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August 23, 2017

Ms. Carlotta Stauffer, Commission Clerk
Florida Public Service Commission
2540 Shumard Oak Boulevard
Tallahassee, Florida 32399-0850

Re: Docket No. 20170007-EI

Dear Ms. Stauffer,

Please find enclosed for filing in the above referenced docket the Direct Testimony and Exhibits of **Sorab Panday**. This filing is being made via the Florida Public Service Commission's Web Based Electronic Filing portal.

If you have any questions or concerns; please do not hesitate to contact me. Thank you for your assistance in this matter.

Sincerely,

Stephanie A. Morse
Associate Public Counsel

cc: All Parties of Record

BEFORE THE FLORIDA PUBLIC SERVICE COMMISSION

In Re: Environmental Cost Recovery Clause.	)))	DOCKET NO. 20170007-EI FILED: August 23, 2017

DIRECT TESTIMONY AND EXHIBITS

OF

SORAB PANDAY

ON BEHALF OF THE CITIZENS OF THE STATE OF FLORIDA

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DIRECT TESTIMONY

OF

SORAB PANDAY

On Behalf of the Office of Public Counsel

Before the

Florida Public Service commission

Docket No. 20170007-EI

I. INTRODUCTION

Q. **PLEASE STATE YOUR NAME AND BUSINESS ADDRESS.**

A. My name is Sorab Panday. My office address is GSI Environmental Inc., 626 Grant Street, Suite C., Herndon, VA 20170.

Q. WHAT IS YOUR OCCUPATION?

A. I am a Principal at GSI Environmental. I am a hydrogeologist and an expert in groundwater modeling.

Q. **ON WHOSE BEHALF ARE YOU APPEARING IN THIS PROCEEDING?**

A. I am appearing in this proceeding on behalf of Florida Office of Public Counsel.

Q. PLEASE DESCRIBE YOUR EDUCATIONAL BACKGROUND AND EXPERIENCE.

A. I earned a Ph.D. in Civil and Environmental Engineering in 1989. During my 28 years of experience, my clients have included numerous private companies and government agencies such as the U.S. Environmental Protection Agency, the U.S. Department of Defense, and the Southwest Florida Water Management District. I am the lead author of the MODFLOW-USG code, released by the U.S. Geological Survey (USGS) in 2013. Additionally, I was elected as a member of the National Academy of Engineering. More details of my educational background and experience are summarized in Exhibit SP-1 of my testimony.

Q. PLEASE ELABORATE ON YOUR EXPERIENCE WITH RESPECT TO HYDROGEOLOGY, CONTAMINANT TRANSPORT MODELING, AND REMEDIATION ANALYSES.

A. My career has been devoted to analyses of groundwater flow, contaminant transport, and numerical modeling. I have evaluated issues of water supply, contaminant transport, remediation, saltwater intrusion, and surface-water/groundwater interaction among other subsurface flow and transport analyses. This information is detailed in my resume which is included in Exhibit SP-1 of my testimony.

Q. PLEASE IDENTIFY SOME OF THE CASES IN WHICH YOU PROVIDED TESTIMONY OR ANALYSIS WITH RESPECT TO HYDROGEOLOGY, SALTWATER INTRUSION ANALYSES, GROUNDWATER FLOW ANALYSES, CONTAMINANT TRANSPORT MODELING AND REMEDIATION ANALYSES.

A. I have provided testimony in the following cases: *State of Florida v. State of Georgia*, No. 142, Original, Supreme Court of the United States, Docket No. 220142; *Tilot Oil, LLC v. BP Products North America, Inc.*, U.S. Eastern District of Wisconsin, Case No. 09-CV-0210; and *Santa Maria Valley Water Conservation District v. City of Santa Maria, et al.*, Santa Clara County Superior Court Case No. 1-97-CV-770214. This information is detailed in my resume which is included in Exhibit SP-1 of my testimony.

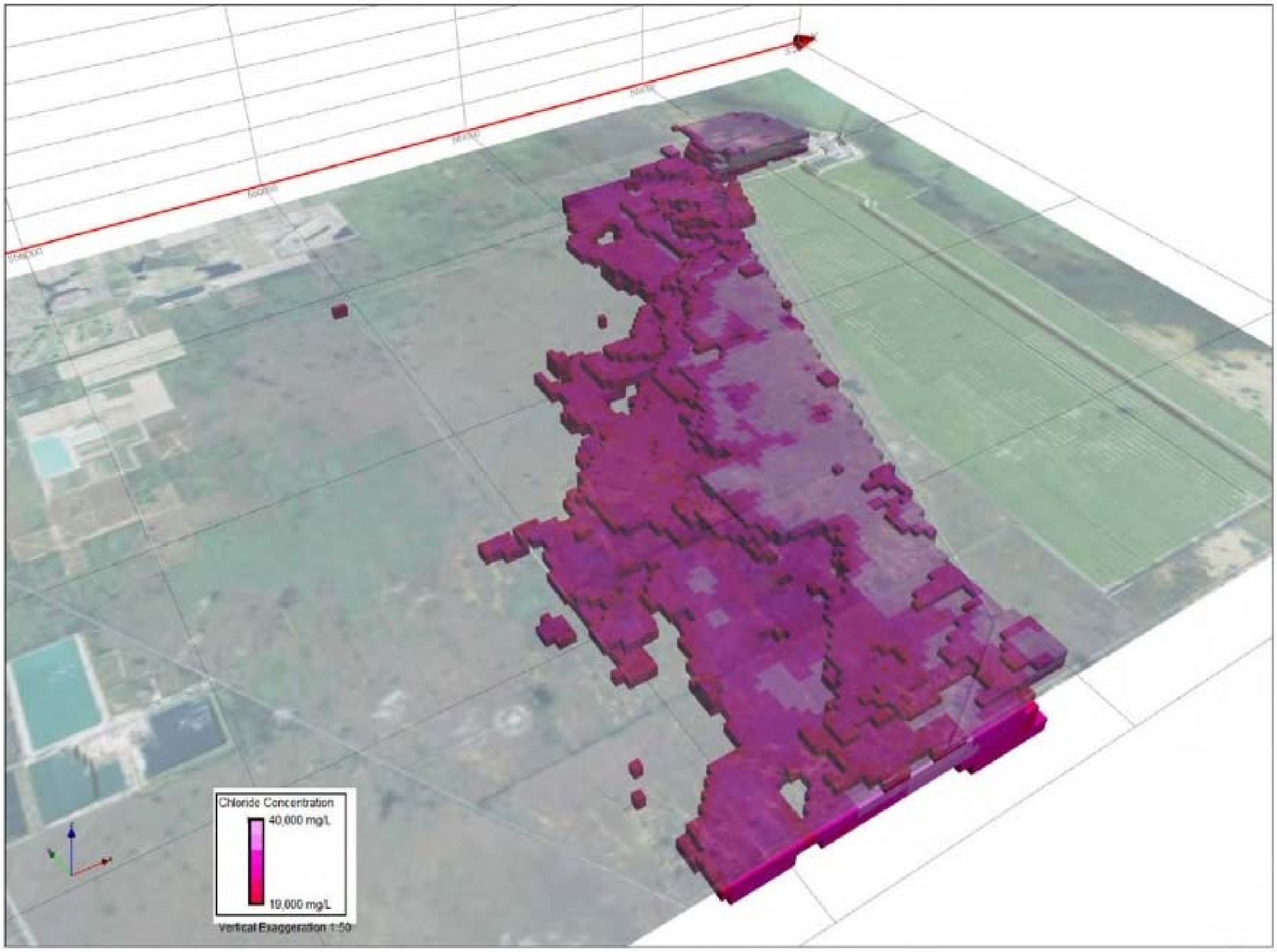
Q. ARE YOU OFFERED AS AN EXPERT IN THIS PROCEEDING?

A. Yes, I am testifying as an expert in hydrogeologic analysis and modeling.

Q. PLEASE DESCRIBE GENERALLY THE ISSUE(S) THAT YOUR TESTIMONY ADDRESSES.

A. Florida Power and Light Company ("FPL") has agreed to implement a process to try to retract a saltwater plume that moved from underneath its Turkey Point Nuclear Generating Plant Cooling Canal System ("CCS") to a location several miles westward. The following is a graphic representation of chloride concentrations greater than seawater, from a study performed for FPL.[1]

[1] Enercon, 2016 Enceron 2016; Exhibit SP-3, Demonstrative 14b. References to studies and data are listed in Exhibit SP-2, Table 1 (Master List).



