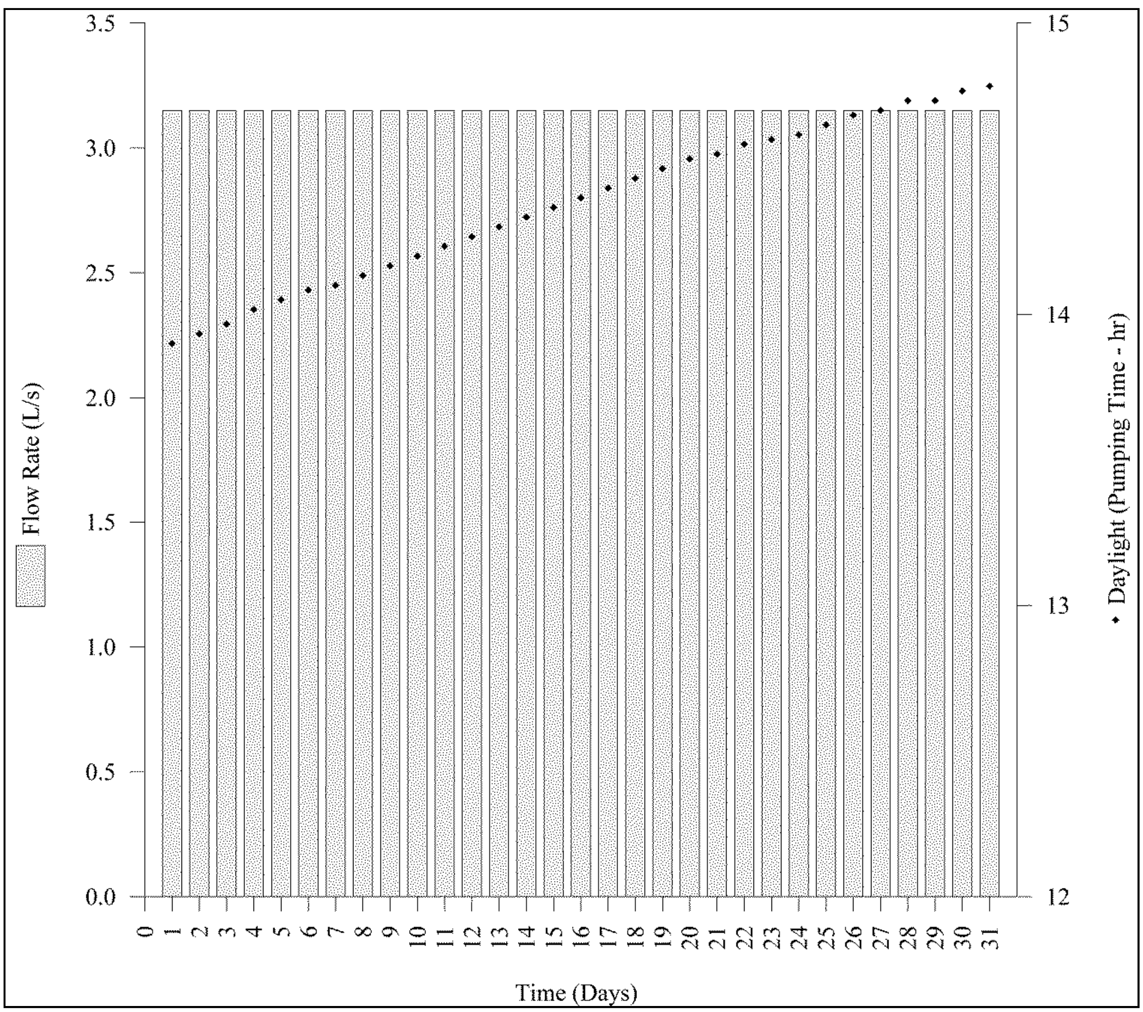

Exhibit 5. Daily constant flow rates and daylight hours for May 2011

A third pumping schedule, a baseline pumping schedule, was developed to characterize continuous pumping for the subject time period at the rate at which the GCWs were operated at the former NOP site (3.16 L/s).

NUMERICAL MODEL

A numerical groundwater flow model was developed using the three-dimensional finite difference groundwater flow model Visual MODFLOW® 2012.1 along with MODPATH (Pollock, 1989) to generate capture zones for the intermittent and continuous pumping schedules. MODPATH uses flow fields generated by MODFLOW to calculate the path lines and travel times of particles placed in the system. The model grid was built to provide a sufficiently large domain to eliminate the effects of boundary conditions. A 1,524 by 1,524 m model grid was created around the extraction well. The model grid was divided into 18 rows of 7.62 m in width and 91 rows of 15.2 m in width, and 24 columns of 7.62 m in width and 88 columns 15.2 m in width. For modeling purposes, the aquifer was divided into seven layers of varying thickness designed to simulate the generalized stratigraphic column of the former NOP site as indicated in Elmore and DeAngelis (2004) and Miller and Elmore (2005). Layer 1 consisted of 4.57 m of loess with a hydraulic conductivity of 7.06×10^{-6} centimeters per second (cm/s). Layers 2 and 3 each consisted of 8.38 m of fine sand with a hydraulic conductivity of 2.91×10^{-2} cm/s. Layers 4, 5, and 7 each consisted of 4.57 m of sand and gravel with a hydraulic conductivity of 9.17×10^{-2} cm/s. Layer 6 consisted of 4.57 m of silt with a hydraulic conductivity of 9.17×10^{-4} cm/s. A cross-section of the aquifer geometry showing the vertical discretization and hydraulic conductivities for each layer of the model is presented in Exhibit 6. The extraction well screen interval was located in Layer 3. A ratio of horizontal to vertical hydraulic conductivity (anisotropy ratio) of 10:1 and an effective porosity of 0.145 were assigned for all layers of the model as indicated in Elmore and DeAngelis (2004). According to Elmore and DeAngelis (2004) the assigned anisotropy ratio was based on information provided in Freeze and Cherry (1979); Fetter (1994), and Spitz (1996). Constant head boundaries were assigned perpendicular to regional groundwater flow. An aquifer recharge of 5.84 cm/year was uniformly distributed throughout the model domain, which according to Elmore and DeAngelis (2004) was based on the water balance performed by Piskin (1971). A measured hydraulic gradient of 0.003 was assigned to all layers as indicated by Elmore and DeAngelis (2004). Exhibit 7 lists the constant parameters used during modeling. To delineate the capture zone created by the P&T system, one hundred backward-tracking particles were added to Layer 3 of the model. The particles were evenly spaced in a circle in the cell containing the P&T system extraction well. To accommodate the intermittent nature of the P&T system, MODFLOW was run in transient mode for the subject time period. The P&T system was assumed to be on during daylight hours and off during night hours.

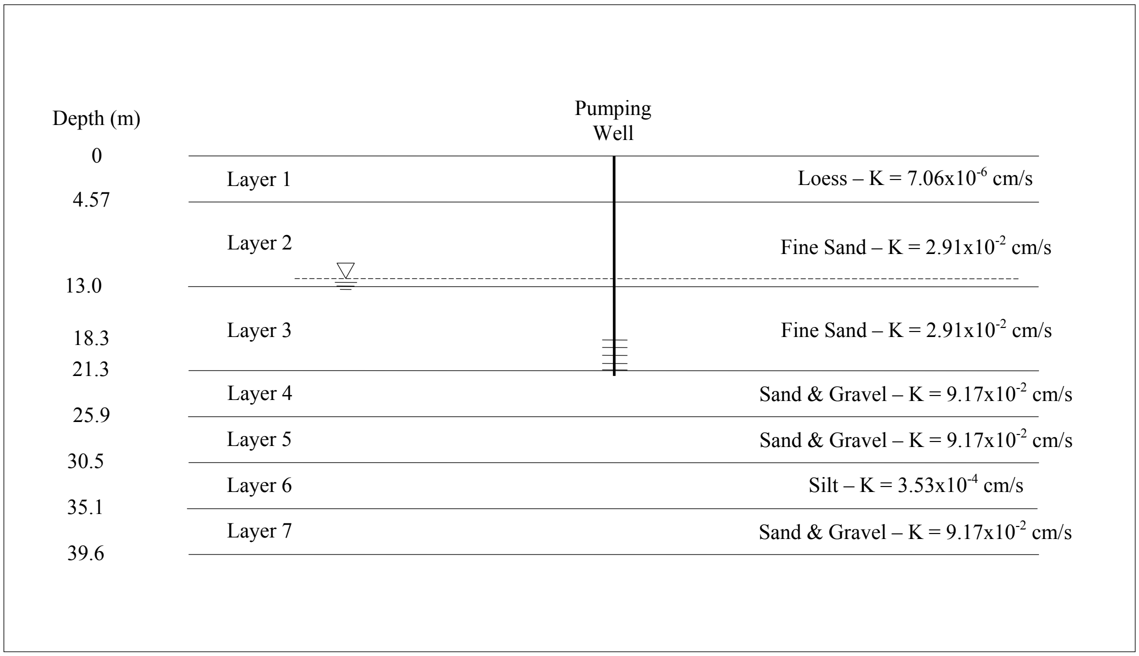

Exhibit 6. Cross section of the aquifer geometry

Exhibit 7. Constant parameters for model

Total porosity	0.145
Anisotropy ratio	10:1
Saturated thickness	27.4 m
Recharge rate	5.84 cm/year
Hydraulic gradient	0.003
Depth to groundwater	12.2 m

RESULTS AND DISCUSSION

Modeling of the baseline pumping schedule over the subject time period resulted in a capture zone, referred to as the baseline capture zone, of approximately 126 m in width with estimated volume of extracted groundwater (baseline volume) of 6.68×10^7 L. The average daily volume of extracted groundwater was estimated to be 2.73×10^5 L.

Assessment of the effectiveness of the capture zones generated by the two developed intermittent pumping schedules, the transient capture zones, was performed by comparing them to the baseline capture zone and computing their capture equivalence ratios (CERs). The CER is a screening level assessment of intermittent pumping feasibility in terms of hydraulic containment. The CER values were calculated by applying the following equation.

$$CER=\left(1-\frac{\text{Number of continously pumped pathlines outside transient capture zone}}{\text{Total number of continously pumped pathlines}}\right)*100$$

CERs of 100 percent imply that the transient capture zones are as effective as the continuously pumped capture zones. Conversely, CERs less than 100 percent indicate that the transient capture zones are less effective than the continuously pumped capture zones.

Modeling of the intermittent pumping schedule with variable flow rates resulted in a capture zone of approximately 68.8 m in width with a CER of 38.0 percent. Modeling of the intermittent pumping schedule with a constant flow rate of 3.16 L/s resulted in a capture zone of approximately 91.4 m in width with a CER of 50.0 percent. Exhibit 8 presents the generated transient capture zones overlaid on the baseline capture zone.

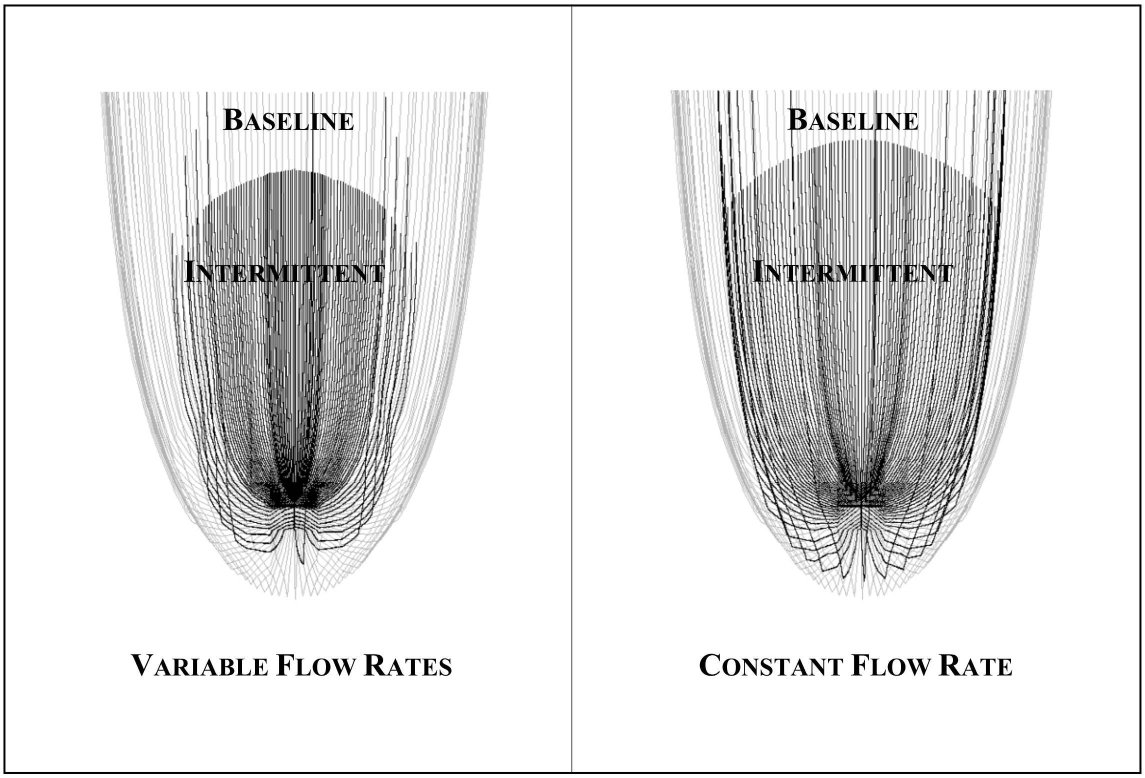

Exhibit 8. Transient capture zones overlaid on the baseline capture zone

As expected, the CER for both intermittent pumping schedules were less than 100 percent. Furthermore, the CER for the intermittent pumping schedule with variable flow rates is less than the CER for the intermittent pumping schedule with the constant flow rate of 3.16 L/s.

The volumes of extracted groundwater by the P&T system when operated intermittently were compared to the baseline volume. The volume of groundwater extracted by the P&T system, when operated intermittently with variable flow rates, is estimated to be 2.12×10^7 L, which is 31.8 percent of the baseline volume. The estimated volume of groundwater extracted by the P&T system when operated intermittently with a constant flow rate of 3.16 L/s is 3.71 x 10^7 L, which is 55.5 percent of the baseline volume.

As expected, the estimated volumes of groundwater extracted by the P&T system when operated intermittently were less than when operated continuously. Additionally, the estimated volume of extracted groundwater for the intermittent pumping schedule with variable flow rates is less than the estimated volume of extracted groundwater for the intermittent pumping schedule with a constant flow rate.

The relationship between the capture zones effectiveness and their associated percent of the baseline volume, referred as the capture zone pumping ratios (CPRs), were estimated for the intermittent pumping schedules using the following equation.

$$CPR=\frac{CER}{Percent\ Baseline\ Volume}*100$$

The CPR is a measure of capture efficiency based on total volume extracted. CPRs less than 100 percent indicate that to develop a transient capture zone as effective as a given percent of the baseline capture zone, the percent of the baseline volume required to be extracted is greater than the percent effectiveness of the transient capture zone. Conversely, CPRs higher than 100 percent indicate that to develop a transient capture zone as effective as a given percent of the baseline capture zone, the percent of the baseline volume required to be extracted is less than the percent effectiveness of the transient capture zone.