It is discussed later in my testimony, but I have included it here as a clear representation of the current (or very recent) extent of saltwater intrusion that has been growing since the CCS has been in operation. I discuss later in my testimony (1) the long-standing body of evidence of the growth of this saltwater and hypersaline plume, (2) FPL's proposed method of trying to address it, (3) the effectiveness of the proposal to remedy the condition, and (4) an allocation percentage for cost recovery. The ultimate issue of concern is whether the ratepayers are being charged appropriately for actions being taken now, or that were taken in the past, by FPL to manage the CCS and underlying aquifer.

Q. **WHAT IS THE PURPOSE OF YOUR TESTIMONY HEREIN?**

A. The purpose of my testimony is to evaluate past actions and proposed remedial solutions by FPL and its contractors regarding the intrusion of saltwater into the Biscayne Aquifer as a result of the CCS. Specifically, I first present testimony regarding the extent to which the hypersaline plume in the Biscayne Aquifer which originated from the CCS was the result of FPL's hydrogeologic decisions associated with groundwater and the CCS.

I also evaluate the proposal by Florida Power & Light (FPL) to conduct hydrogeologic projects termed Alternative 3D, proposed by FPL to correct FPL's violations of groundwater standards and environmental regulations. The proposal consists of a project for freshening the CCS to seawater conditions using 14 million gallons per day ("MGD") of Floridan Aquifer water, and another project for construction of a system of wells to retract the hypersaline plume in the Biscayne Aquifer which has migrated from the CCS. I have evaluated the feasibility and projected efficacy of each of these proposals.

Finally, I have also evaluated FPL's proposed allocation of costs for the system of retraction wells between retraction and containment of the hypersaline water within the boundaries of the CCS.

The fact that I do not address any other particular issue or aspect of the salinity caused by the CCS in my testimony, or that I am silent with respect to any portion of FPL's direct testimony in this proceeding, should not be interpreted as an approval of any position taken by FPL in its direct testimony or the projects discussed in this matter.

I have based my analyses and recommendations on the information that FPL has provided in discovery.

Q. PLEASE DESCRIBE WHAT YOU REVIEWED AND ANALYZED IN PREPARING YOUR DIRECT TESTIMONY.

A. I have reviewed the documents referenced in this testimony, including those listed in Exhibit SP-2, Tables 1-4. I have also reviewed the model files for the following models developed on behalf of FPL: the three-dimensional density-dependent flow and saltwater transport SEAWAT models described by Tetra Tech[2] and the transient CCS spreadsheet model described by GeoTrans and Tetra Tech[3] . I have also conducted an analysis of the impact of the proposed retraction wells by performing my own simulations with the SEAWAT model, and conducted analysis using a steady-state spreadsheet model of the CCS for different cases. Some of these documents and model files were produced by FPL in discovery. While I have also reviewed other production by FPL in discovery, I have only referenced in my testimony those documents that I have expressly relied upon in preparing my testimony.

Q. PLEASE SUMMARIZE YOUR CONCLUSIONS.

A. My evaluation of the documents produced by FPL related to salinity in the Biscayne Aquifer indicates that FPL should have known about the salinity intrusion that resulted due to the presence of the CCS at least by 1992. There were other indications as well, in monitoring reports through 2013, that salinity and hypersalinity

[2] Tetra Tech, 2016c, 2016f, 2016m.
[3] GeoTrans, 2010a, 2010b Appendix E and Tetra Tech, 2014a.

in the Biscayne Aquifer was increasing as a result of the CCS. In addition, my evaluation of the modeling efforts by FPL's contractors regarding Remedial Alternative 3D indicates that the pumping wells are ineffective in retracting the hypersaline plume. Finally, my evaluation of the simulations conducted to apportion costs for these remediation wells between hypersaline plume retraction and containment indicates that the apportioning proposed by FPL was incorrect.

Q. WHAT IS AN AQUIFER AND WHY IS IT IMPORTANT?

A. An aquifer is the permeable rock under the ground that can contain and transmit groundwater. Groundwater enters the ground by a process called recharge. Recharge occurs as a result of precipitation seeping into the soil. Groundwater leaves the subsurface by a process called discharge. Water in aquifers discharges into water wells and surface water bodies (e.g., rivers, canals, bays or the ocean), or is lost to evapotranspiration or deeper aquifers. Aquifers are a significant source of freshwater and one of the most important natural resources of Florida.

Q. WHAT IS SALINITY AND HOW IS IT DEFINED?

A. Salinity is the mass of dissolved salts per mass of solution. Salinity of seawater is approximately 34 ppt (parts per thousand or PSUs or ‰). Salinity is also sometimes expressed in terms of a chloride concentration or chlorinity. Seawater has a chlorinity of approximately 19 ppt (or 19,000 mg/L)[4]. "Brackish" water has a salinity that is below the salinity level of seawater, while "hypersaline" is the generalized

[4] Miami Dade County, 2015b.

classification of water that has a salinity level above that of seawater. Generally, saltwater and saline water are generic terms that mean water containing any amount of salt. The drinking water standard for chlorides is 250 mg/L, above which water tastes salty. The drinking water standard for Total Dissolved Solids (TDS) is 500 mg/L (0.5 ppt or PSU). It is not safe for humans to drink water containing a chloride concentration greater than the drinking water standard (i.e., TDS greater than 0.5 PSU).

Q. WHAT IS SALTWATER INTRUSION INTO AN AQUIFER AND HOW DOES IT OCCUR?

A. Saltwater intrusion occurs when saline water moves into freshwater aquifers. It occurs naturally in most coastal aquifers due to the hydraulic connection between groundwater and seawater, as a result of the higher density of saline water as compared to freshwater. The heavier saline water sinks to the bottom of the aquifer in offshore regions and forms a wedge of saltwater that intrudes landward. Saltwater intrusion can be further exacerbated by anthropogenic or (human-caused) factors such as groundwater withdrawals further inland, or engineered structures such as the CCS. Hypersaline water is even heavier than seawater which will cause a wedge to intrude even further landward. Saltwater intrusion erodes the natural resource within an aquifer and it is a process that can be costly and slow to reverse.

<u>II. EVIDENCE REGARDING THE HISTORY OF WATER FLOW AND SALINITY IN AND AROUND THE CCS</u>

Q. TO YOUR KNOWLEDGE, WHAT DATA AND STUDIES HAVE BEEN AVAILABLE REGARDING SALINITY WITHIN THE CCS AND ITS EFFECT ON GROUNDWATER AND THE BISCAYNE AQUIFER SINCE THE TIME FPL BEGAN USING THE CCS?

A. Data and studies dating from 1978 to 2017 regarding salinity within the CCS are listed in Exhibit SP-2, Table 1.

Q. TO YOUR KNOWLEDGE, WHAT ANALYSES WERE CONDUCTED BY OR ON BEHALF OF FPL SINCE 1978 TO EVALUATE SALTWATER MIGRATION IN THE BISCAYNE AQUIFER AND THE IMPACT OF HYPERSALINE WATER FROM THE CCS?

A. Analyses conducted by or on behalf of FPL since 1978, as disclosed by FPL in response to discovery, are listed in Exhibit SP-2, Table 2.

Q. TO YOUR KNOWLEDGE, WHAT ANALYSES HAVE BEEN AVAILABLE TO WHICH FPL HAD, OR SHOULD HAVE HAD, ACCESS (STUDIES BY OTHERS SUCH AS UNITED STATES GEOLOGICAL SURVEY, ET AL.)

A. Analyses available to FPL as disclosed in response to discovery, are listed in Exhibit SP-2, Table 3.

Q. TO YOUR KNOWLEDGE, WERE ANY ANALYSES CONDUCTED BY OR ON BEHALF OF FPL TO MEASURE THE EFFECT, IF ANY, OF FPL'S EFFORTS TO REDUCE SALINITY IN THE CCS?