The intermittent pumping schedule with variable flow rates resulted in a CPR of 119 percent, whereas the intermittent pumping schedule with a constant flow rate of 3.16 L/s resulted in a CPR of 91.0 percent. Exhibit 9 summarizes the results of the capture zone comparisons. The 119 percent CPR value is the result of requiring only 31.8

percent of the baseline volume to be extracted in order to generate a transient capture zone as effective as 38.0 percent of the baseline capture zone. The CPR of 91.0 percent is the result of requiring 55.5 percent of the baseline volume to be extracted in order to generate a transient capture zone as effective as 50.0 percent of the baseline capture zone.

Exhibit 9. Comparison between the transient and baseline capture zones

Pumping Type	**Capture Zone Width (m)**	**CER (%)**	**Extracted Groundwater Volume (L)**	**% of Baseline Volume**	**CPR (%)**
Constant	126	N/A	6.68×10^7	N/A	N/A
Intermittent-Variable	68.8	38.0	2.12 x 107	31.8	119
Intermittent-Constant	91.4	50.0	3.71 x 107	55.5	91.0

CONCLUSIONS

The study shows that smaller and, therefore, less effective, capture zones will be generated from intermittent pumping due to the inherent variability of solar power when compared to continuous pumping. As with continuously operated P&T systems, which generate steady state capture zones, modeling of intermittent pumping schedules can be used when designing P&T systems to ensure the desired hydraulic containment is being achieved. The limited available data indicate that in the designing phase of a P&T system as a preliminary approximation, a CPR of 90.0 percent along with the total volumes of groundwater expected to be pumped (continuously and intermittently) can be used to estimate the CER of intermittent pumping schedules. Modeling of intermittent pumping schedules could also provide a potentially effective method of reducing non-renewable energy costs and the associated carbon footprint, by allowing prediction of the required pumping frequency and duration to meet a given capture zone.

REFERENCES

Aksoy, A., & Culver, T. (2004). Comparison of continuous and pulsed pump-and-treat for mass transfer-limited aquifers. Turkish Journal of Engineering and Environmental Science, 28, 307-316.

Chandrasekaran, N., & Thyagarajah, K. (2011). Modeling and MATLAB simulation of pumping system using PMDC motor powered by solar system. European Journal of Scientific Research, 59, 6-13.

Collins, E., Elmore, A. C., & Crow, M. (2013). Using conditional probability to predict solar-powered pump-and-treat performance. Journal of Hazardous, Toxic, and Radioactive Waste, 17, 31-37.

Dellens, A. D. (2007). Green remediation and the use of renewable energy sources for remediation projects. Washington, DC: U.S. Environmental Protection Agency (EPA), Office of Solid Waste and Emergency Response, Office of Superfund Remediation and Technology Innovation.

Elmore, A. C., & DeAngelis, L. (2004). Modeling a ground water circulation well alternative. Ground Water Monitoring & Remediation, 24(1), 66-73.

Elmore, A. C., & Graff, T. (2002). Best available treatment technologies applied to groundwater circulation wells. Remediation, 12(3), 63-80.

Fetter, C. W. (1994). Applied hydrology (3rd ed.). Columbus, OH: Merrill.

Freeze, R. A., & Cherry, J. A. (1979). Groundwater . Englewood Cliffs, NJ: Prentice-Hall, Inc.

Keely, J. F. (1989). Performance evaluations of pump-and-treat remediations. EPA/540/4-89/005. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development, Office of Solid Waste and Emergency Response.

Liu, W., Medina, M. A., Thomann, W., Piver, W. T., & Jacobs, T. (2000). Optimization of intermittent pumping schedules for aquifer remediation using a generic algorithm. Journal of the American Water Resources Association, 36, 1335-1348.

Mackay, D. M., Wilson, R. D., Brown, M. J., Ball, W. P., Xia, G., & Durfee, D. P. (2000). A controlled field evaluation of continuous vs. pulsed pump-and-treat remediation of a VOC-contaminated aquifer: Site characterization, experimental setup, and overview of results. Journal of Contaminant Hydrology, 41, 81-131.

Miller, G. R., & Elmore, A. C. (2005). Modeling of a groundwater circulation well removal action alternative. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, 9, 122-129.

Piskin, R. (1971). Hydrology of the University of Nebraska Field Laboratory at Mead, Nebraska (Ph.D. Dissertation). Department of Geology, University of Nebraska-Lincoln.

Pollock, D. W. (1994). User's guide for MODPATH/MODPATH-PLOT, version 3: A particle tracking post-processing package for MODFLOW, the U. S. Geological Survey finite-difference ground-water flow model. Open-File Report No. 94-464, Reston, VA: U.S. Geological Survey.

Spitz, K., & Moreno, J. (1996). A practical guide to groundwater and solute transport modeling. New York, NY: John Wiley & Sons, Inc.

US Environmental Protection Agency (US EPA) (2008a). Green remediation: Incorporating sustainable environmental practices into remediation of contaminated sites. EPA 542-R-08-002. Washington, DC: Office of Solid Waste and Emergency Response.

US Environmental Protection Agency (US EPA) (2008b). A systematic approach for evaluation of capture zones at pump and treat systems. EPA 600/R-08-003. Washington, DC: Ground Water and Ecosystems Restoration Division, National Risk Management Research Laboratory, Office of Research and Development.

BIOGRAPHICAL SKETCHES

Yovanna Cortes Di Lena, E.I. received her B.S. and M.S. degrees in geological engineering from the University of Missouri-Rolla. She has over seven years of experience performing environmental and geotechnical assessments with consulting companies located in St. Louis, Missouri and Phoenix, Arizona. She is currently completing her Ph.D. degree in geological engineering at the Missouri University of Science and Technology, Rolla, Missouri.

Andrew Curtis Elmore, Ph.D., P.E. received a B.S. degree in geological engineering from the University of Missouri-Rolla, and his M.S. and Ph.D. degrees in civil engineering from the University of Arizona, Tucson. He was employed as a consulting engineer with URS Group, Overland Park, Kansas, where he specialized in green and sustainable environmental remediation. He is currently a professor of geological engineering at the Missouri University of Science and Technology, Rolla.

John Conroy, E.I. received his B.S. degree in environmental engineering and M.S. in geological engineering from the Missouri University of Science and Technology, Rolla, Missouri. His master's research focused on modeling capture zones for PV microgrid powered pump and treat remediation systems with energy storage. He is currently employed as an environmental engineer with Geosyntec Consultants, Santa Barbara, California.

II. PERFORMANCE EVALUATION OF PV-POWERED PUMP AND TREAT SYSTEMS USING TYPICAL METEOROLOGICAL YEAR 3 DATA

Byline: Yovanna Cortes Di Lena, E.I., A.M.ASCE[1] and Andrew Curtis Elmore, Ph.D, P.E., M.ASCE[2].

Subject Headings: Renewable Energy, Pump and Treat, Remediation, Intermittent Pumping, Capture Zones, TMY3

ABSTRACT

Pump and treat (P&T) is a technology that has been extensively used to remove and/or contain contaminated groundwater. P&T systems conventionally operate continuously which require significant amounts of energy. The use of renewable energies to meet power demands of remedial systems may reduce a project's carbon dioxide emissions. This paper analyzes the performance of a hypothetical PV-powered P&T system that operates both intermittently by assuming that the system does not include an energy storage component and continuously by assuming that the system includes a relatively small capacity energy storage component using widely available Typical Meteorological Year 3 (TMY3) data. The results are compared against a baseline case of continuous pumping at a constant rate using volume of groundwater removed and capture zone width. The comparison shows that the cost-benefit of increasing the capture zone widths and volume of extracted groundwater by increasing

Department of Geological Sciences and Engineering, Missouri University of Science and Technology, 129 McNutt Hall, Rolla, MO 65409. (email: yc96e@mst.edu)
Department of Geological Sciences and Engineering, Missouri University of Science and Technology, 129 McNutt Hall, Rolla, MO 65409. (email: elmoreac@mst.edu)

the rated flow rate is greater than by including a relatively small capacity energy storage component. PV-powered P&T system performance, without or with limited relatively small capacity energy storage, is conditioned to site-specific hydrologic and seasonal characteristics. The methodology presented in this paper can be used to assess and compare the performance of each alternative.

INTRODUCTION

Pump and treat (P&T) is a technology that has been extensively used to remove and/or contain contaminated groundwater. P&T systems can be designed to prevent the spread of contaminants by hydraulic containment or to restore the quality of the aquifer by removing/reducing the contaminant concentration in groundwater. The United States Environmental Protection Agency (EPA) (1996) indicates that P&T groundwater remediation efforts typically include elements of both hydraulic containment and restoration through mass removal. Hydraulic containment is achieved by generating a capture zone through aquifer pumping. P&T systems conventionally operate continuously to create steady-state capture zones. Capture zone evaluations are performed in the designing phase of P&T systems as a tool to determine both the location of the extraction wells and pumping rates necessary to achieve hydraulic containment of the contaminant plume.

P&T systems require significant amounts of energy to operate continuously. According to the EPA (2008), green remediation has emerged as a way to reduce the demand placed on the environment during cleanup activities and to maximize their net benefits. One main element of green remediation is the reduction in fossil fuel consumption and emission of green house gasses. The EPA (2008) suggests that the use of renewable energies to meet power demands of remedial systems and/or auxiliary equipment may reduce a project's carbon dioxide emissions. The same document states that using renewable energies to power P&T systems provides significant opportunities at sites that are located in remote areas since they can operate independently without connection to a utility grid.

A challenge associated with photovoltaic (PV) powered P&T systems is the assessment of their performance given the potential intermittent nature of the power availability. Collins et al. (2013) considered the volume of groundwater extracted from a contaminated aquifer using both monthly predictions of solar insolation and measured values of insolation where the PV system did not include an energy storage component. However, this study did not characterize the nature of the capture zone generated by the P&T system. Conroy et al. (2013) compared transient capture zones generated by a hypothetical PV-powered P&T system that included a relatively high capacity energy storage component that allowed a binary step function. Cortes Di Lena et al. (2013) characterized the hydraulic containment equivalency of a PV-powered P&T system without energy storage using measured weekly average volumes of groundwater extracted and the available daylight hours. The study showed that capture zones predicted using the PV-powered intermittent pumping schedules were smaller relative to the capture zones predicted from a schedule of continuous pumping. However, allowing the P&T system to operate intermittently could improve contaminant removal especially where mass transfer limitations exist as indicated by Keely (1989), Liu et al. (2000), Mackay et al. (2000), and Aksoy and Culver (2004).

The literature review indicated that others have used site-specific solar insolation data to predict the performance of PV-powered P&T systems. The work presented in this paper uses estimates of hourly solar insolation data that is available for locations throughout the United States to develop pumping schedules for a hypothetical PV-powered P&T system. To illustrate the potential practical application of using the hourly solar insolation data, two systems are considered, one that operates intermittently when solar insolation is available by assuming that the PV system does not include an energy storage component and one that operates continuously by assuming that the PV system includes a relatively small capacity energy storage component. The PV-based pumping schedule is variable in both instances with increase pumping with increasing levels of solar insolation. The results are compared against a baseline case of continuous pumping at a constant rate using two metrics: volume of groundwater removed and capture zone width. This paper analyzes the performance of a hypothetical PV-powered P&T system using published data for Omaha, Nebraska and the nearby former Nebraska Ordnance Plant (FNOP) Superfund site located in adjacent Saunders County. This study is based on theoretical modeling and has not been corroborated by field testing.

The Methodology section of this paper explains how hourly insolation data available from the National Renewable Energy Laboratory (NREL) can be used to develop variable pumping schedules using a specific set of pump specifications, and the

Application section demonstrates the use of the variable pumping schedules to characterize remedial action capture zones.

METHODOLOGY

To predict the capture zones generated by the two scenarios of the hypothetical PV-powered P&T system, pumping schedules were developed using Typical Meteorological Year 3 (TMY3) data. The NREL National Solar Radiation Data Base is a publically-available source for hourly values of solar radiation and meteorological data for more than 1,400 sites in the U.S. Wilcox and Marion (2008) indicate that TMY3 data are the most recent based on input data from 1961 to 2005.

A submersible pump was selected given the remediation goals and subsurface hydrogeology conditions of the subject site. A fixed PV array was oriented to the south and tilted at an angle equal to the site latitude to achieve best year-round results. Pump performance data provided by the manufacturer can be used to predict pump discharge (Q_y) as a function of beam radiation on the tilted surface (I_{bc}) and PV cell temperature (T_c) for the given the PV orientation, tilt, and latitude using:

$$Q_y = f(I_{bc}, T_c) \tag{1}$$

Hourly instantaneous beam solar radiation per unit area normal to the sun (I_{bN}) from a TMY3 dataset were converted to I_{bc} by applying the following solar geometry equations from Goswami et al. (2000).

Solar declination angle (δ) was calculated using:

$$\delta = 23.45 \text{ deg} * \sin[360 \text{ deg} * (284 + n) / 365 \text{ deg}] \quad (2)$$

where n is the day number during a year with $n = 1$ on January 1st.

The hour angle (h_s) was calculated by:

$$h_s = 15 \text{ deg} * (12 - \text{ST}) \quad (3)$$

where ST is the solar time. ST is calculated by:

$$\text{ST} = \text{LST} + \text{ET} + (\text{LL} - \text{LS}) * 4 \text{ min/deg} \quad (4)$$

where LST is the local standard time, ET is the equation of time, LL is the local longitude, and LS is the standard longitude. ET is calculated by:

$$\text{ET} = 9.87 * \sin(2 * B) - 7.53 * \cos(B) - 1.5 * \sin(B) \quad (5)$$

where

$$B = 360 \text{ deg} * (n - 81) / 364 \text{ deg} \quad (6)$$

Solar altitude (α) was calculated by:

$$\sin(\alpha) = \cos(L) * \cos(\delta) * \cos(h_s) + \sin(L) * \sin(\delta) \qquad (7)$$

where L is the latitude.

The solar azimuth angle (a_s) was calculated by:

$$\sin(a_s) = \cos(\delta) * \sin(h_s) / \cos(\alpha) \qquad (8)$$

The solar radiation angle of incidence (i) on a tilted surface was calculated by:

$$\cos(i) = \cos(\alpha) * \cos(a_s - a_w) * \sin(\beta) + \sin(\alpha) * \sin(\beta) \qquad (9)$$

where β is the tilt angle of the surface from the horizontal and a_w is the surface azimuth angle.

The beam radiation on the tilted surface was calculated by:

$$I_{bc} = I_{bN} * \cos(i) \qquad (10)$$

Ambient temperature (T_A) TMY3 data were used to estimate the PV T_c by applying the following equation from Davis et al. (2001):

$$T_c - T_A = \text{GHI} / \text{G}_{\text{NOCT}} * (\text{NOCT} - \text{T}_{\text{A,NOCT}}) * [1 - (\eta_c / \tau * \alpha)] \quad (11)$$

where GHI is the global horizontal irradiance, NOCT is the normal operating cell temperature provided by the manufacturer, $G_{NOCT} = 800$ W/m^2, $T_{A,NOCT} = 20^\circ$ C, ηc is the module electrical efficiency, τ is the solar transmittance of glazing, and α is the solar absorptance of the PV cell. Skoplaki and Palyvos (2008) indicates that $(\eta c/\tau*\alpha) << 1$; therefore, Equation (11) can be simplified:

$$T_c - T_A = \text{GHI} / \text{G}_{\text{NOCT}} * (\text{NOCT} - \text{T}_{\text{A,NOCT}}) \quad (12)$$

For this study a total of 8,760 I_{bc} and T_c values were calculated using hourly $I_{bN,}$ GHI, and T_A inputs for 365 days. Table 1 presents the TMY3 data record for one of those hours.