A. Analyses available to FPL, according to FPL's responses to discovery, are listed in Exhibit SP-2, Table 4, attached.

III. MIGRATION OF THE HYPERSALINE PLUME BEYOND THE GEOGRAPHIC BOUNDARIES OF THE CCS AND MOVEMENT OF THE SALINE INTERFACE AS A RESULT OF OPERATION OF THE CCS

Q. WHEN DOES FPL CLAIM TO HAVE BECOME AWARE THAT THE SALINE WATER FROM THE CCS CAUSED THE SALTWATER INTERFACE TO MOVE WESTWARD, AND WHEN DO YOU AS A HYDROGEOLOGIST BELIEVE THAT THEY SHOULD HAVE BEEN AWARE OF THIS?

A. FPL's response to OPC's First Set of Interrogatories, No. 14, suggests that 2013 was the first indication that salt concentrations were increasing through time in the Biscayne Aquifer west of the CCS, and that the saltwater plume was moving westward to the degree that FPL should have considered taking some action to mitigate the conditions.

However based on my expertise and review of the available studies and data, and contrary to FPL's suggestion, the 1978 salinity investigation and the 1990 and 1992 groundwater monitoring reports by Dames & Moore[5] sufficiently demonstrated a

[5]Dames & Moore, 1990, 1992.

significant salinity contribution from the CCS moving westward of L-31 (which is a levee that travels the length of and just west of the western edge of the CCS). As early as 1978 and at least by 1990 or 1992, FPL should have known that saline water from the CCS was intruding into groundwater outside of FPL's property. Subsequent groundwater monitoring reports made available by FPL for the period between 2003 and 2010[6] also contained salinity data that indicated the need to consider taking corrective action. The conclusions of these reports by FPL and its contractors, however, downplay the significance of such correction-suggestive data.

Q. ARE THERE OTHER INDICATORS THAT THE CCS WAS THE SOURCE OF THIS CONTRIBUTION TO THE SALINITY OF THE GROUNDWATER WEST OF THE CCS?

A. Yes. Tritium levels in groundwater also indicated increasing contributions of contaminated water from the CCS to the Biscayne Aquifer. The CCS' tritium fingerprint was identified in groundwater west of the CCS in the 1975 and 1976 data found in the 1978 Dames & Moore report.[7] The tritium markers in the 2011 and 2012 Uprate Project Semi-Annual and Annual Reports further evidenced a progression of CCS-contributed saltwater from the 1976 position to a point as far as 3 miles out in 2012.[8]

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[6] FPL, 2003, FPL, 2004, Golder, 2008c, 2008d, 2008e, 2008f, Golder, 2009, Golder, 2010

[7] Dames & Moore, 1978 [Figure 5.1]

[8] Ecology and Environment, 2011a, 2011b, 2012a showed increased tritium concentrations west of the CCS compared to 1978 Dames & Moore report conditions; the 2012 Initial Ecological Conditions report showed elevated tritium levels in groundwater locations to the west of L-31 (Ecology and Environment, 2012b); the 2012 Comprehensive Pre-Uprate report for the Units 3 and 4 Uprate Project (Ecology and Environment, 2012c, page 5-11, second paragraph and page 7-1, third bullet) reported that CCS water was in groundwater immediately to the west and extending 3 miles away.

Q. AFTER 2013, WHAT DID THE DATA TO WHICH FPL HAD ACCESS SHOW REGARDING THE WESTWARD MIGRATION OF CCS-INFLUENCED SALTWATER?

A. Studies conducted after 2013 show that saltwater from the CCS had migrated from the western boundary of the CCS westward by about 3,300 to 8,200 feet, at a depth of about 55 feet below ground surface. There was even evidence that before 2010, the saltwater boundary had moved to well G-28 and G-21, which are 3.3 and 4.1 miles due west of the CCS western boundary respectively.[9]

Q. GIVEN THE INFORMATION FROM 1975 AND 1976 THAT WAS CONTAINED IN THE 1978 REPORT WHAT DID FPL DO TO ADDRESS THE INFORMATION CONTAINED IN THAT REPORT?

It is unclear that FPL took any affirmative action in response to this report. The 1978 Dames & Moore report identified saltwater migrating west of the system as a result of the presence of the CCS. Specifically, the report indicated increasing concentrations of salinity west of L-31 directly attributable to saline water contribution from the CCS.[10] This is also indicated in plots of salinity through time, shown on Exhibit SP-3, Demonstrative 1. The report further identified salinity contours at different times, indicating a growing saltwater wedge west of the CCS, as noted on

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[9] 2014 Annual Post-Uprate report and 2016 Comprehensive Post-Uprate Report (Ecology and Environment, 2014, 2016b) which evaluated the western extents of hypersalinity in groundwater west of the CCS; the 2016 Enercon report which estimated that hypersaline groundwater extended from the margin of the CCS westward between 3,300 and 8,200 feet, at a depth of about 55 feet below ground surface (Enercon, 2016); and the 2016 Tetra Tech groundwater flow and transport model which reiterated that the freshwater-saltwater interface moved to well G-28 and G-21 prior to 2010 (Tetra Tech, 2016c).

[10] Dames & Moore, 1978, page 60.

Exhibit SP-3, Demonstrative 2. Further evidence of the CCS' role in the westward migration of saltwater was in the form of tritium found in groundwater west of the L-31 levee[11] and according to that 1978 report, "evidence that cooling canal water is found in the aquifer … a portion of the chloride increases is due to the mixing of the saline cooling canal waters with brackish ground waters."[12]

Dames and Moore also developed a conceptual model for the CCS' contribution to the saltwater wedge.[13] According to this conceptual model, CCS salinity increases as a result of evaporation. In addition to precipitation, freshening of the CCS naturally occurs as dense (saltier) water from the CCS sinks below the CCS and is replaced with less salty groundwater.[14] A key assumption in this conceptualization is that the exchange between the saline CCS waters and groundwater will cease once the CCS' water and groundwater salt concentrations are similar.[15] Based upon the CCS and Biscayne Bay chlorinities being similar at the time of the report, estimated at approximately 23 ppt,[16] Dames & Moore calculations suggested that "by the mid-1980's to mid-1990's the chloride levels should stabilize and the wedge should extend inland [westward] on the order of a mile farther, and with little change in vertical movement."[17] As will be discussed later, this assumption was flawed, given the way FPL would operate the CCS, and chloride levels did not stabilize. Although FPL submitted monitoring reports that showed that the chloride levels had not stabilized,

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[11] Exhibit SP-3, Demonstrative 3.
[12] Dames & Moore, 1978, page 58.
[13] Dames & Moore, 1978, page 68.
[14] Dames and Moore, 1978, page 68.
[15] Dames and Moore, 1978, page 69.
[16] Dames and Moore, 1978, page 69, Section 6.2.
[17] Dames and Moore, 1978, Table 6.2 on page 71, Table 6.4 on page 85.

FPL appears to have done no follow-up analysis or meaningful corrective action on this issue for at least the next two decades.

Q. ARE YOU SAYING THAT THE CONCEPTUAL MODEL THAT WAS POSTULATED IN THE 1978 REPORT WAS IN ERROR?

A. No, I am not. The conceptual model presented for the CCS saline contribution to the Biscayne Aquifer remains applicable even when salinity in the CCS is greater than the salinity of Biscayne Bay or Card Sound. For example, when FPL was not allowed to discharge water from the CCS into Biscayne Bay for managing CCS salinity (when it became 110% of that of the surrounding bay),[18] it would have been reasonable to conclude that CCS salinities would continue to get higher due to the process of evaporation, which would then contribute additional salt mass to the Biscayne Aquifer due to the exchange with groundwater. This is actually what happened, and as discussed later, I believe that this circumstance required FPL to consider other operational actions to lessen the impact of the CCS on Aquifer salinity.

Q. SHOULD FPL HAVE BEEN AWARE THAT THE SALTWATER PLUME WOULD HAVE MOVED FURTHER WESTWARD AS A RESULT OF THE CCS OPERATION?