The developed pumping schedules were used to estimate the quantity of water extracted from the aquifer for comparison to the volume extracted by continuous pumping at a constant flow rate (baseline case). The pumping schedules were also used as inputs to the numerical groundwater flow and pathline models to predict the capture zones width.

APPLICATION

The FNOP Superfund site provided the basis for the model used to analyze the hypothetical PV-powered P&T systems. The site is located in unconsolidated Pleistocene glacio-fluvial deposits consisting mostly of fine to medium sand and gravel covered by loess and underlain by Cretaceous shale and sandstone.

Both hypothetical PV-powered P&T system scenarios include a south-facing fixed PV array horizontally inclined at approximately the latitude angle to power a SunPumps, Inc. DC submersible pump (model SCS 50-100) rated at 3.16 L/s (Q_r) and when applicable, limited energy storage. This pump was selected because it has the same flow rate as the groundwater circulation well (GCW) at the FNOP site described by Elmore and DeAngelis (2004).

The manufacturer's pump performance data were arbitrarily divided into eight ranges based on T_c, and scattergrams were generated by plotting I_{bc} against the manufacturer's flow rates (Q). Figure 1 is a scattergram for T_c values ranging from 10 to 20˚ C. Linear correlations were performed on the scattergrams, and the equations of the best-fit lines given in Table 2 were used to estimate Q_y.

Normalized flow rates (Q_n) were calculated by dividing the Q_y values by Q_r. Normalizing the flow rates allowed evaluation of pumps with different ratings assuming the performance is proportional to the base pump. Three pump sizes were selected for simulation. Q_r was selected as one alternative. A drawdown analysis showed that the aquifer could support significantly higher pumping rates; therefore pumps with rated flow rates of 6.32 L/s (two times Q_r) and 12.6 L/s (four times Q_r) were selected as two other alternatives.

To predict the capture zones associated with the hypothetical PV-powered P&T system without energy storage, intermittent variable pumping schedules were developed. Flow rates (Q_{nv}') for these schedules were calculated by multiplying the Q_n values by the desired pump size.

To predict the capture zones associated with a hypothetical PV-powered P&T system with a limited capacity energy storage component, continuous variable pumping schedules were developed by assuming that the PV system could be designed to always provide sufficient power for a specific minimum flow rate. Arbitrary minimum flow rates, intended to maintain the variability of the pumping schedules, were selected as a fraction of the assumed pump rating. The previously developed pumping schedules were then searched, and flow rates which were less than the minimum flow rate were replaced with the minimum flow rate. Two pumping schedules were developed for each pump by calculating minimum flow rates that were 10 or 25 percent of the rated flow rates.

To reduce the required time for the numerical flow model execution, the time increment was increased to two hours. The pumping schedules for the entire year were divided into four quarters with the time periods centered on the solar solstices and equinoxes in order to evaluate the effect of seasonality on the P&T systems performance. Time periods centered on the equinoxes ranged from February 4 to May 6 for spring and August 5 to November 4 for fall. Time periods centered on the solstices ranged from May 6 to August 5 for summer and November 4 to February 4 for winter. Figure 2 shows the Q_n values for the P&T system that includes a 10 percent of Q_r energy storage capacity.

A numerical groundwater flow model was developed using the three-dimensional finite difference groundwater flow model Visual MODFLOW® Classic 2011.1 along with MODPATH 3 to generate capture zones for the intermittent and continuous pumping schedules. MODPATH uses flow fields generated by MODFLOW to calculate the path lines and travel times of particles placed in the system. The model grid was built to provide a sufficiently large domain to eliminate the effects of boundary conditions. A 1,524 by 1,524 m model grid was created around the extraction well. The single layer model grid was divided into 18 rows of 7.62 m in width and 91 rows of 15.2 m in width, and 24 columns of 7.62 m in width and 88 columns 15.2 m in width. The modeled aquifer was designed to simulate unconfined flow of a simplified version of the stratigraphic column of the FNOP site as indicated in Elmore and DeAngelis (2004) and Miller and Elmore (2005). It consisted of 39.6 m of well sorted sand with a hydraulic conductivity of 3.53×10^{-2} cm/s, which is within the hydraulic conductivity range for well sorted sands provided in Fetter (2001). A conceptual cross-section of the aquifer and the aquifer parameters is presented in Figure 3. Constant head boundaries were assigned perpendicular to regional groundwater flow. No flow was assigned to the other boundaries. To delineate the capture zone created by the P&T system, one hundred backward-tracking particles were added to the model. The particles were evenly spaced in a circle in the cell containing the P&T system extraction well. To accommodate the intermittent nature of the P&T system, MODFLOW was run in transient mode for the subject time periods. It was assumed that the outermost pathlines defined the capture zone generated by the P&T system.

RESULTS

Modeling of the continuous pumping schedule at a constant flow rate of 3.16 L/s resulted in a baseline capture zone 79.3 m in width. The baseline volume of ground water extracted during the approximately 91 day evaluation period was 2.49×10^7 L. Figures 4, 5, and 6 show the predicted capture zones widths, volumes of groundwater extracted, and time of operation of the pump by time period for the intermittent and continuous variable pumping schedules. The results show that for variable pumping schedules, capture zone widths and volume of groundwater extracted increase with increasing flow rates and pumping time. Figure 7 is an example of the capture zone results. The plan view figure shows the capture zones simulated for the P&T systems without energy storage and with limited energy storage to accommodate a minimum flow rate equal to 10 percent of the rated flow rate.

Wider capture zones were generated and larger volumes of groundwater were extracted for the time period centered in the summer solstice when longer days provided the most solar energy. Narrower capture zones were generated and lesser volumes of groundwater were extracted for the time period centered in the winter solstice when solar energy was at the minimum. The generated capture zones for the time period centered in the summer solstice were approximately 1.13 to 1.66 times wider than the capture zones generated for the time period centered in the winter solstice. The extracted groundwater volumes for the time period centered in the summer solstice were 1.14 to 1.69 times larger than the volumes of groundwater extracted for the time period centered in the winter solstice.

A relative comparison of the predicted volumes of groundwater extracted presented in Figure 4 to actual volumes of water pumped by the PV-powered P&T system without energy storage reported by Collins et al. (2013) reveal a significant inconsistency. Seasonally, the TMY3 method estimates that the greatest volumes will be pumped in the summer and fall while the actual fall volume reported by Collins et al. (2013) was approximately one-half of the summer volume. A comparison of PV-based system performance at different locations is problematic; however, it highlights the importance of accounting for site-specific hydrologic conditions as Collins et al. (2013) concludes that the full potential of the PV-powered pump was not realized due to competing remediation efforts.

The capture zone results developed in this study differ significantly from those presented in Conroy et al. (in press) as the widths of the generated capture zones achieved in the earlier work ranged from 78 to 95 percent the baseline capture zone width. However, in Conroy et al. (in press) a relatively high capacity energy storage component that allowed a binary step function was included as part of the hypothetical PV-powered P&T system.

The variability of the predicted capture zone widths for each hypothetical PV-powered P&T system scenario was measured by computing their coefficients of variation. Table 3 summarizes the statistical characteristics of the predicted capture zones widths. The coefficients of variation decrease as the energy storage capacity increased, indicating that more consistent capture zone widths are generated with increasing energy storage.

The intermittent and continuous variable pumping capture zones widths along with the estimated volumes of extracted groundwater were normalized by the baseline capture zone width and the baseline volume of extracted groundwater. The change in the normalized capture zone widths (W_N) and normalized volumes of extracted groundwater (V_N) with change in rated flow rate were compared. V_N increases at a ratio of 1 to 1 with respect to rated flow rate, while W_N increase at a lower ratio, which indicates that an increase in the rated flow rate is less efficient at increasing W_N relative to increasing V_N. The relationship between the normalized time the pump was on (t_N) and W_N and V_N for each of the selected rated flow rate alternatives were also assessed and are presented in Figures 8 and 9. The figures show that better correlations exist between t_N and V_N than between t_N and W_N, as the coefficients of determination are higher between t_N and V_N than between t_N and W_N. This indicates that time of operation is a reliable volume of extracted groundwater predictor. The coefficients of determination also indicate that the correlation between t_N and, V_N and W_N increases with increasing rated flow rates.

It is relatively straightforward to increase the pumping rate of a system by selecting an appropriately sized PV array matched to power the pump rating. A larger flow rate pump requires more power which equates to more PV panels relative to a lower flow rate pump. Therefore, increasing flow rate results in higher equipment costs without adding significant complexity to the PV system design. However, PV system costs and complexity may be significantly greater when energy storage components are included. A comparison of the approximate costs of the PV-powered P&T system was performed when the rated flow rate is increased and an energy storage component is included. The comparison shows that the cost-benefit of increasing the capture zone widths and volume of extracted groundwater by increasing the rated flow rate is greater than by including an energy storage component. Increasing the rated flow rate from 3.16 L/s to 6.32 L/s represents an increment in cost of approximately 20 percent, capture zone width of 68 to 77 percent, and extracted groundwater volume of 100 percent. On the other hand, including an energy storage component with a 10 percent of the rated flow rate (3.16 L/s) capacity represents an increment in cost of approximately 70 percent, capture zone width of 18 to 43 percent, and extracted groundwater volume of 27 to 58 percent.

CONCLUSIONS

The work presented in this paper demonstrates that hourly values of solar insolation and ambient temperature that are widely available can be used to develop pumping schedules for PV-powered P&T systems with and without energy storage components. The results show that the width of the capture zones generated, and volumes of groundwater extracted by a PV-powered P&T system can be increased by increasing the pump size and/or having the pump operate continuously by establishing a threshold flow rate at which the pump will be operated using stored energy when incident solar insolation is not available. However, it is more cost effective to increase the pump rating than to add a relatively small energy storage component. PV-powered P&T system performance, without or with limited capacity energy storage, is conditioned to site-specific hydrologic and seasonal characteristics. The methodology presented in this paper can be used to assess and compare the performance of each alternative.

REFERENCES

Aksoy, A. and Culver, T. (2004). "Comparison of continuous and pulsed pump-and-treat for mass transfer-limited aquifers." *Turkish Journal of Engineering and Environmental Science*, 28(5), 307-316.

Collins, E., Elmore, A. C., and Crow, M. (2013). "Using conditional probability to predict solar-powered pump-and-treat performance." *Journal of Hazardous, Toxic, and Radioactive Waste*, 17(1), 31-37.

Conroy, J. P., Elmore, A. C., and Crow, M. (2013). "Capture zone comparison for photovoltaic microgrid-powered pump and treat remediation." *Journal of Hazardous, Toxic, and Radioactive Waste*, in press.

Cortes Di Lena, Y., Elmore, A. C., and Conroy, J. (2013). "Effectiveness of capture zones generated by intermittent pumping of a PV-powered pump-and-treat system without energy storage." *Remediation*, 23(3), 111-122.

Davis, M. W., Dougherty, B. P., and Fanney, A. H. (2001). "Prediction of building integrated photovoltaic cell temperatures." *Journal of Solar Energy Engineering*, 123(3), 200-210.

Elmore, A. C., and DeAngelis, L. (2004). "Modeling a ground water circulation well alternative." *Ground Water Monitoring & Remediation*, 24(1), 66-73.

Fetter, C. W. (2001). "Properties of aquifers." *Applied hydrogeology*, 4th ed., Prentice-Hall, Upper Saddle River, NJ, 66-112.

Goswami, D. Y., Kreith, F., and Kreider, J. F. (2000). "Fundamentals of solar radiation." *Principles of solar engineering*, 2nd ed., Taylor & Francis Group, New York, NY, 13-80.

Keely, J. F. (1989). *Performance evaluations of pump-and-treat remediations*. United States Environmental Protection Agency, Robert S., Kerr Environmental Research Laboratory, Ada, OK.

Liu, W., Medina, M. A., Thomann, W., Piver, W. T., and Jacobs, T. L. (2000). "Optimization of intermittent pumping schedules for aquifer remediation using a genetic algorithm." *Journal of the American Water Resources Association*, 36(6), 1335-1348.

Mackay, D. M., Wilson, R. D., Brown, M. J., Ball, W. P., Xia, G., and Durfee, D. P. (2000). "A controlled field evaluation of continuous vs. pulsed pump-and-treat remediation of a VOC-contaminated aquifer: Site characterization, experimental setup, and overview of results." *Journal of Contaminant Hydrology*, *41(1-2*), 81-131.

Miller, G. R. and Elmore, A. C. (2005). "Modeling of a groundwater circulation well removal action alternative." *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 9(2), 122-129.

Skoplaki, E. and Palyvos, J. A. (2009). "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations." *Solar Energy*, 83(5), 614-624.

U.S. Environmental Protection Agency (EPA) (1996). *Pump-and-treat ground-water remediation: A guide for decision makers and practitioners*, United States Environmental Protection Agency Office of Research and Development, Washington D.C.

EPA (2008). *Green remediation: incorporating sustainable environmental practices into remediation of contaminated sites*, United States Environmental Protection Agency Office of Solid Waste and Emergency Response.

Wilcox, S. and Marion, W. (2008). *Users Manual for TMY3 Data Sets*, National Renewable Energy Laboratory, Golden, CO.

Table 1. Relevant data used to calculate I_{bc} and T_c.

Site Identification Code	Site Latitude (deg)	Date	Time	GHI (W/m^2)	I_{bN} (W/m^2)	T_A (˚C)
725500	41.3	10/09/2005	11.00	403	206	11.7

Table 2. Pump performance scattergrams linear correlation.

Temperature Range (˚C)	Equation	Coefficient of Determination (R^2)
<10	$Q_y = 4.44 * I_{bc} + 0.348$	0.970
10 – 20	$Q_y = 4.97 * I_{bc} – 0.007$	0.977
20 – 30	$Q_y = 4.60 * I_{bc} + 0.054$	0.975
30 – 40	$Q_y = 4.20 * I_{bc} + 0.269$	0.972
40 – 50	$Q_y = 4.25 * I_{bc} + 0.127$	0.971
50 – 60	$Q_y = 4.80 * I_{bc} – 0.057$	0.974
60 – 70	$Q_y = 5.60 * I_{bc} – 0.306$	0.995
>70	$Q_y = 6.46 * I_{bc} – 0.455$	0.999

Table 3. Statistical characteristics of the capture zones widths.

Parameter	P&T w/o Energy Storage Capacity	P&T w/ a 10% of Rated Flow Rate Energy Storage Capacity	P&T w/ a 25% of Rated Flow Rate Energy Storage Capacity
Mean	21.6 - 61.3	28.4 - 77.1	38.1 - 96.2
Standard Deviation	4.27 - 10.5	3.32 - 7.69	2.92 - 5.09
Coefficient of Variation	0.198 - 0.212	0.099 - 0.128	0.053 - 0.077

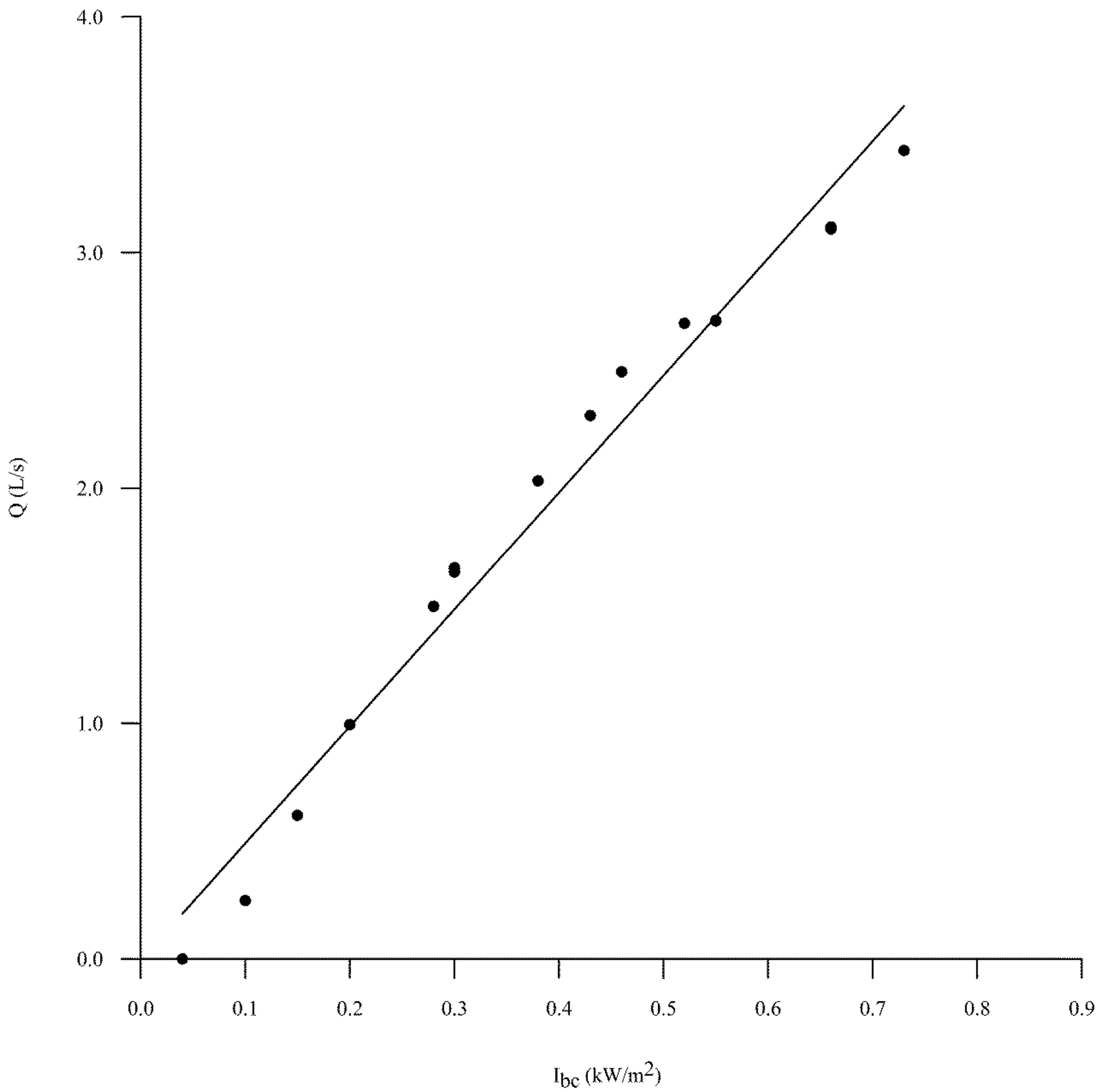

Figure 1. I_{bc} and flow rates scattergram for T_c values ranging from 10 to 20˚ C.

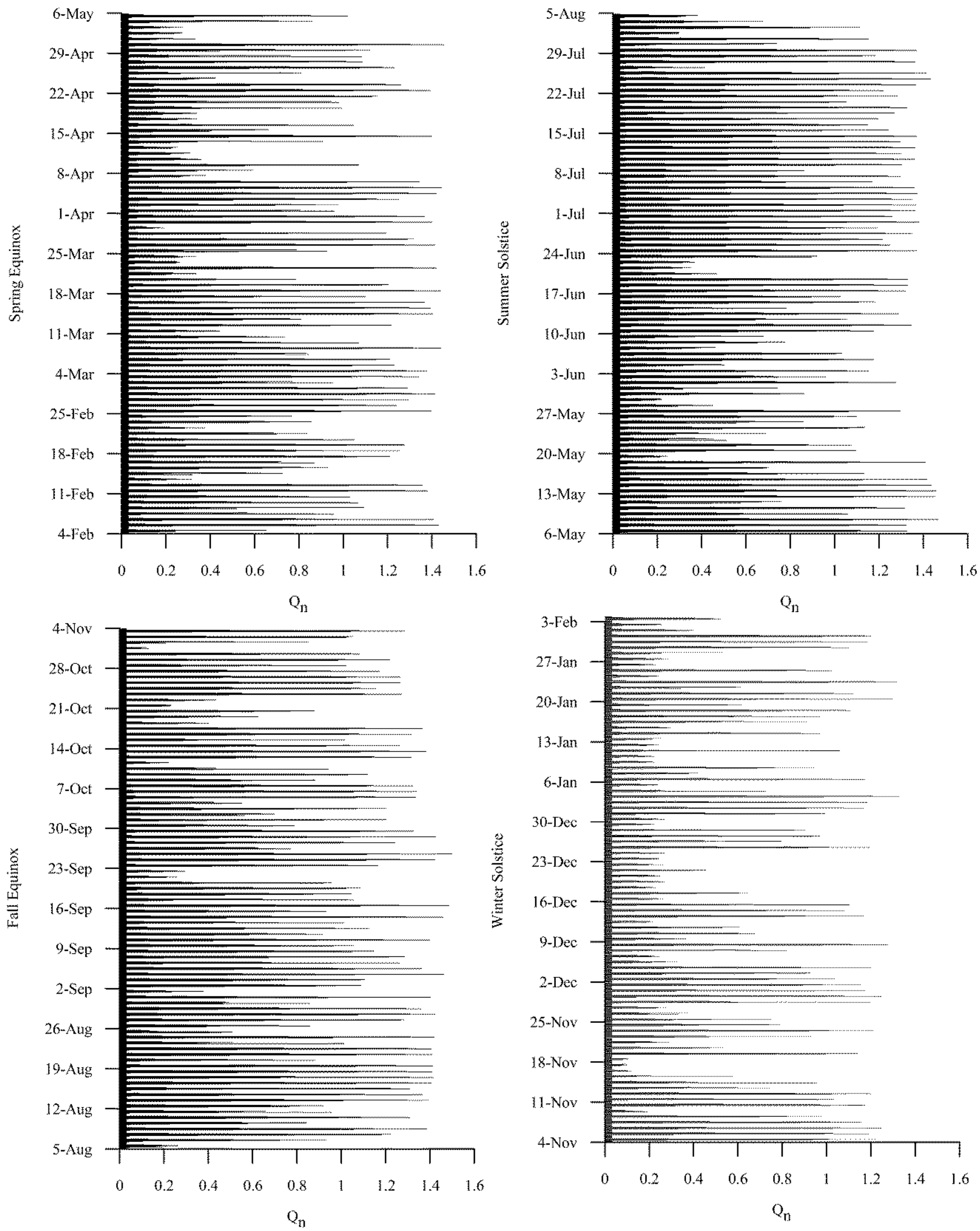

Figure 2. Q_n for the P&T system with a 10 percent of Q_r energy storage capacity. The continuous pumping at a flow rate 10 percent of Q_r is represented by the black band adjacent to the ordinate axis.

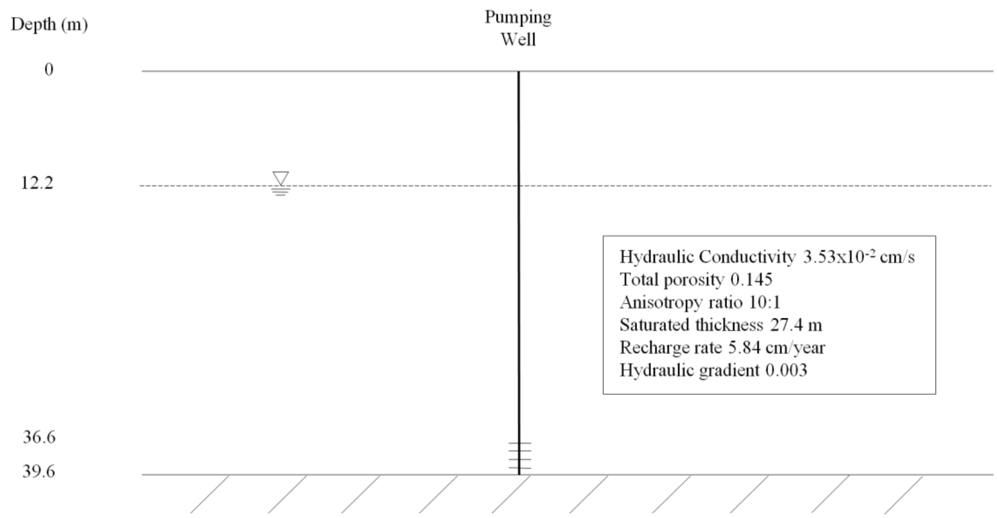

Figure 3. Conceptual cross section of the aquifer geometry.

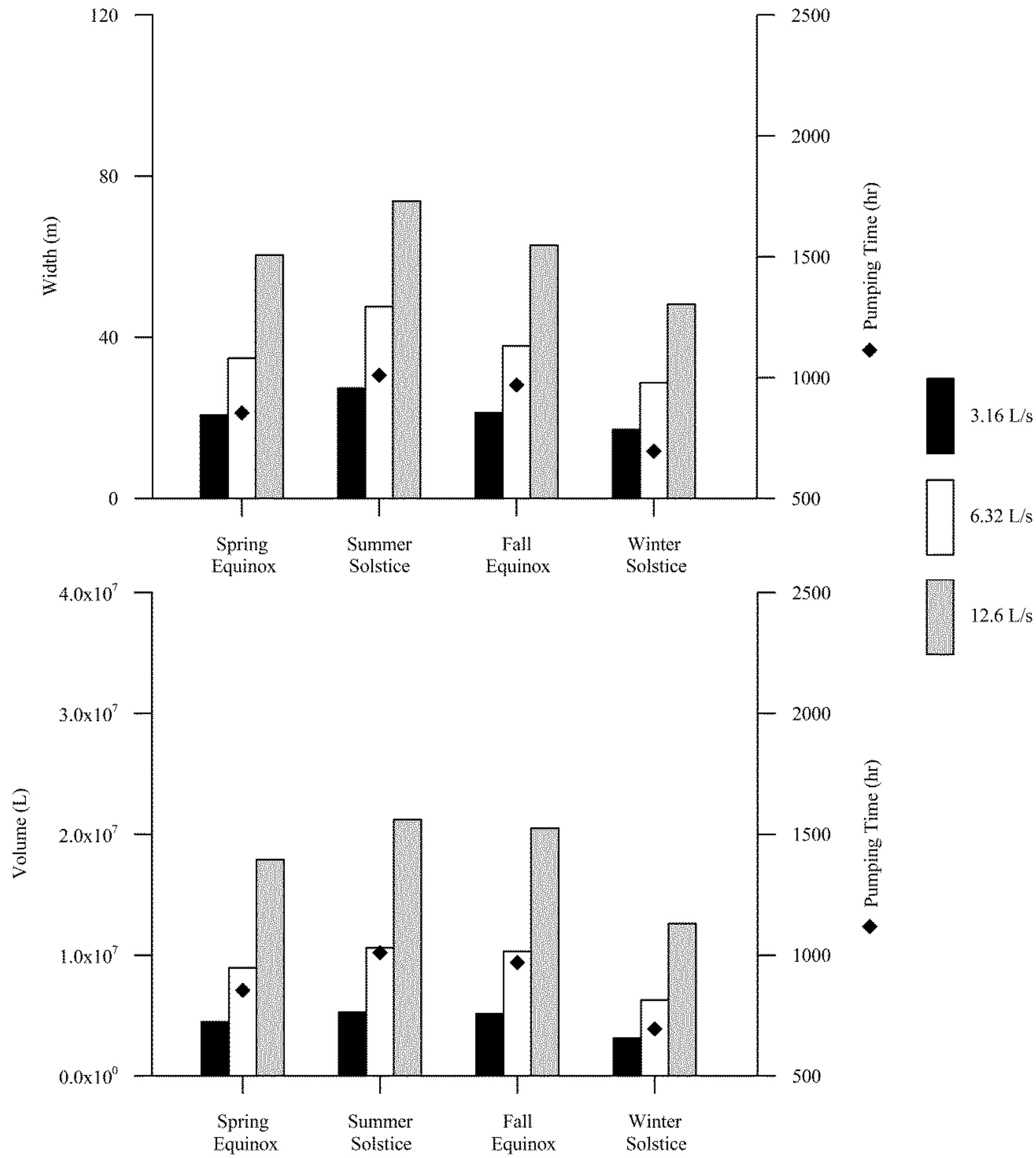

Figure 4. Capture zone metrics – P&T system without energy storage.

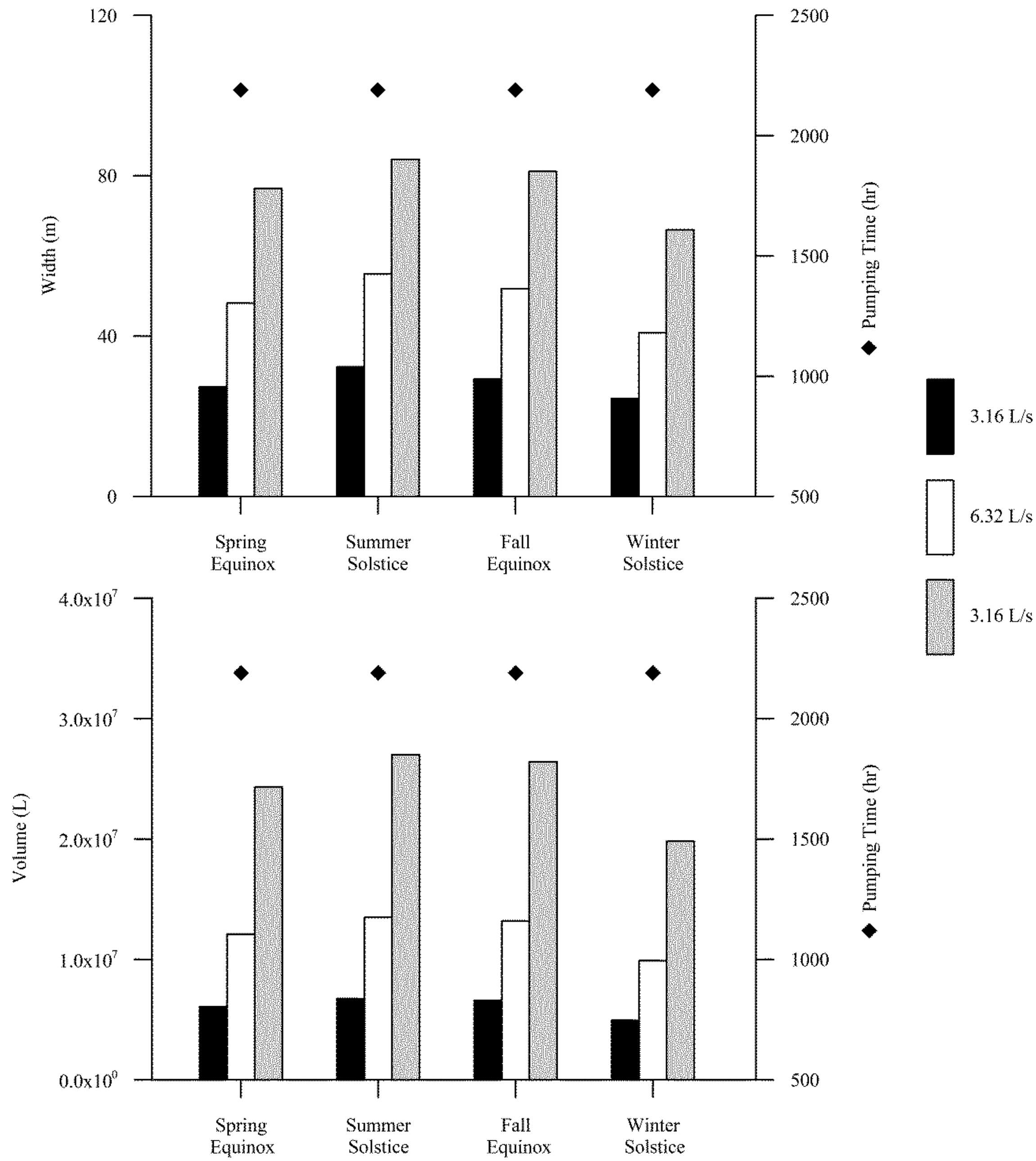

Figure 5. Capture zone metrics – P&T system with 10 percent of rated flow rate energy storage capacity.