A. Yes, it appears reasonable to assume that FPL should have realized that the operation of the CCS was influencing a westward movement of the saltwater plume and that stabilization had not occurred. Dames & Moore's monitoring report from 1990

[18] See, FPL's Response to OPC's First Set of Interrogatories, Nos. 14 and 32.

shows FPL possessed groundwater monitoring salinity data prior to 1990 with concentrations of salt in the groundwater steadily rising and exceeding the salinity values from the Biscayne Bay referenced in 1978,[19] clearly indicating that stabilization of groundwater salinity had not occurred from 1978 to 1990. These saltwater concentrations should have prompted FPL to, at a minimum, consider pursuing actions (such as additional CCS freshening) to reduce the CCS' contribution of salinity to the Biscayne Aquifer west of the CCS. The FPL data showed that salinity in groundwater at the CCS had continued to increase since 1978 across multiple depth intervals (20 to 60 feet below the top of the casing). The time history plot of chlorinity (saltwater concentration) for well L-3 located west of the Interceptor Ditch is provided as Exhibit SP-3, Demonstrative 4. Although no measurements of salinity of the CCS water itself have been made available for the period 1972-1990, FPL appears to have been required by its 1972 Agreement with the South Florida Water Management District (SFWMD)[20] to sample surface water (in the CCS) and groundwater for water conductivity measurements of salinity on a frequent basis (daily to bi-weekly) and provide that data to SFWMD.[21] A plot of salinity in the CCS since inception published by Chin on behalf of the Miami-Dade County Division of Environmental Resources (DERM) in 2016 is shown on Exhibit SP-3, Demonstrative 5. This plot, based on site data, shows that salinity within the CCS was steadily increasing. This data plot is consistent with average yearly salinity values tabulated by FPL in response to Staff's First Set of Interrogatories, No. 2, which is reproduced here as Exhibit SP-3, Demonstrative 6.

[19] Dames & Moore, 1990, Appendix A, PDF pp. 38 to 45.
[20] The SFWMD was formerly called the Central and Southern Florida Flood Control (FCD).
[21] Agreement between FPL and FCD dated February 1972, pp. 6 and 7.

Dames & Moore, in the 1990 report, note that the monitoring wells display chlorinity excursions (or readings) above historical limits for the October 1989 data and also note that they represent a continuation of a slightly increasing trend.[22] However, this was not considered by Dames & Moore in further evaluations, or in its conclusions of the report, which mainly attributed the chlorinity excursions to decreased rainfall.

Q. GIVEN THE DATA REPORTED BETWEEN 1978 AND 1990 BY DAMES & MOORE, SHOULD FPL HAVE KNOWN THERE WAS AN ISSUE WITH WESTWARD MIGRATION IN THE BISCAYNE AQUIFER OF SALINE AND HYPERSALINE WATER INFLUENCED BY THE CCS?

A. My expert review of data and analyses reported by Dames & Moore in their 1978 and 1990 reports clearly indicate that these reports reveal the impact of the CCS on the groundwater.

Only two years later, the 1992 Dames & Moore monitoring report continued to show a trend of increasing chlorinity.[23] Exhibit SP-3, Demonstrative 7 shows the chlorinity with depth plots for 1990 and 1992 for well L-3, which is west of the interceptor ditch (see discussion of Interceptor Ditch at the end of Section III), illustrating the increasing trend of CCS influence on saltwater in the Biscayne Aquifer. Maximum chlorinity at this well was close to 30 ppt, which was well above the range of values for Biscayne Bay and also above values for chloride concentration of

[22] Dames & Moore, 1990, p. 8.
[23] Dames & Moore, 1992, Appendix A, PDF Page 36 to 43

seawater. Therefore, the CCS water was known to have impacted the groundwater beyond the CCS boundaries by 1992. This should have come to no surprise to FPL, given the data trends since 1976. The emphasis on rainfall-related justifications appears to have masked the long-term data trends, and thus lent superficial support for Dames & Moore's conclusions regarding the aquifer that "the increase in ground-water salinity has been very small and does not represent significant change in the wedge movement or configuration."[24] This is verbatim the same conclusion from the 1990 report, which focused on rainfall patterns, without addressing the increasing groundwater concentrations.[25] Ultimately, FPL's contractor Dames & Moore in 1990 and 1992 failed to address or act upon the most relevant point, which was the evidence of increasing concentrations of salinity in the groundwater.

Q. AFTER THE 1992 REPORT, WHAT DID THE EVIDENCE FPL PRODUCED SHOW ABOUT WHAT WAS OBSERVED, REPORTED AND ACTED UPON BY FPL BETWEEN 1992 AND 2013?

A. I am not aware of reports or data collection activities for the period between 1992 and 2003. Nor have I seen evidence of actions initiated as a result of the three earlier Dames & Moore reports during this time. Annual monitoring reports provided for 2003 to 2011 continued to show increases in electrical conductivity measurements (or saltwater concentrations) in the groundwater. However, this information was downplayed or even ignored in the Annual Reports' conclusions, which were uniformly

[24] Dames & Moore, 1992, p. 12.
[25] Dames & Moore, 1990, p. 11.

stated as “no adverse impacts.[26] In the cover letter, Golder emphasized the increases in groundwater salinity concentration were occurring at depth for 2005, 2006, 2007, and 2008, and later reports indicated salinity exceeding historical levels at depth. [27] Yet in all cases, FPL’s contractor Golder, appears to have de-emphasized this information by contending that the saltwater wedge movement typically is seasonal in response to variations in rainfall and water levels. Thus, while each annual report focused on potential short-term explanations for salinity trends, the evidence of a long-term trend of increasing salinity of CCS water steadily moving westward was obscured or ignored.

The annual reports from 2003 through 2008 provided plots of chloride relative to depth which showed further exceedances in chlorinity from the historical envelope (or boundary) identified in the 1992 Dames & Moore report. Also, the time-history plots that indicated salinity trends at various wells at different depths since the 1970s[28] were not presented in any of these later monitoring reports until the 2009 monitoring report.[29] As a result of these omissions, the indications of long-term changes through time were not presented again (or re-evaluated) even though that data was readily available or should have been periodically collected.

The time series plots of salinity at various wells at different depths were produced in the 2009-2011 groundwater monitoring reports in an appendix to the report. The 2009 and 2010 monitoring reports made no mention of this appendix, thus effectively neglected the trend data. Exhibit SP-3, Demonstrative 8[30] shows chloride

[26] FPL, 2003; FPL, 2004; Golder, 2008c, 2008d, 2008e, 2008f; Golder, 2009; Golder, 2010; Golder, 2011a.
[27] Golder, 2008c, 2008d, 2008e, 2008f, 2009, 2010.
[28] From Dames & Moore 1990 and 1992, and as presented in Exhibit SP-3, Demonstrative 4.
[29] Golder, 2009.
[30] Golder, 2011a

concentrations in well G-28 at depths of 15, 30, and 45 feet bgs (below ground surface). From this plot, it is noted that although the Biscayne Aquifer at Tallahassee Road had not yet reached the hypersaline threshold by 2011, contribution of salinity from the CCS had reached well G-28 at Tallahassee Road. It is further noted that the level and extent of salinity was steadily increasing in that portion of the aquifer. In addition, the increase in salinity at well G-28 is similar to the rise in hypersalinity observed at well L-3.[31] This evidence was later confirmed by the estimates from a salinity model constructed using electric resistivity measurements which estimated that hypersalinity extended westward from the CCS about 8,200 feet by 2016.[32]

FPL's monitoring reports, tables, and figures refer to depths below -15 feet msl (mean sea level) as being "intermediate" and "deep." However, the Biscayne Aquifer bottom (underlying confining layer) occurs at about 80 to 100 feet below sea level.[33] Therefore, samples from 30 or 45 feet below sea level still represent only the upper portion of the Biscayne Aquifer and may not have reflected the true extent of the saltwater intrusion that resulted from the CCS.

As shown in Exhibit SP-3, Demonstrative 10, the 2011 Uprate Project Semi-Annual and Annual Reports and 2012 Uprate Project Semi-Annual Report showed elevated values of the unique CCS tritium fingerprint in groundwater west of the CCS, with concentrations increasing with depth, indicating that this tritium was not deposited through the atmosphere.[34] The CCS tritium concentration values shown in Exhibit SP-

[31] Reproduced from Golder, 2011a, as shown in Exhibit SP-3, Demonstrative 9.
[32] Enercon, 2016.
[33] Ecology and Environment, 2012c, Figure 5.1-2.
[34] Ecology and Environment, 2011a, 2011b, 2012a.

3, Demonstrative 10 are also much increased from the estimated 1970s concentrations shown in Exhibit SP-3, Demonstrative 3.