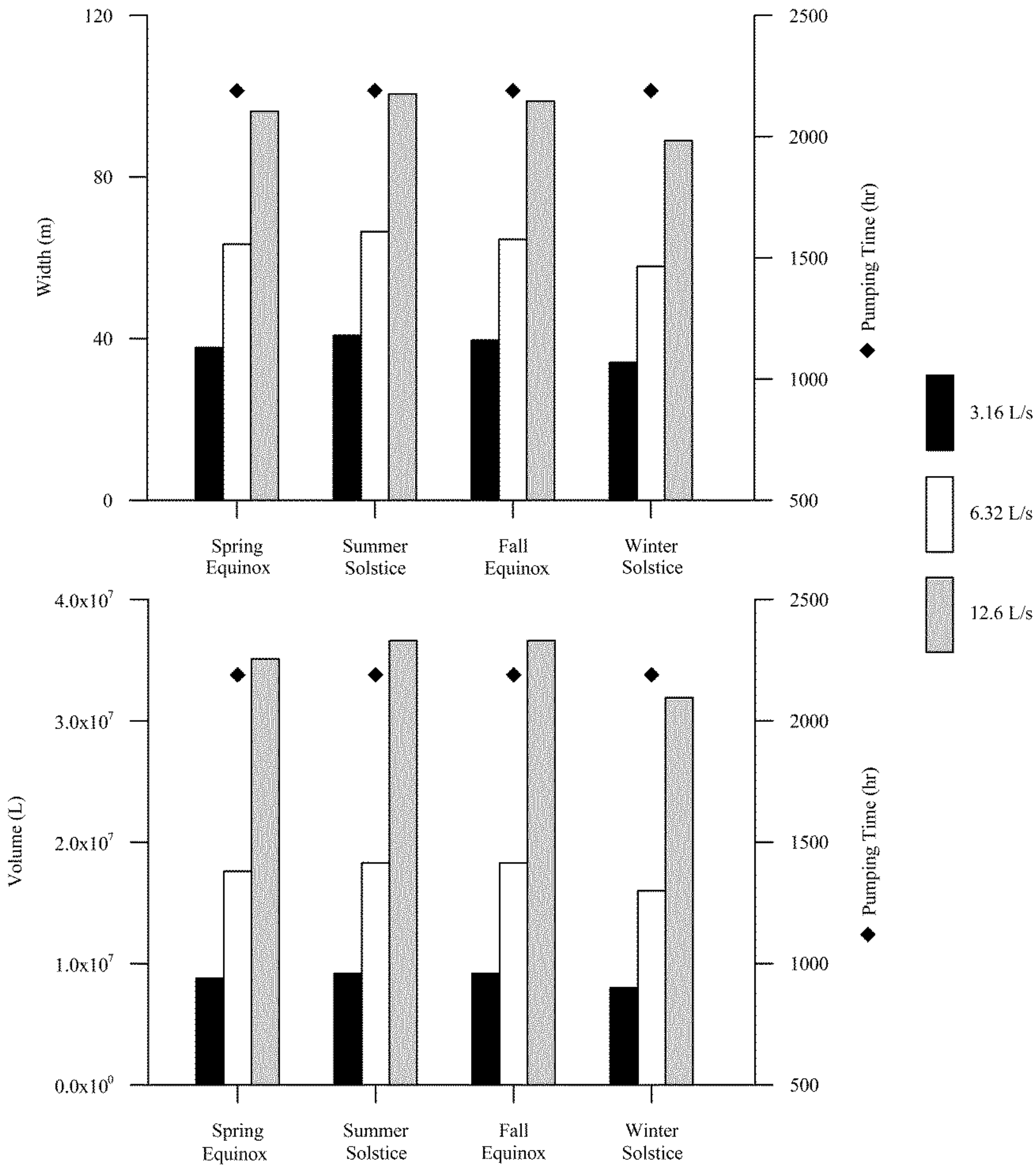

Figure 6. Capture zone metrics – P&T system with 25 percent of rated flow rate energy storage capacity.

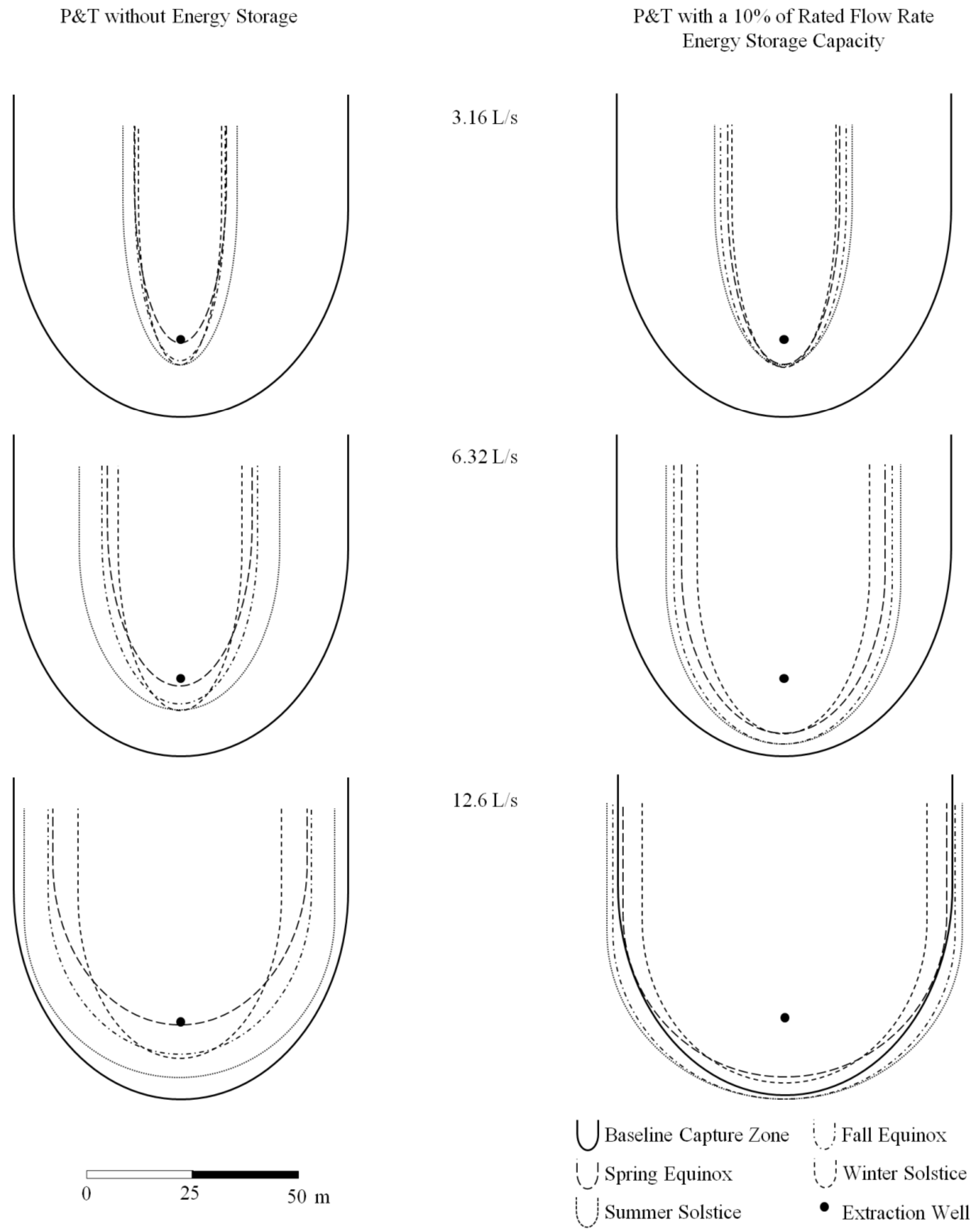

Figure 7. Plan view of the capture zones for the P&T systems without energy storage and with 10 percent of rated flow rate energy storage capacity overlaid on the baseline capture zone.

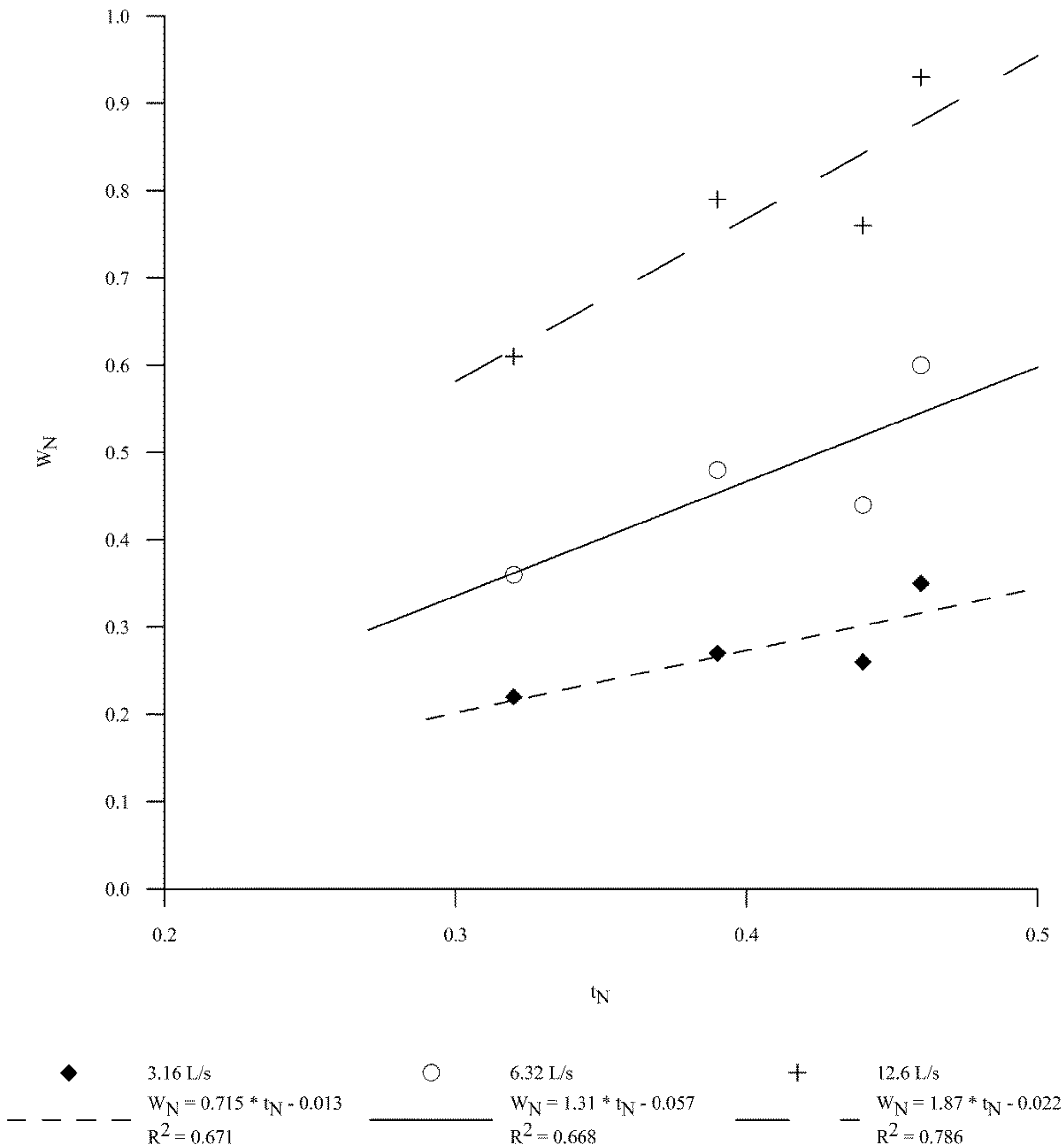

Figure 8. Relationship between the t_N and W_N.

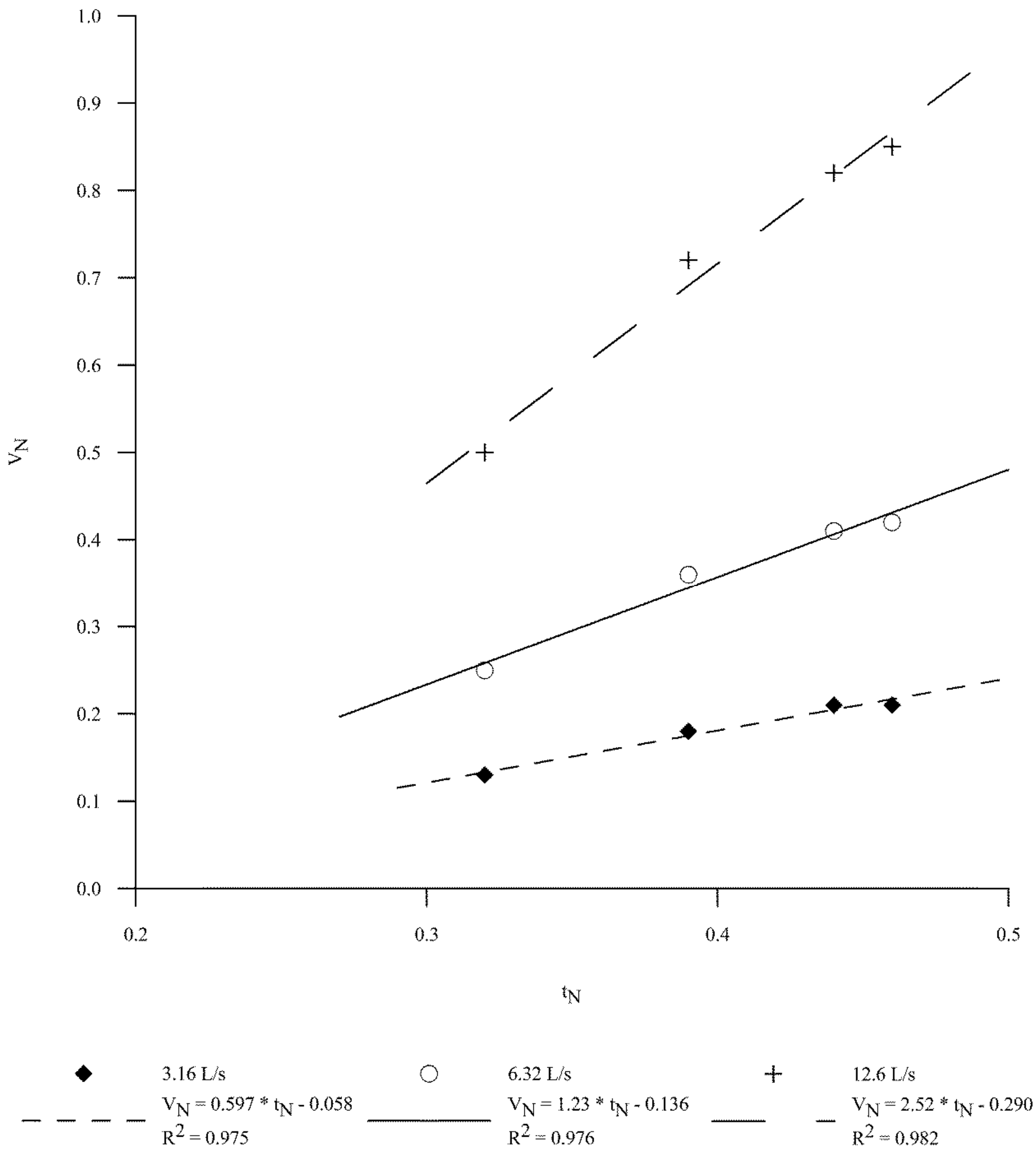

Figure 9. Relationship between the t_N and V_N.

III. GENERAL METHOD FOR PREDICTING CAPTURE ZONE WIDTHS FOR PV-POWERED PUMP AND TREAT SYSTEMS USING PVWATTS AND BASIC HYDROGEOLOGIC DATA

Byline: Yovanna Cortes Di Lena, E.I., A.M.ASCE[1] and Andrew Curtis Elmore, Ph.D, P.E., M.ASCE[2].

Subject Headings: Renewable Energy, Pump and Treat, Remediation, Intermittent Pumping, Capture Zones, PVWATTS, Transmissivity, Hydraulic gradient.

ABSTRACT

Pump and treat (P&T) is one of the most commonly used technologies to remove and/or contain contaminated groundwater. An appropriate delineation of capture zones is necessary to design an effective P&T system. The study presented in this paper focuses on developing a methodology to estimate capture zone widths for photovoltaic (PV)-powered P&T systems without energy storage throughout the continental United States (U.S.) as a function of daily average solar insolation data, transmissivity, and hydraulic gradient. Maps depicting predicted capture zone widths for specified transmissivity values and a hydraulic gradient are developed. The applicability of the developed methodology is illustrated with two actual sites where groundwater remediation has taken place. The methodology presented in this study can be used to assess the feasibility of PV-powered P&T systems without energy storage, in terms of capture zone width,

---

Department of Geological Sciences and Engineering, Missouri University of Science and Technology, 129 McNutt Hall, Rolla, MO 65409. (email: yc96e@mst.edu)
Department of Geological Sciences and Engineering, Missouri University of Science and Technology, 129 McNutt Hall, Rolla, MO 65409. (email: elmoreac@mst.edu)

anywhere within the continental U.S. or as a point of departure for more detailed studies. Site-specific detailed analysis of the hydrogeologic and solar radiation characteristics and numerical groundwater modeling is necessary when designing PV-powered systems without energy storage.

INTRODUCTION

Pump and treat (P&T) is one of the most commonly used technologies to remove and/or contain contaminated groundwater. Hydraulic containment of contaminants is accomplished by generating capture zones through pumping of groundwater. Therefore, an appropriate delineation of capture zones is necessary to design an effective P&T system. Capture zones are controlled by time and the site's hydrogeologic characteristics. Capture zone analyses are included in the designing phase of P&T systems to determine the appropriate number of extraction wells and the extraction rates to achieve hydraulic containment of contaminant plume.

P&T systems conventionally operate continuously to create steady-state capture zones, which requires significant amounts of energy. The United States (U.S.) Environmental Protection Agency (EPA) (2008a) suggests that the use of renewable energies to meet power demands of remedial systems and/or auxiliary equipment may reduce a project's demand on the environment during cleanup activities and maximize its net benefits. Additionally, it indicates that the use of renewable energies to power remedial systems provides significant opportunities at sites located in remote areas where extension of utility lines might be cost prohibited or infeasible due to difficult access.

The literature review revealed that site-specific solar insolation data to predict the performance of photovoltaic (PV)-powered P&T systems have been used. Collins et al. (2013) assessed the performance of a PV-powered P&T system without energy storage using the volume of extracted contaminated groundwater and, monthly predictions and measured values of solar insolation. However, characterization of the developed capture zone was not performed. Conroy et al. (2013) compared transient capture zones generated by a hypothetical PV-powered P&T system that included a relatively high capacity energy storage component. The study showed that capture zones generated by PV-powered systems that include a high capacity energy storage component can be 90 percent as effective as those generated by utility powered systems. Hydraulic containment equivalency of a PV-powered P&T system without energy storage using weekly average volumes of groundwater extracted and available daylight hours was characterized by Cortes Di Lena et al. (2013). The study showed that the capture zones generated from intermittent pumping due to the power inherent variability are less effective when compared to the capture zones generated by continuous pumping. Cortes Di Lena and Elmore (2013) analyzed the performance of a hypothetical P&T system that operates both intermittently by assuming that the system does not include an energy storage component and continuously by assuming that the system includes a relatively small capacity energy storage component using widely available Typical Meteorological Year 3 (TMY3) data. The study showed that the cost-benefit of increasing the capture zone widths and volume of extracted groundwater by increasing the rated flow rate is greater than by including a relatively small capacity energy storage component.

Javandel and Tsang (1986) presents an analytical approach to calculate capture zones based on a series of curves developed for steady-state flow and ideal conditions. While this approach is very useful, it cannot be applied for more complex flow fields under non-ideal conditions such as intermittent pumping. The study presented in this paper focuses on developing a methodology to estimate capture zone widths for PV-powered P&T systems without energy storage throughout the continental U.S. as a function of daily average solar insolation data, transmissivity, and hydraulic gradient. The study uses published hydrogeologic data for the Ogallala aquifer and solar irradiation characteristics at selected Typical Meteorological Year 2 (TMY2) stations to model capture zones developed by a hypothetical PV-powered P&T system. Maps depicting predicted capture zone widths as a function of the intermittent operation of the hypothetical system and specified transmissivity values and a hydraulic gradient are developed.

MODELED SITE

The Ogallala formation provided the hydrogeologic parameters for the model used to analyze the hypothetical PV-powered P&T system. The Ogallala is the principal geologic unit in the High Plains aquifer system, which is the primary source of groundwater in the High Plains region of the U.S. The High Plains aquifer system covers approximately 174,000 square miles extending through portions of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas (U.S. Geological Survey (USGS) 2013). The Ogallala formation consists of Neogene-age fluvial deposits derived from the Rocky Mountains overlain by Quaternary-age deposits and underlain by Permian, Triassic, and Cretaceous strata.

STATION SELECTION

The National Renewable Energy Laboratory (NREL) (2013) Annual Average Daily Solar Radiation per Month map, which shows the general trend of the amount of daily solar radiation per unit area received in the U.S. and the location of the 239 TMY2 stations, was used as the basis for station selection. Station selection was performed by overlying a 5 degree north-south by 10 degree east-west grid starting at latitude 40 degrees north and longitude 100 degrees west on the map and applying the following criteria:

- A minimum of three stations per solar insolation area were required.
- One station per grid square was selected as close to the center as possible.
- One station per solar radiation area was selected for grid squares covering more than one solar insolation area.
- Aerial coverage within each solar radiation area was required.

Figure 1 illustrates the designed grid overlaid on the Annual Average Solar Radiation per Month map and the application of the established criteria for site selection. A map showing the selected stations and the general trends of solar radiation received in the U.S. is presented in Figure 2.

DATA ANALYSIS

The hypothetical PV-powered P&T system includes a south-facing fixed PV array horizontally inclined at the latitude angle of each of the selected stations to power a SunPumps, Inc. DC submersible pump (model SCS 50-100) rated at 3.16 L/s (Q_r). Pump discharges (Q_y) for the selected stations were predicted as a function of daily average beam radiation on the tilted surface ($I_{bc,ave}$) and daily average PV cell temperature ($T_{c,ave}$).

Daily average solar radiation per unit area from the NREL program PVWATTS Version 2 and the available daylight hours were used to estimate $I_{bc,ave}$. PVWATTS is an internet accessible simulation tool that provides monthly and annual estimates of solar radiation, alternating current (AC), and cost savings for user-defined PV systems for any location in the U.S. using hourly TMY2 data. According to Marion and Urban (1995), TMY2 is a dataset of solar radiation and meteorological elements for one year period based on measurements from 1961 to 1990.

$T_{c,ave}$ were calculated using hourly estimates of PV cell temperature (T_c). Ambient temperature (T_A) TMY3 data for the selected stations were used to estimate T_c by applying the following equation from Cortes Di Lena and Elmore (2013), which is a simplification of Davis et al. (2001) equation to calculate cell temperature at any irradiance level and ambient temperature:

$$T_c - T_A = \mathrm{G} / \mathrm{G}_{NOCT} \times (\mathrm{NOCT} - \mathrm{T}_{A,NOCT}) \qquad (1)$$

where G = solar irradiance, NOCT is the normal operating cell temperature provided by the manufacturer, G_{NOCT} = 800 W/m^2, $T_{A,NOCT}$ = 20˚ C. Wilcox and Marion (2008) indicate that TMY3 datasets are an update and expansion of the TMY2 data to include measurements from 1991 to 2005.

Cortes Di Lena and Elmore (2013) developed equations to estimate Q_y as a function of I_{bc} and T_c for the same pump, make and model used in this study. Therefore, these equations were used to estimate Q_y for the selected stations. The estimated Q_y values were divided by Q_r to calculate normalized flow rates (Q_n). Normalizing Q_y allowed the assessment of other pump flow rates assuming that the performance is proportional to the base pump.

To predict the capture zones associated with the hypothetical PV-powered P&T system intermittent variable pumping schedules were developed for each of the selected stations. Flow rates (Q'_n) for the schedules were calculated by multiplying Q_n values by 3.16 L/s, which is the pump flow rate selected for this study. The developed pumping schedules were used as inputs to the numerical groundwater flow and pathline model to predict the capture zones width.

NUMERICAL MODEL

A numerical groundwater flow model was developed using the three-dimensional finite difference groundwater flow model Visual MODFLOW® Classic 2011.1 along with MODPATH 3 to generate capture zones for the intermittent pumping schedules.

MODPATH uses flow fields generated by MODFLOW to calculate the path lines and travel times of particles placed in the system. The model grid was built to provide a sufficiently large domain to eliminate the effects of boundary conditions. A 1,524 by 1,524 m model grid was created around the extraction well. The model grids were divided into 18 rows of 7.62 m in width and 91 rows of 15.2 m in width, and 24 columns of 7.62 m in width and 88 columns 15.2 m in width. The modeled aquifer, which consisted of a 57.2 m single layer, was designed to simulate unconfined flow of the Ogallala aquifer. The model aquifer thickness, which is within the range indicated in Nativ and Smith (1987), was selected to accommodate the pump parameters. The saturated thickness, specific yield, and recharge rate assigned to the model are the midpoints of the ranges indicated in Native and Smith (1987). The mean hydraulic gradient indicated in Nativ and Smith (1987) and the ratio of horizontal to vertical hydraulic conductivity (anisotropy ratio) indicated in Freeze and Cherry (1979) for unconsolidated alluvium were assigned to the model. Three hydraulic conductivity values, included in the range provided in Nativ and Smith (1987), were assigned to the numerical groundwater flow model. Two of the assigned values coincide with the midpoint (K_m) and upper limit (K_u) of the range. However, the third hydraulic conductivity value (K_l) does not coincide with the lower limit of the range. A higher hydraulic conductivity value was selected to allow a capture zone to be developed in the subject time period. A conceptual cross-section of the aquifer and the aquifer parameters is presented in Figure 3. Constant head boundaries were assigned perpendicular to regional groundwater flow. No flow was assigned to the other boundaries. To delineate the capture zone created by the P&T system, one hundred backward-tracking particles were added to the model. The particles were evenly spaced in a circle in the cell containing the P&T system extraction well. To accommodate the intermittent nature of the P&T system, MODFLOW was run in transient mode for the subject time period. It was assumed that the outermost pathlines defined the capture zone generated by the P&T system.

MAP DELINIATION

The widths of the generated capture zones for the selected stations were imported into ArcMap version 10.0. Latitude and longitude values of the selected stations were provided by the NREL program PVWATTS Version 2. Interpolation between the data points was performed using spline analysis. Spline analysis is a deterministic interpolation technique that assigns values to locations based on the surrounding values using a mathematical function that minimizes overall surface curvature (Esri 2013). Contour intervals in 2 m increments over the entire range of the data were developed for each map.

RESULTS

Modeling of the variable intermittent pumping schedules resulted in capture zones widths ranging from 19.9 to 47.2 m for the transmissivity value of 47.7 cm^2/s, 2.44 to 8.97 m for the transmissivity value of 159 cm^2/s, and 1.34 to 5.86 m for the transmissivity value of 311 cm^2/s.

Maps depicting the predicted capture zone widths when the hypothetical PV-powered P&T system is operated intermittently for the considered transmissivity values are presented in Figures 4, 5, and 6. The figures show that the areas with the widest predicted capture zone intervals tend to be located in the southern states of the U.S. where higher solar radiation values are perceived. Conversely, the areas with the narrower predicted capture zone intervals tend to be located in the northern states of the U.S. where lower solar radiation values are perceived.

Additional simulations using alternative pump flow rates (Q_i) and hydraulic gradients (i_i) were performed for several of the selected stations to assess the effect of these parameters on the capture zone widths. The results indicate that the capture zone widths are approximately directly proportional to the ratio between Q_i and 3.16 L/s and inversely proportional to the ratio between i_i and 0.003. Where 3.16 L/s and 0.003 are the pump flow rate and hydraulic gradient values used to generate the maps depicting the predicted capture zones. Therefore, the width of capture zones can be estimated using the maps depicting the predicted capture zone widths and applying the following equation:

$$W_i = W_m \times [(Q_i / 3.16 \text{ L/s}) / (i_i / 0.003)] \quad (2)$$

where W_i = capture zone width to be estimated and W_m = predicted capture zone width obtained from maps.

The developed methodology to estimate the width of capture zones generated by PV-powered P&T systems without energy storage throughout the continental U.S. involves the following steps:

1. Select the predicted capture zone map with the transmissivity value closest to the subject aquifer transmissivity.
2. Select the capture zone width range based on the subject site location.
3. Apply Equation (2) to estimate the width range of the capture zone.

APPLICATION

The developed methodology was applied to two actual sites where groundwater remediation has taken place to illustrate its potential use to estimate the width of capture zones generated by PV-powered systems without energy storage. The following discussions, which contain the data used to apply the methodology, are based on information provided by U.S. EPA (2008) and Elmore and DeAngelis (2004).

Milan Operable Unit 4 Region 1 (OU4) Site

The Milan OU4 site is located within the Milan Army Ammunition Plant (MAAP), which is a 91.1-square kilometer active military installation southeast of Milan in western Tennessee. The Milan OU4 site currently hosts two lines of extraction wells that operate continuously intended to provide hydraulic containment of an approximately 549 m wide RDX plume located within the Memphis aquifer. The Memphis aquifer consists of fine- to coarse- grained sand deposits overlain by alluvium and underlain by clay of the Flour Island Formation. A conceptual cross-section of the aquifer and the aquifer parameters is presented in Figure 7.

A capture zone evaluation was performed approximately one year after system startup and calculations to estimate the width of the capture zone developed by each line of extraction wells were performed. One "equivalent well" was used for each line of extraction wells and the capture zone width calculations were performed independently. Estimates of the capture zone widths were based on a transmissivity of 203 cm^2/s, i_i of 0.0012, and combined Q_i values of 35.1 and 36.6 L/s for the northern and southern lines of extraction wells, respectively. Therefore, the developed methodology was applied to the simplified version of two equivalent wells, one per line of extraction wells, using the previously indicated Q_i values and ignoring the potential interference between them.