The 2012 Comprehensive Uprate Report hydrogeological assessment performed on behalf of FPL contained additional pre-2013 evidence of the westward progression of saltwater from the CCS. It stated that "[t]here are two surface water stations located in canals immediately adjacent to the CCS that potentially could be affected by the CCS via a groundwater pathway (TPSWC-4 and TPSWC-5). At both locations, tritium values approached or exceeded 1000 pCi/L at depth during one sampling event."[35] The report further states:

> [f]or groundwater, there are also stations that show evidence of CCS water via a groundwater pathway. Figure 5.2-35 shows the wells that are suspected to be influenced by a groundwater pathway. The tritium concentrations in the shallow samples at fully screened wells L-3 and L-5 may be attributable to atmospheric influences, however, the higher values found at depth are associated with a groundwater pathway. The westerly extent of CCS water in the groundwater is near Tallahassee Road.

In other words, tritium found at deeper intervals in the wells indicated in the figure was a result of water that moved from the CCS into the ground (the groundwater pathway) rather than due to deposition from the atmosphere (the atmospheric pathway). Exhibit SP-3, Demonstrative 11, is a reproduction of Figure 5.2-35 from Ecology and Environment (2012c).

Based on the CCS tritium fingerprint data, the rate of CCS water migration westward within the Biscayne Aquifer was estimated by 2012 to be about 525 feet per

[35] Ecology and Environment, 2012c, Page 5-12

year in the northern portion of CCS, to 660 feet per year in the southern portion of CCS.[36]

The 2012 Comprehensive Uprate Report also estimated the contribution of CCS water at different wells based on well chloride concentrations, background chloride concentrations and CCS concentrations of chlorides.[37] This computation also shows that CCS water has had an impact west of L31E canal.

Q. DID FPL APPROPRIATELY MONITOR THE PLUME SINCE THE 1970's?

A. No, FPL did not appropriately monitor the plume since the 1970s. The monitoring record provided in discovery is poor for the 1970s, 1980s, and 1990s. The reports from the 2000s demonstrate long delays in FPL's submittal of data to SFWMD: the 2005, 2006, and 2007 monitoring reports were submitted in 2008, just prior to the drafting of the 2009 Supplemental Agreement with SFWMD which dictated much more stringent monitoring requirements (SFWMD, 2009). The long delays in FPL's submittal of data to SFWMD appears to be inconsistent with FPL's apparent obligations to provide the information. Additionally, as SFWMD indicated in 2010 based on their 2009 review of FPL's monitoring data (SFWMD, 2010), the monitoring reports and monitoring efforts by FPL did not evaluate the impact of the CCS or identify saltwater migration west of L31E canal in groundwater that occurs with/without the existence of the CCS.[38]

[36] Ecology and Environment, 2012c, Page 5-12, second to last paragraph
[37] Exhibit SP-3, Demonstrative 12.
[38] SFWMD, 2010, paragraph 3.

Q. WHAT DOES THE EVIDENCE AFTER 2013 SHOW ABOUT THE WESTWARD MIGRATION OF CCS-FED SALINE GROUNDWATER?

A. The 2014 USGS report on saltwater in the Biscayne Aquifer found that groundwater samples within 8.5 kilometers from the CCS contained elevated tritium compared to samples from the rest of the study area which is within the eastern portion of Miami-Dade County. [39] Groundwater samples near the CCS averaged 12.4 tritium units (TU) instead of 1.3 TU over the study area and ranged from 4.1 to 53.3 TU. [40]

As shown in Exhibit SP-3, Demonstrative 13, the 2016 Comprehensive Post-Uprate Report corroborates the Pre-Uprate reports and confirms that the CCS has impacted water in the Biscayne Aquifer west of the CCS towards Tallahassee Road and past Tallahassee Road since <u>at least</u> the early 2010s.[41] Wells TPGW-4 and TPGW-5 are located along Tallahassee Road.

The 2016 areal electromagnetic survey (AEM) by Enercon, as shown in Exhibit SP-3, Demonstrative 14, estimated the extent of hypersaline water from the CCS to extend "westward 3,300 to 8,200 feet west from the margin of the CCS" water[42] with maximum salinity at a depth of about 55 to 65 feet below land surface The highest concentrations of chloride, up to 40,000 ppm (twice the concentration of sea water) occur within 3,300 feet of the western and northern boundaries of the CCS (Enercon, 2016, Bottom of Page 13). This clearly shows the impact of CCS water on the Biscayne aquifer west of the CCS.

[39] USGS, 2014.
[40] USGS, 2014, p. 38, top right and p. 47, top right.
[41] Ecology and Environment, 2016b, Figure 5.2-7.
[42] Enercon, 2016, p. 11.

Q. WERE THERE ANY ANALYSES PERFORMED INDICATING THE CCS COULD HAVE AN IMPACT ON THE SALINE PLUME'S MOVEMENT WESTWARD OF THE L-31 IN EXCESS OF THOSE AMOUNTS THAT WOULD HAVE OCCURRED BUT FOR THE EXISTENCE OF THE CCS?

A. Yes, there were analyses performed, because there was concern that the CCS would impact saline plume movement westward of the L-31 canal as early as 1978. Studies regarding the CCS's role in saltwater intrusion include the 1978 Dames & Moore salinity migration evaluation; the 2009 publication by Hughes, et al. in Hydrogeology Journal numerically demonstrating the behavior of CCS water migrating beyond its boundaries; the GeoTrans 2010[43] and Tetra Tech 2013 models based on Hughes, et al.; and the Tetra Tech flow and transport model of 2016. Also, in 2010, the SFWMD indicated that data FPL submitted was insufficient to evaluate impacts of the CCS on the Biscayne Aquifer.

As far back as 1978, FPL's contractor Dames & Moore provides an analysis of the impact of the CCS on salinity conditions as compared to baseline conditions without the existence of the CCS. They computed the position and the shape of the interface and presented their results to FPL in Figures 6.5-6.8 of their 1978 report, indicating that saltwater intrusion at the base of the Biscayne Aquifer could have been as much as a mile westward at that time. Also, the computed interface was higher by 1990 (about 10 feet under L-31) taking into account the operation of the CCS, as opposed to without it. This is clearly shown in Exhibit SP-3, Demonstrative 15 which includes Figures 6.7

[43] Appendix D.

and 6.8 of the Dames & Moore 1978 report showing the computed interface with and without the CCS.

Another analysis of the impact of the CCS on the movement of the saline plume (portions of which were hypersaline) was provided in 2009.[44] They present a cross-sectional density-dependent saltwater intrusion model to demonstrate the impact of the CCS on the underlying saline plume. Due to uncertainty of hydraulic conductivity values (the ease with which water can flow in the aquifer), they simulated four cases that bracket the range of values reported at the site. Exhibit-SP-3, Demonstrative 16 from Hughes et al (2009), which shows the results of simulating hypersaline water in the CCS interacting with the Biscayne Aquifer, indicates that hypersaline CCS water sinks to the bottom of the aquifer and migrates westward.[45] The saltwater wedge did not reach equilibrium within the 25-year simulation period for these simulations which considered the extent of hypersaline water in the CCS.

Exhibit SP-3, Demonstrative 17 reproduced from Hughes, et al. (2009) indicates that the 1 ppt TDS concentration moves as much as 400 to 11,000 meters in 25 years at the base of the aquifer as a result of the CCS. Note that 1 ppt is about twice the drinking water standard for TDS. Exhibit SP-3, Demonstrative 18 reproduced from Hughes, et al. (2009) indicates that salt content in the aquifer increases by 40 to 160 million kilograms in 25 years. Thus, it was clearly demonstrated in 2009 that the CCS increased the Biscayne Aquifer's salinity.

[44] Hughes, et al. in 2009
[45] Exhibit SP-3, Demonstrative 16; Hughes, et al, 2009, Figure 4

The 2013 cross-sectional model of the CCS by Tetra Tech simulates salinity reduction of the hypersaline plume in the Biscayne Aquifer.[46] The 2015 conditions for the remediation simulations show a hypersaline plume with salinity greater than 35 ppt extending westward from the CCS to Tallahassee Road, as shown in Exhibit SP-3, Demonstrative 19.

The 2017 groundwater flow and transport model of the Biscayne Aquifer notes that model wells G-21 and G-28 (west of the CCS along Tallahassee Road) were used as targets for chloride breakthrough (i.e., saltwater concentrations through time were evaluated at these locations to consider if the model represents observed conditions) between 1968 and 2010.[47] Though this breakthrough does not directly demonstrate the extent of an accompanying hypersaline plume, the model results were generally consistent with the 2016 electromagnetic survey, and simulated a hypersaline plume with similar extents.[48] In my expert opinion, considering the data provided by FPL and in the references included with my direct testimony, and subject to additional data that I have not been provided which may indicate otherwise, the models of Tetra Tech[49] are a reasonable representation of the saltwater intrusion processes and hydrogeology of the Biscayne Aquifer in the vicinity of the CCS.