1. The first step is to select the predicted capture zone map with the transmissivity value closest to the subject aquifer transmissivity. The map depicting predicted capture zone widths for a transmissivity of 159 cm^2/s (Figure 5) was selected.
2. The second step is to select the corresponding capture zone width range based on the site location. The selected map indicates that W_m ranges from 6 to 8 m.
3. The third step is to apply Equation (2) using Q_i and i_i. W_i ranges from 174 to 232 m.

To verify the results obtained from the developed methodology numerical groundwater modeling to characterize the capture zone generated by each of the equivalent wells was performed. The two intermittent variable pumping schedules used as input to the numerical groundwater flow and pathline model were developed as indicated in the Data Analysis section using $I_{bc,ave}$, T_A, and GHI data from the station located in Memphis, Tennessee to estimate Q_y and Q_n. Q_i values of 35.1 and 36.6 L/s were used to calculate Q'_n. The modeled aquifer was designed to simulate unconfined flow of the generalized stratigraphic column of the Milan OU4 site.

Modeling of the variable intermittent pumping schedules for the Milan OU4 site resulted in a capture zone 221 m in width for the equivalent well used for the northern line of extraction wells and 232 m in width for the equivalent well used for the southern line of extraction wells.

Former Nebraska Ordnance Plant (FNOP) site

The FNOP is a 69.8-square kilometer site located near Mead, Nebraska. Two predominant contaminants have been characterized in the groundwater at the FNOP, trichloroethylene (TCE) and RDX. The FNOP site is located in unconsolidated Pleistocene glaciofluvial deposits consisting mostly of fine to medium sand and gravel overlain by loess and underlain by Cretaceous shales and sandstones. A conceptual cross-section of the aquifer and the aquifer parameters is presented in Figure 8. The site hosts a variety of groundwater remediation systems including a groundwater circulation well (GCW) that operates continuously at a Q_i of 3.16 L/s used to remove and treat groundwater contaminated by TCE.

The developed methodology was applied to the GCW assuming a one layer aquifer with a transmissivity of 86.6 cm^2/s. The assigned transmissivity value was calculated by taking the geometric mean of the aquifer two main layers and multiplying it by the saturated thickness.

1. The first step is to select the predicted capture zone map with the transmissivity value closest to the subject aquifer transmissivity. The map depicting predicted capture zone widths for a transmissivity of 47.7 cm^2/s (Figure 4) was selected.
2. The second step is to select the corresponding capture zone width range based on the site location. The selected map indicates that W_m ranges from 32 to 34 m.
3. The third step is to apply Equation (2) using Q_i and i_i. W_i ranges from 38.4 to 40.8 m.

To verify the results obtained from the developed methodology numerical groundwater modeling to characterize the capture zone generated by GCW was performed. The intermittent variable pumping schedule used as input to the numerical groundwater flow and pathline model was developed as indicated in the Data Analysis section using $I_{bc,ave}$, T_A, and GHI data from the station located in Omaha, Nebraska to estimate Q_y and Q_n. A Q_i of 3.16 L/s was used to calculate Q'_n. The modeled aquifer was designed to simulate unconfined flow of the stratigraphic column of the FNOP site as presented in Figure 8.

Modeling of the variable intermittent pumping schedule for the FNOP site resulted in a capture zone 44.1 m in width.

CONCLUSIONS

The work presented in this paper demonstrates that daily average values of solar insolation that are readily available can be used to develop pumping schedules for PV-powered P&T systems without energy storage components. Wider capture zones are developed at locations where higher solar radiation values are perceived. The methodology presented in this study to estimate the widths of capture zones developed by PV-powered P&T systems without energy storage can be used to assess the feasibility of such systems anywhere within the continental U.S. or as a point of departure for more detailed studies. Site-specific detailed analysis of the hydrogeologic and solar radiation characteristics and numerical groundwater modeling is necessary when designing PV-powered systems without energy storage.

REFERENCES

Collins, E., Elmore, A. C., and Crow, M. (2013). "Using conditional probability to predict solar-powered pump-and-treat performance." *Journal of Hazardous, Toxic, and Radioactive Waste*, 17(1), 31-37.

Conroy, J. P., Elmore, A. C., and Crow, M. (2013). "Capture zone comparison for photovoltaic microgrid-powered pump and treat remediation." *Journal of Hazardous, Toxic, and Radioactive Waste*, in press.

Cortes Di Lena, Y., Elmore, A. C., and Conroy, J. (2013). "Effectiveness of capture zones generated by intermittent pumping of a PV-powered pump-and-treat system without energy storage." *Remediation*, 23(3), 111-122.

Cortes Di Lena, Y., and Elmore, A. C. (2013). "Performance evaluation of PV-powered pump and treat systems using typical meteorological year 3 data." *Journal of Hazardous, Toxic, and Radioactive Waste*, in press.

Davis, M. W., Dougherty, B. P., and Fanney, A. H. (2001). "Prediction of building integrated photovoltaic cell temperatures." *Journal of Solar Energy Engineering*, 123(3), 200-210.

Elmore, A. C., and DeAngelis, L. (2004). "Modeling a ground water circulation well alternative." *Ground Water Monitoring & Remediation*, 24(1), 66-73.

Esri (2013). "GIS dictionary." *Support*, <http://support.esri.com/en/knowledgebase/Gisdictionary/browse> (Dec. 5, 2013).

Freeze A., and Cherry, J.A. (1979). Groundwater, Prentice- Hall, Englewood Cliffs, NJ.

Javandel, I., and Tsang, C. (1986). "Capture-zone type curves: a tool to aquifer cleanup." *Ground Water*, 24(5), 616-625.

Marion, W., and Urban, K. (1995). *User's Manual for TMY2s*, National Renewable Energy Laboratory, Golden, CO.

National Renewable Energy Laboratory (NREL) (2013). "U.S. solar radiation resource maps: atlas of the solar radiation data manual for flat-plate and concentrating collectors." *National solar radiation data base 1961-1990*, <http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/> (Aug. 26, 2013).

Nativ, R. and Smith, D. A. (1987). "Hydrogeology and geochemistry of the Ogallala aquifer, southern High Plains." *Journal of Hydrology*, 91 (3-4), 217-253.

U.S. Environmental Protection Agency (EPA) (2008). *A systematic approach for evaluation of capture zones at pump and treat systems. Final project report*, Office of Research and Development, Cincinnati, OH.

U.S. EPA (2008a). *Green remediation: incorporating sustainable environmental practices into remediation of contaminated sites*, Office of Solid Waste and Emergency Response, Washington, DC.

U.S. Geological Survey (USGS) (2013). "Study area setting." *National water-quality assessment (NAWQA) program – High Plains regional groundwater (HPGW) study*, <http://co.water.usgs.gov/nawqa/hpgw/html/SETT.html> (Dec. 6, 2013).

Wilcox, S., and Marion, W. (2008). *Users Manual for TMY3 Data Sets*, National Renewable Energy Laboratory, Golden, CO.

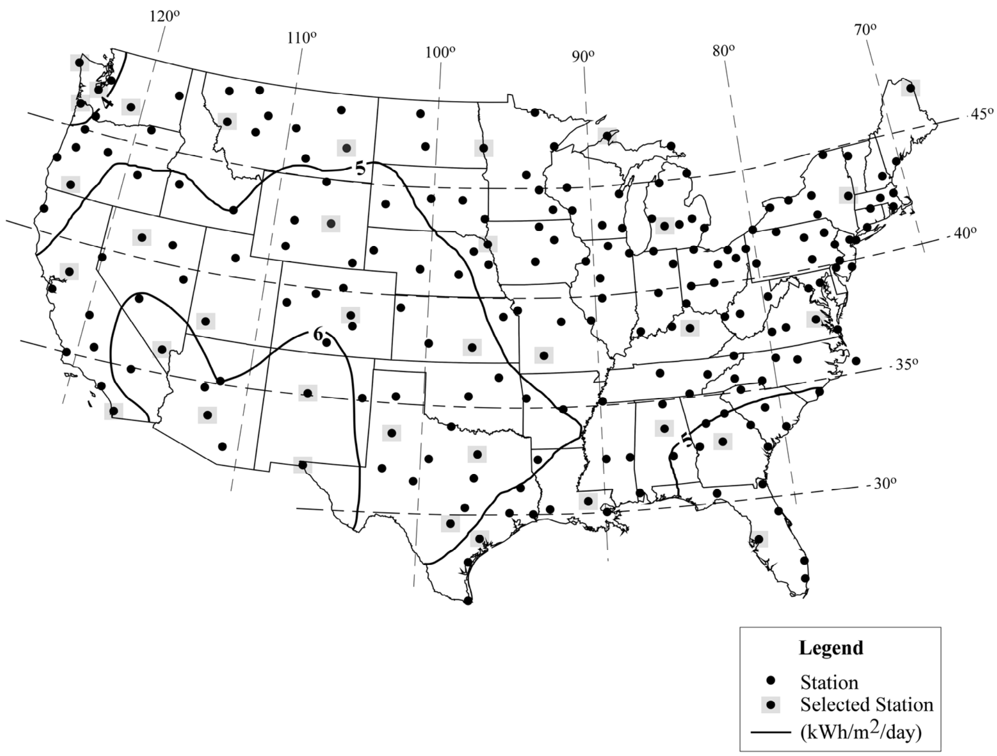

Figure 1. Design grid and Annual Average Solar Radiation per Month map (after NREL 2013).

Figure 2. Selected stations and general trend of solar radiation (after NREL 2013).

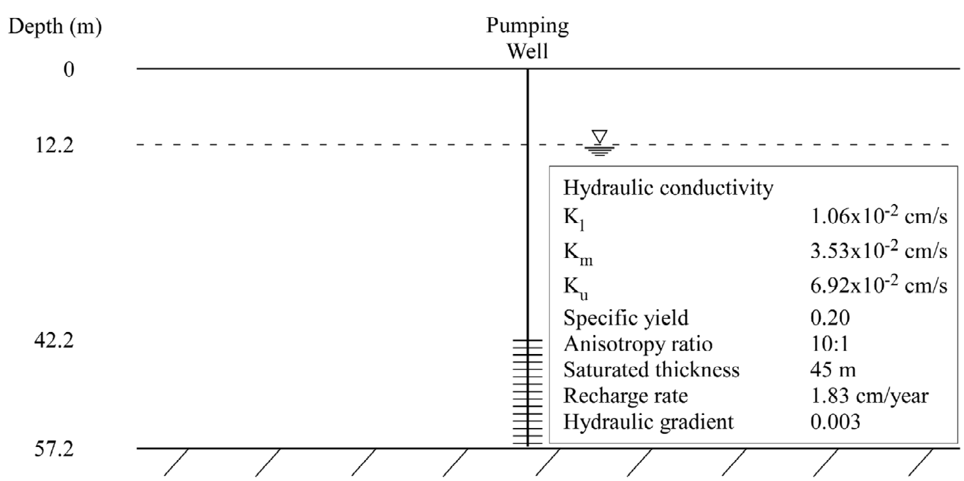

Figure 3. Conceptual cross-section of the aquifer geometry.

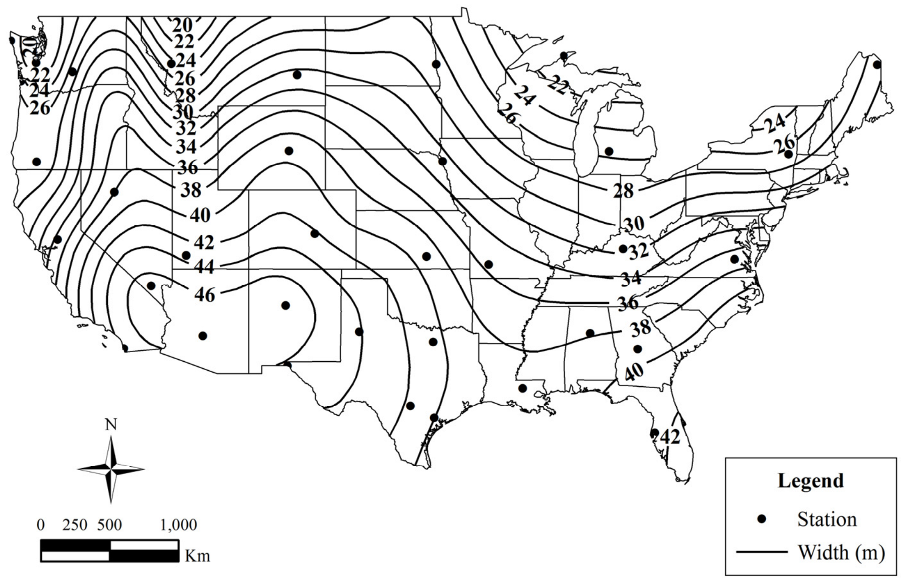

Figure 4. Predicted capture zone widths – Transmissivity = 47.7 cm^2/s.

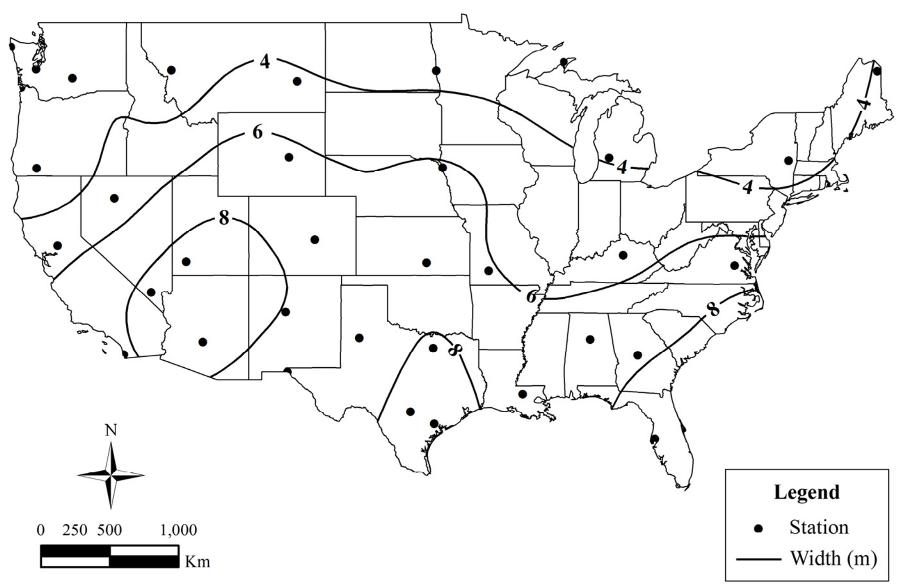

Figure 5. Predicted capture zone widths – Transmissivity = 159 cm^2/s.