[46] Tetra Tech, 2013b
[47] Tetra Tech, 2016c, p. 13.
[48] Enercon, 2016; Tetra Tech, 2016c, p. 16
[49] Tetra Tech (2016c), Tetratech (2016d), and Tetra Tech (2016f)

Q. IS THERE EVIDENCE THAT FPL PRESENTED ANY ANALYSES PRIOR TO 2009 TO DEMONSTRATE WHETHER THE INTERCEPTOR DITCH OR THE "ID" WAS EFFECTIVE IN CONTROLLING THE WESTWARD MOVEMENT OF THE HYPERSALINE PLUME?

A. Effectively, no. FPL collected sufficient data to perform an evaluation of the effect of the ID on CCS water within the Biscayne Aquifer; however, in all monitoring reports but one, FPL failed to analyze or address the effectiveness of the ID in preventing westward movement of CCS water. Despite its collection of this chloride data, FPL failed to provide its analysis of the data, in terms of the effectiveness of the ID prior to 2011. Only in the 2011 annual groundwater monitoring report did FPL directly address the purpose of the ID operations by discussing the effect of the ID on CCS saline water. FPL acknowledged the presence of and westward migration of CCS water within the Biscayne Bay below the depth of the Interceptor Ditch.[50]

The stated original purpose of the Interceptor Ditch when it was placed in service at the inception of the CCS was to restrict movement of saline water from the cooling canal system westward of L31 canal to those amounts that would occur without the existence of the cooling canal system.[51] Prior to the 2009 revision to the CCS monitoring plan, FPL's reports did not include an analysis of whether CCS saline water was present in the Biscayne Aquifer or whether CCS saline water, if present, was moving westward. The data necessary to address the purpose of the ID were collected and presented by FPL in the annual groundwater monitoring reports in the form of

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[50] Golder, 2011c, p. 12.
[51] CFD, 1972

excursion plots and time history plots of chlorides (Demonstratives 4 and 7 in Exhibit SP-3).[52] FPL's subsequent (after 2009) reporting of the ID relapsed into discussions of relative trends of chloride within wells and groundwater gradients, and ignored the effect ID operations had, if any, on the hypersaline conditions within the Biscayne Aquifer.[53]

A review by SFWMD in 2009 described these monitoring practices as "errors, omissions and inconsistencies that raise concern as to whether the operations of the Interceptor Ditch were always consistent with the Revised Operating Manual contained in the 1983 Agreement."[54] SFWMD further stated that "the reports contain conclusions that are inconsistent with the objectives identified in Paragraph A.1. of the Agreement…the subject reports do not identity the location and orientation of the saline water westward of Levee 31E[55]… and "[t]he conclusions….that the Interceptor Ditch is continuing to be responsive and effective in performing its design function, is not recognized as a performance measure within the Agreement" …"[56] In short, FPL's conclusions about "effective" ID operations were based on groundwater gradients or historical landward sea water extents, but were not related to the presence of CCS water in the Biscayne Aquifer or the migration of this water.

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[52] Dames & Moore, 1990, 1992, FPL, 2003, 2004; Golder, 2008c, 2008d, 2008e, 2008f, 2009, Golder, 2010.
[53] Ecology and Environment, 2012c, p. 6-5; Ecology and Environment, 2014, Page 6-4; Ecology and Environment, 2016, Page 7-6.
[54] SFWMD, 2010, PDF Page 3 second paragraph
[55] SFWMD, 2010, PDF Page 3, third paragraph
[56] SFWMD, 2010, PDF Page 3, fourth paragraph

<u>IV. EVALUATION OF THE FEASIBILITY AND EFFECTIVENESS OF FPL'S PROPOSAL TO HALT THE MIGRATION OF THE HYPERSALINE PLUME, STABILIZE SALINITY LEVELS WITHIN THE CCS, AND RETRACT THE HYPERSALINE PLUME FROM AREAS BEYOND THE CCS BOUNDARIES</u>

Q. PLEASE DESCRIBE THE HYDROGEOLOGIC STRUCTURE OF THE BISCAYNE AQUIFER.

A. The Biscayne Aquifer is about 100 feet thick in the vicinity of the CCS, but it thins to the north and west. The Aquifer consists of two primary water-bearing units: the near-surface Miami Limestone, and the underlying Fort Thompson Formation. These hydrogeologic units contain areas with extensive tubes, channels and voids that likely act as preferential subsurface flow pathways. Such zones are identified by JLA Geosciences (2010) in the vicinity of the CCS. Unconsolidated sediments (weathered rock) overlying the Miami Limestone are thin and include coarse-textured fill, organic-rich soils and marls. The less permeable units of the Tamiami Formation that underlie the Fort Thompson Formation form the base of the Biscayne Aquifer.

Q. HAVE YOU ANALYZED FPL'S THREE DIMENSIONAL DENSITY-DEPENDENT SALTWATER INTRUSION MODEL, AND IF SO, WHAT ARE YOUR OBSERVATIONS?

A. Yes I have analyzed the model. FPL has developed a three-dimensional saltwater intrusion model of the Biscayne Aquifer in the vicinity of and beneath the CCS. I have reviewed Tetra Tech's reports documenting the model and the related modeling files.[57] Generally, the model simulated conditions in the Biscayne Aquifer both before and after creation of the CCS, and it simulated the movement of salinity in the water under various conditions through 2010. Specifically, the calibrated model simulated the predevelopment steady-state conditions prior to 1940, followed by transient salinity movement under steady flow conditions for 1940-1968, which represent the start of groundwater development in the model domain. The model then simulated seasonal transient conditions between 1968 and 2010 with the CCS beginning in May 1973. Finally, the calibrated model then simulated conditions from 2010-2015 on a monthly stress-period basis.

Tetra Tech then applied the model to evaluate the impact of several alternative remedial solutions for retracting the hypersaline plume in Biscayne Aquifer back into FPL's Turkey Point plant boundaries. FPL ultimately selected the remedial scheme named Alternative 3D as the desirable methodology for retracting the hypersaline plume; it is a predictive simulation that starts in 2016 and goes through 2025 for a total simulation time of 10 years. This alternative consists of pumping hypersaline water from the Biscayne Aquifer within the CCS boundary for one year followed by pumping saline and hypersaline water from the Biscayne Aquifer from a set of wells along the western periphery of the CCS for nine years. Disposal plans for extracted water were not explicitly detailed. The well placement for Alternative 3D is shown on Figure 19 of Tetra Tech, 2016c, reproduced here as Exhibit SP-3, Demonstrative

[57] Tetra Tech, 2016c, 2016d, 2016f. The model development effort is documented in Tetra Tech, 2016c.

20. The remedial scheme named Alternative 3D also includes the assumption that the CCS salinity is at 35 PSUs, which is roughly the same salinity as seawater.[58]

The Tetra Tech, 2016f report documents a recalibration effort of the 2016c model using the parameter estimation software named PEST. Ultimately, the results reflected in Tetra Tech's earlier model were similar to the results shown in the PEST model.[59] Tetra Tech's report states that "both models similarly simulate breakthrough" at wells G-21 and G-28 aside from the G-28 deep screen.[60] Tetra Tech concluded that "while there are subtle differences between the modeled salt concentrations throughout the 10-year predictive timeframe, in general, the simulated salt concentrations and the manner in which they change over time are similar in the two models."[61] Finally, comparisons of the predictive analyses from the 2016c and 2016f models show the two models are also generally similar in that respect.[62]

From my review of the hydrogeology of Biscayne Aquifer in the vicinity of the CCS,[63] the models seems to be representative of the hydrogeologic system, unless either Tetra Tech or FPL possesses other undisclosed compelling data or unless additional data becomes available that denotes otherwise.

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[58] Further modifications were made to the model boundary conditions and documented in Tetra Tech, 2016d. As noted in their conclusions (Tetra Tech, 2016d), "Based on an evaluation of calibration and prediction models' results, the revisions have an overall minor impact to the historical and future simulated hydrologic and water quality conditions".

[59] Table 6 and Figures 7 through 15 of Tetra Tech, 2016f show a comparison of the manually calibrated results of Tetra Tech, 2016c, against the PEST calibrated results. The quality of the calibration was only marginally improved in the 2016f model as compared to the 2016c model. Figures 7 and 8 of Tetra Tech 2016f indicate that PEST achieved a model calibration slightly better, yet very similar to that achieved by manual calibration." Tetra Tech, 2016f, p. 9.

[60] 2016f; Page 9 and Figure 9.

[61] Tetra Tech, 2016f, page 10 and Figures 10 through 12.

[62] Tetra Tech 2016f , Figures 13 through 15. The slightly larger differences between the predictive simulation results of the two models may be attributed to the slightly different configuration of the remedial extraction wells of Alternative 3D simulated with the later model (also shown in Figure 1 of Tetra Tech, 2016m and reproduced here as Exhibit SP-3, Demonstrative 21.

[63] Hughes et al, 2009; JLA Geosciences, 2010; Tetra Tech, 2016c.

The model domain was divided vertically into 11 numerical model layers – from top to bottom, these are the unconsolidated sediments (layer 1); Miami Limestone (layers 2 and3); a high hydraulic conductivity zone at the base of the Miami Limestone (layer 4); and the Ft. Thompson Formation (layers 5-11). Layer 8 is a high hydraulic conductivity zone within the Ft. Thompson Formation. Multiple numerical layers were used in the numerical model of the aquifer, so as to provide vertical resolution for the density effects of flow of saline water in the aquifer from the CCS and from Biscayne Bay.

FPL produced two Tetra Tech models to OPC in response to discovery requests. Both of the Tetra Tech models are constructed on the same hydrogeologic conceptualization, use identical numerical gridding, have acceptable calibration statistics that are alike, generally replicate historical or expected behavior of salinity, and give similar predictive results for application of remedial Alternative 3D. Both models appear to be generally representative of the system and adequate in evaluating historical migration of saline water in the aquifer, movement of hypersaline water from the CCS into the aquifer, and future salinity conditions subject to salinity management in the CCS, the remediation extraction well system, or changes in the other external stresses such as canal stages and depths, lateral boundary conditions or pumping within the aquifer.[64]

[64] The models appear to be generally representative and adequate, but as with any model, they are subject to uncertainties and unknowns within the aquifer, vertical and horizontal resolution of the numerical grid, time-scales of simulation, and modeling assumptions.

Q. **HAVE YOU FORMED AN OPINION REGARDING FPL'S PROPOSED PROJECT FOR RETRACTING THE HYPERSALINE PLUME AND HALTING ITS MIGRATION OUTSIDE THE BORDERS OF THE CCS?**

A. Yes, I have. FPL's proposal titled "Alternative 3D," as outlined in the Tetra Tech Reports includes both "freshening" which means adding water with less or no salinity to the CCS, and "retraction" which means removing hypersaline water from the aquifer west of the CCS via so-called "retraction wells."[65] Review and evaluation of the model used to simulate the proposed remediation project indicates that the freshening component of the proposal may be a viable method for decreasing Biscayne Aquifer groundwater hypersalinity. However, the retraction well component, as proposed, would have only a marginal effect on hypersalinity in the groundwater west of the CCS. In any event, the combined remedial measures proposed by FPL (freshening and retraction wells), do not retract either the saline plume that is further west of the CCS, or the hypersaline portions immediately west of the CCS, to the Turkey Point boundary within the simulation period of 10 years.

FPL used Tetra Tech's three-dimensional density-dependent saltwater intrusion model to evaluate the proposed project for retracting the saline plume, i.e., Alternative 3D, which consists of two components.[66] The first component of this project is to stabilize the CCS salinity at a concentration of 35 PSUs, with a related freshening impact on the aquifer. The model assumes that the CCS salinity will be immediately decreased to 35 PSUs and held constant at that concentration. The second component

[65] Tetra Tech 2016c, 2016f.
[66] Tetra Tech 2016c, 2016f.

of this project consists of retraction wells with operations as detailed in Tetra Tech reports 2016c and 2016f, and summarized above.[67] Tetra Tech's model therefore simulates the combined impact of both project components simultaneously; however, that methodology hinders the ability to establish the impact of one project component versus that of the other. The simulation period is 10 years, and is intended to cover the period from January 2016 through December 2025.

Because of the deficiencies in the way that the simulations were conducted, which simulates the combined impacts of both project components simultaneously, I have conducted simulations with the Alternative 3D model files without the retraction well component, in order to compare the effectiveness of the two components independently of each other. Exhibit SP-3, Demonstrative 22 compares the simulation results in layer 8 after 1 year for this case without pumping of the retraction wells versus the case with pumping of the retraction wells. The model results showed that the simulated concentrations are not materially different between the two cases, even though the case with retraction wells includes a well pumping within the footprint of the CCS for the first year. Exhibit SP-3, Demonstrative 23 compares the simulation results in layer 8 after 10 years for the case without pumping of the retraction wells versus the case with pumping of the retraction wells. The results show that the impact of the retraction wells is minor; most of the freshening that was simulated in the aquifer occurred as a result of CCS salinities being modeled at 35 PSUs, not as a result of retraction well pumping. Exhibit SP-3, Demonstrative 24 compares the simulation results in layer 11 after 10 years for the case without pumping of the retraction wells

[67] See, Exhibit SP-3, Demonstrative 18 or 19 for the locations of the retraction wells.

versus the case with pumping of the retraction wells. Again, the model results show that the simulated concentrations are similar, which indicates that the impact of the retraction well system was minor in comparison to that of the CCS freshening to 35 PSUs. Note in Exhibit SP-3, Demonstratives 23, 24 and 25 that concentration units are relative to seawater concentration, and therefore, a concentration of unity (one) represents seawater while a concentration greater than one indicates hypersalinity.

Exhibit SP-3, Demonstrative 25 shows the difference in concentration values between the simulations with and without pumping for layers 8 and 11 (in 25a and 25b respectively) after 10 years of simulation. This difference represents the freshening that would occur due to the retraction wells alone (without impact of CCS concentrations being stabilized at 35 PSUs or other simulated differences that may be present between the calibration and prediction simulations). The maximum impact of retraction well pumping on groundwater salinity is about 8 PSUs within 2.5 miles west of the CCS in model layer 8 after 10 years of simulation. However, this is a region where the plume is largely not hypersaline (see Exhibit SP-3, Demonstrative 23). The impact of remedial pumping is negligible in model layer 11 after 10 years as shown in Exhibit SP-3, Demonstrative 25b. Thus, pumping is noted to have some impact on salinity in shallower layers, *but not in deeper layers where the salinity is greatest and where the plume is hypersaline*. In Tetra Tech's remedial simulations of Alternative 3D, freshening of the CCS to 35 PSUs had, by far, the greater impact on salinity in the Biscayne Aquifer, compared to using retraction wells. Nonetheless, while reducing and stabilizing CCS salinity appears to be a viable way to reduce hypersalinity within the Biscayne Aquifer, timeframes for reduction in hypersalinity in the aquifer will vary depending on many factors of the project implementation, including the rate at which the CCS is stabilized at 35 PSUs and the successful maintenance of such concentrations.

Q. HAVE YOU FORMED AN OPINION REGARDING FPL'S PROPOSAL FOR FRESHENING OF THE CCS TO 35 PSU?

A. Yes, I have. FPL proposes that 14 MGD of Floridan Aquifer water would freshen up the CCS to 35 PSU. I do not believe that the analysis conducted on behalf of FPL[68] can provide an appropriate solution in terms of required volume and timing for the necessary freshening. Contrary to FPL's assertion, my analysis shows that 31 MGD of Floridan Aquifer water would be required to freshen up the CCS to 35 PSU, and the number could be higher due to other uncertainties. Because FPL's groundwater remediation project proposal is based on an invalid underlying assumption regarding its ability to freshen the CCS to 35 PSU, the proposal itself is flawed.