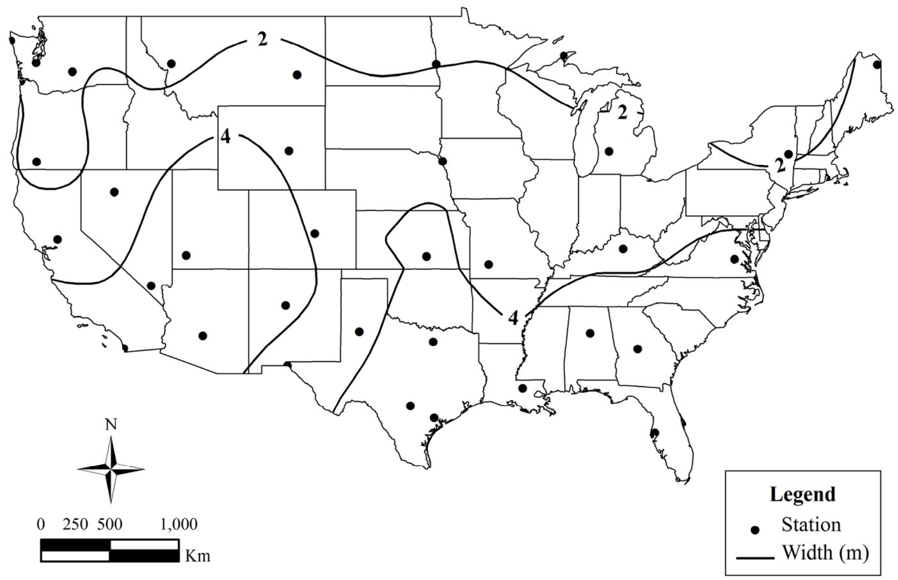

Figure 6. Predicted capture zone widths - Transmissivity = 311 cm^2/s.

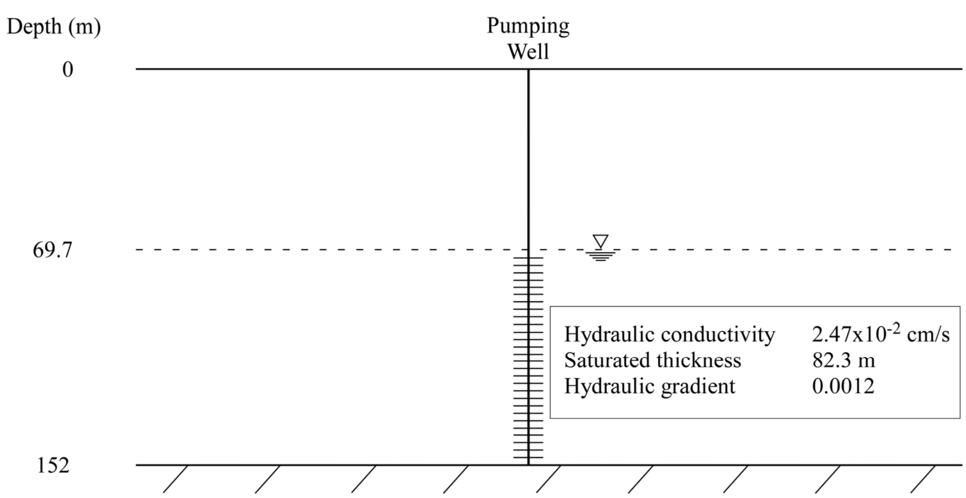

Figure 7. Conceptual cross-section of the Milan OU4 aquifer geometry.

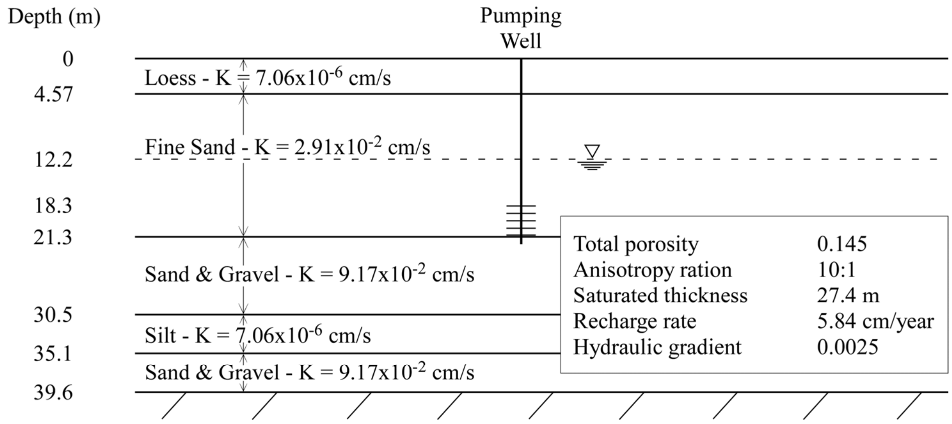

Figure 8. Conceptual cross-section of the FNOP aquifer geometry.

SECTION

2. CONCLUSIONS

Smaller and, therefore, less effective, capture zones will be generated from intermittent pumping due to the inherent variability of solar power when compared to continuous pumping. Values of solar insolation and ambient temperature that are widely available can be used to develop pumping schedules for PV-powered P&T systems with and without energy storage components. As with continuously operated P&T systems, which generate steady state capture zones, modeling of intermittent pumping schedules can be used when designing P&T systems to ensure the desired hydraulic containment is being achieved. Modeling of intermittent pumping schedules could also provide a potentially effective method of reducing non-renewable energy costs and the associated carbon footprint, by allowing prediction of the required pumping frequency and duration to meet a given capture zone.

The width of the capture zones generated, and volumes of groundwater extracted by a PV-powered P&T system can be increased by increasing the pump size and/or having the pump operate continuously by establishing a threshold flow rate at which the pump will be operated using stored energy when incident solar insolation is not available. However, it is more cost effective to increase the pump rating than to add a relatively small energy storage component.

PV-powered P&T system performance, without or with limited capacity energy storage, is conditioned to site-specific hydrologic and seasonal characteristics. The presented methodologies can be used to assess the feasibility of such systems or as a point of departure for more detailed studies.

2.1 ORIGINAL CONTRIBUTION

The research presented in this dissertation analyzed the performance of P&T systems that operate intermittently due to the inherent variability of solar energy as the power source using two metrics: capture zone width and volume of groundwater extracted. Some of the original aspects of this research included:

- Consideration PV-powered P&T system that operates intermittently with variable flow rates when solar radiation is available by assuming that the system does not include energy storage (no batteries).
- Consideration PV-powered P&T system that operates continuously with variable flow rates by assuming that the system includes a relatively small capacity energy storage component (limited batteries) that could provide sufficient power for a specific minimum flow rate when solar insolation is not available.
- Characterization of the hydraulic containment effectiveness of a PV-powered P&T system without energy storage for a site using real data collected at two different remediation sites.
- Development of a new variable to define hydraulic containment effectiveness of PV-powered P&T systems without energy storage.
- Development of a methodology to estimate the effectiveness of the hydraulic containment of PV-powered P&T systems without energy storage as a function of total volume of groundwater expected to be extracted.

- Development of equations to estimate pump discharges of PV-powered P&T systems without and with a relatively small capacity energy storage component as a function of solar radiation and PV cell temperature.
- Use of hourly values of solar insolation and ambient temperature that are widely available to develop pumping schedules for PV-powered P&T systems without and with a relatively small capacity energy storage component.
- Evaluation of the effect of seasonality on the performance of the PV-powered P&T systems without and with a relatively small capacity energy storage system.
- Comparison of the approximate costs when the rated flow rate of a PV-powered P&T system without energy storage is increased and when a relatively small capacity energy storage component is included.
- Analysis of the variability of the capture zones generated by PV-powered P&T systems without and with a relatively small capacity energy storage system.
- Assessment of the relationship between the PV-powered P&T system without and with a relatively small capacity energy storage component time of operation and, generated capture zone width and estimated volume of extracted groundwater.
- Use of daily average values of solar insolation that are widely available to develop pumping schedules for PV-powered P&T systems without energy storage.
- Development of maps for the continental U.S. depicting predicted capture zone widths for a PV-powered P&T system without energy storage as a function of solar insolation for specified transmissivity values and a hydraulic gradient.

- Development of a feasibility-level methodology to estimate the width of capture zones generated by PV-powered P&T systems without energy storage using maps depicting the predicted capture zone widths for the continental U.S., transmissivity, and hydraulic gradient.

To date, the original contribution of this research has been recognized by the scientific community as the following two papers were published by peer reviewed journals:

- Effectiveness of Capture Zones generated by Intermittent Pumping of a PV-Powered Pump-and-Treat System Without Energy Storage
- Performance Evaluation of PV-Powered Pump and Treat Systems Using Typical Meteorological Year 3 Data

The third paper, General Method for Predicting Capture Zone Widths for PV-Powered Pump and Treat Systems Using PVWATTS and Basic Hydrogeologic Data, is currently under peer review.

2.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The research conducted in this dissertation has led to some useful results and conclusions that can be the basis for further research. The following recommendations for future research are suggested:

- Compare the width of capture zones generated by PV-powered P&T systems using hourly and monthly averages of solar radiation.

- Assess the effect that the intermittent operation with variable flow rates of PV-powered P&T systems have on contaminant transport.
- Broaden the applicability of the developed methodology to estimate the width of capture zones generated by PV-powered P&T systems without energy storage by developing worldwide maps depicting the predicted capture zone widths.
- Assess the effect of the on/off cycles of PV-powered P&T systems without energy storage on the expansion/contraction of capture zones.
- Perform a stochastic analysis using Monte Carlo simulation to estimate the uncertainty associated with the width of capture zones generated by the intermittent operation of PV-powered P&T systems.
- Perform field assessments of the performance of PV-powered P&T systems without and with a relatively small capacity energy storage component.

BIBLIOGRAPHY

Aksoy, A., and Culver, T. (2004). "Comparison of continuous and pulsed pump-and-treat for mass transfer-limited aquifers." *Turkish Journal of Engineering and Environmental Science*, 28(5), 307-3016.

Chandrasekaran, N., and Thyagarajah, K. (2011). "Modeling and MATLAB simulation of pumping system using PMDC motor powered by solar system." *European Journal of Scientific Research*, 59(1), 6-13.

Collins, E., Elmore, A. C., and Crow, M. (2013). "Using conditional probability to predict solar-powered pump-and-treat performance." *Journal of Hazardous, Toxic, and radioactive Waste*, 17(1), 31-37.

Conroy, J. P., Elmore, A. C., and Crow, M. (2013). "Capture zone comparison for photovoltaic microgrid-powered pump and treat remediation." *Journal of Hazardous, Toxic, and Radioactive Waste*, in press.

Cortes Di Lena, Y., Elmore, A.C., and Conroy, J. (2013). "Effectiveness of capture zones generated by intermittent pumping of a PV-powered pump-and-treat system without energy storage." *Remediation*, 23(3), 111-122.

Cortes Di Lena, Y., and Elmore, A. C. (2013). "Performance evaluation of PV-powered pump and treat systems using typical meteorological year 3 data." *Journal of Hazardous, Toxic, and Radioactive Waste*, in press.

Davis, M. W., Dougherty, B., and Faney, A. H. (2001). "Prediction of building integrated photovoltaic cell temperatures." *Journal of Solar Engineering*, 123(3), 200-210.

Dellens, A. D. (2007). *Green remediation and the use of renewable energy sources for remediation projects*, U.S. Environmental Protection Agency office of Solid Waste and Emergency Response, office of Superfund Remediation and Technology Innovation, Washington, D.C.

Elmore, A. C., and DeAngelis, L. (2004). "Modeling a ground water circulation well alternative." *Ground Water Monitoring & Remediation*, 24(1), 66-73.

Elmore, A. C., and Graff, T. (2002). "Best available treatment technologies applied to groundwater circulation well." *Remediation*, 12(3), 63-80.

Esri (2013). "GIS dictionary." *Support*, <http://support.esri.com/en/knowledgebase/Gisdictionary/browse> (Dec. 5, 2013).

Fetter, C. W. (2001). "Properties of aquifers." *Applied hydrogeology*, 4th ed., Prentice-Hall, Upper Saddle River, NJ, 66-112.

Freeze, A., and Cherry, J.A. (1979). *Groundwater*, Prentice- Hall, Englewood Cliffs, NJ.

Goswami, D. Y., Kreith, F., and Kreider, J. F. (2000). "Fundamentals of solar radiation." *Principles of solar engineering*, 2nd ed., Taylor & Francis Group, New York, NY, 13-80.

Javandel, I., and Tsang, C. (1986). "Capture-zone type curves: a tool to aquifer cleanup." *Ground Water*, 24(5), 616-625.

Keely, J. F. (1989). *Performance evaluations of pump-and-treat remediations*, U.S. Environmental Protection Agency, Robert S., Kerr Environmental Research Laboratory, Ada. OK.

Liu, W., Medina, M. A., Thomann, W., Piver, W. T., and Jacobs, T. L. (2000). "Optimization of intermittent pumping schedules for aquifer remediation using a genetic algorithm." *Journal of the American Water Resources Association*, 36(6), 1335-1348.

Mackay, D. M., Wilson, R. D., Brown, M. J., Ball, W. P., Xia, G., and Durfee, D. P. (2000). "A controlled field evaluation of continuous vs. pulsed pump-and-treat remediation of a VOC-contaminated aquifer: site characterization, experimental setup, and overview of results." *Journal of Contaminant Hydrology*, 41(1-2), 81-131.

Marion, W., and Urban, K. (1995). *User's Manual for TMY2s*, National Renewable Energy Laboratory, Golden, CO.

Miller, G. R., and Elmore, A. C. (2005). "Modeling of a groundwater circulation well removal action alternative." *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 9(2), 122-129.

National Renewable Energy Laboratory (NREL) (2013). "U.S. solar radiation resource maps: atlas of the solar radiation data manual for flat-plate and concentrating collectors." *National solar radiation data base 1961-1990*, <http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/> (Aug. 26, 2013).

Nativ, R., and Smith, D. A. (1987). "Hydrogeology and geochemistry of the Ogallala aquifer, southern High Plains." *Journal of Hydrology*, 91(3-4), 217-253.

Pollock, D. W. (1994). *User's guide for MODPATH/MODPATH-PLOT, version 3: A particle tracking post-processing package for MODFLOW, the U. S. Geological Survey finite-difference ground-water flow model*, U.S. Geological Survey, Reston, VA.

Skoplaki, E., and Palyvos, J. A. (2009). "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations." *Solar Energy*, 83(5), 614-624.

U.S. Environmental Protection Agency (EPA) (1996). *Pump-and-treat ground-water remediation: a guide for decision makers and practitioners*, office of Research and Development, Washington, D.C.

U.S. EPA (2008). *A systematic approach for evaluation of capture zones at pump and treat system. Final Report*, office of Research and Development, Cincinnati, OH.

U.S. EPA (2008a). *Green remediation: incorporating sustainable environmental practices into remediation of contaminated sites*, office of Solid Waste and Emergency Response, Washington, D.C.

U.S. Geological Survey (USGS) (2013). "Study area setting." *National water-quality assessment (NAWQA) program – High Plains regional groundwater (HPGW) study*, <http://co.water.usgs.gov/nawqa/hpgw/html/SETT.html> (Dec. 6, 2013).

Wilcox, S. and Marion, W. (2008). *Users Manual for TMY3 Data Sets*, National Renewable Energy Laboratory, Golden, CO.

VITA

Yovanna Cortes Di Lena obtained her B.S. and M.S. in Geological Engineering from the University of Missouri-Rolla (currently Missouri University of Science and Technology) in 2000 and 2001, respectively. She obtained her Ph.D. in Geological Engineering from the Missouri University of Science and Technology in May 2014.

Ms. Cortes Di Lena has over seven years of experience performing environmental and geotechnical assessments with consulting companies located in St. Louis, Missouri and Phoenix, Arizona. Prior work experience included approximately 1.5 years as the department manager for environmental services for Professional Service Industries, Inc. in Tempe, Arizona. She was also employed for approximately 5 years as a project manager with GeoTek Insite, Inc. in Scottsdale, Arizona.

Ms. Cortes Di Lena is a member of the American Society of Civil Engineers, Society of Women Engineers, and Society of Hispanic Professional Engineers. She is an Engineer in Training and 40-Hour Hazardous Waste Operations and Emergency Response certified.