FPL has used a steady-state spreadsheet-based water and salt balance CCS model to evaluate the impacts of adding 14 MGD of Floridan Aquifer water to the CCS.[69] The Tetra Tech model concluded that 14 MGD of Floridan Aquifer water will be sufficient to ultimately freshen the CCS from 60 to 35 PSUs. However the CCS model includes the exchange of salts with the Biscayne Aquifer, and therefore, the CCS freshening scheme also considers a mechanism for the exchange of salts between the CCS and groundwater. As I noted above regarding the three-dimensional density-

[68] Tetra Tech, 2014a

[69] Tetra Tech, 2014a; the water and salt balance model formulations are discussed by GeoTrans (2010b) which is also presented as Appendix E of Geo Trans (2010b).

dependent saltwater intrusion model, groundwater freshening was dependent largely on the CCS being at 35 PSUs. The steady-state CCS freshening analysis discussed here depends on (and assumes) groundwater salinity being at 35 PSUs to simulate total added water of about 14 MGD. Essentially, each model assumes that the other model instantly reaches 35 PSUs, in order for that model to be valid. Therefore, because the assumptions underlying each model are not valid, and because each model is dependent on the other for validity, the plan developed by FPL on the strength of these two models is itself invalid. Specifically, Tetra Tech stated that groundwater beneath the CCS has a salinity of about 55 PSU.[70] As noted on Exhibit SP-3, Demonstrative 26, if the groundwater salinity was 55 PSUs in the Tetra Tech 2014c CCS model, then 31 MGD of Floridan Aquifer water would be required to freshen the CCS to a salinity of 35 PSUs, assuming that all other numbers are similar to Table 1b of Tetra Tech (2014a).

Exhibit SP-3, Demonstrative 26 does not account for the impact of added water on groundwater inflow or outflow to the CCS though Tetra Tech estimates that impact to CCS water level is negligible, being 0.1 foot for 10 MGD of added water to the CCS.[71] However, Exhibit SP-3, Demonstrative 26 clearly shows the impact of errors or uncertainties in model inputs. If estimates of groundwater inflow/outflow or evaporation are incorrect, then the computation for required additional Floridan Aquifer water for freshening is also incorrect. Moreover, the impact of such errors on the ultimate model computation can be substantial.

[70] Figure 14 of Tetra Tech, 2016c.
[71] 2015a, top of page 6.

The transient CCS spreadsheet model described by Tetra Tech (2014a) similarly uses estimates of groundwater exchange flux (inflow or outflow) with the CCS, groundwater concentrations, precipitation / runoff into the CCS, and evaporation fluxes from the CCS to evaluate CCS salinity, subject to adding 14 MGD of Floridan Aquifer freshening water. If Tetra Tech's estimates are incorrect, then as a result, their transient flow computations are also incorrect. Consequently, the incorrect transient flow computations invalidate not only the computed dilution, but also the time to dilution.

FPL's method of modeling of the CCS separately from the three-dimensional density-dependent saltwater intrusion model therefore does not provide a reliable solution to the two interdependent problems which include interactions between both the CCS and groundwater, and which depends on the respective water levels and salinities. Lack of feedback between the various models makes FPL's steady-state and transient spreadsheet model results inaccurate, as demonstrated above. In addition, significant uncertainties exist in the CCS steady-state spreadsheet model that translate to large changes in the calculated Floridan Aquifer freshening water volumes.

Q. BASED ON THE DOCUMENTATION PRODUCED IN THIS CASE, DID FPL IDENTIFY MORE THAN ONE OPTION TO REDUCE SALINITY IN THE CCS? IF SO, HOW WAS THE PROPOSAL AT ISSUE CHOSEN?

A. Yes, more than one option was proposed or considered. FPL's contractor Tetra Tech has evaluated alternative measures for CCS salinity reduction.[72] The transient

[72] Tetra Tech, 2015a.

water and salt balance model was used for the evaluations by running a 2-year time period for a “normal weather scenario” and another two-year time period for a “dry weather scenario.” CCS freshening alternatives were also considered by GeoTrans for FPL as a remedial measure for retracting the hypersaline plume from beyond the CCS boundaries and halting further migration.[73]

Tetra Tech evaluated six alternatives and three additional alternatives termed “sensitivity.” The alternatives included freshening water from Floridan Aquifer wells, the interceptor ditch, L-31 Canal and Card Sound, and sediment removal. Tetra Tech then ranked these options considering the efficiency (defined in terms of the long-term salinity reduction) of the alternative in freshening the CCS depending on different initial CCS salinities. Ultimately, FPL chose the alternative of using 14 MGD of Floridan Aquifer water for freshening.

Q. **BASED ON THE DOCUMENTATION PRODUCED IN THIS CASE, DID FPL IDENTIFY MORE THAN ONE OPTION TO HALT MIGRATION OF THE HYPERSALINE PLUME AND REDUCE THE SIZE OF THE HYPERSALINE PLUME SO THAT IT DOES NOT EXTEND BEYOND THE BOUNDARIES OF THE CCS? IF SO, HOW WAS THE PROPOSAL AT ISSUE CHOSEN?**

A. Yes., more than one option was proposed or considered. GeoTrans, on behalf of FPL, evaluated several options for stopping westward migration of saline and hypersaline water as a result of the CCS.[74] Remediation options identified by GeoTrans included stopping westward migration of saltwater within groundwater; lowering

[73] GeoTrans, 2010b.
[74] GeoTrans 2010b

concentrations within the CCS to those of seawater; replacing the CCS with an alternate system consisting of cooling towers; and desalinating a portion of the CCS to lower concentrations within the CCS. GeoTrans outlined thirty-two preliminary alternatives. The thirty-two preliminary alternatives were narrowed down to thirteen for a more detailed feasibility study which, in turn, identified five alternatives that GeoTrans postulated had the greatest chance of success. The five alternatives selected by GeoTrans included the following: a slurry wall around the CCS; Interceptor Ditch modifications; shallow pumping wells in CCS; freshening of CCS with Floridan Aquifer water; and hydraulic barrier pumping and injection.

GeoTrans used a cross-sectional, variable-density groundwater flow and saltwater transport model to evaluate the impact of the selected five alternatives on saltwater movement in the Biscayne Aquifer beneath, and in the vicinity of, the CCS. The cross-sectional model development and calibration was described in GeoTrans 2010b, Appendix D of and in Tetra Tech 2013b. GeoTrans further estimated quantities of water required for the CCS freshening alternative by using the water and salt balance models for the CCS described by GeoTrans (2010a), and Tetra Tech (2014a).

The results of GeoTrans' model showed that Interceptor Ditch (ID) modifications such as lowered head, deeper ID, or pumping beneath the ID were not effective, especially with deeper portions of the hypersaline plume. Pumping from beneath the CCS was determined to be ineffective, and the westward migration of saltwater during the 15-year simulation was only about 250 feet less than for a simulation with current operational conditions. CCS freshening had a large simulated impact on the saline plume even though it did not retract or affect the westward migration of the plume. The slurry wall alternative was not accurately simulated by a cross-sectional model; however, the simulations indicated that a slurry wall would not be as effective as originally envisioned unless it was also anchored into the confining unit at the bottom.

In 2016, Tetra Tech developed a three-dimensional density-dependent groundwater flow and salt transport model of the CCS and vicinity.[75] This model was used to test seven remediation scenarios including a no-action case. Alternatives 2 through 5 evaluated CCS salinity abatement along with extraction wells to retract the hypersaline groundwater plume west of the CCS footprint. Alternatives 6 and 7 were intended to stabilize or retract the toe, or front edge, of the saltwater interface. The alternatives were ranked according to several criteria and Alternative 3D, a CCS freshening alternative in conjunction with groundwater pumping, was selected by Tetra Tech as the one with the highest ranking.

Q. HAS THE METHOD CHOSEN BY FPL BEEN EMPLOYED SUCCESSFULLY ANYWHERE ELSE?

A. The method selected by FPL (Alternative 3D of Tetra Tech, 2016c) includes a combination of freshening of the CCS and pumping from retraction wells along the CCS western boundary. I am not aware of any systems where this combination has been deployed.

[75] Tetra Tech 2016c.

Freshening of the CCS is viable, and is noted to occur during wet periods (though it has not been freshened to Biscayne Bay salinity values). If the CCS can be freshened to 35 PSUs and maintained at that concentration level, the density dependent flow and transport modeling analyses also indicated that freshening of groundwater was viable.

Injection barriers and retraction/containment wells have been employed successfully elsewhere to prevent contaminant migration in groundwater from occurring, as well as to form barriers to saltwater intrusion. Modeling analyses have successfully guided these operations in Florida, California and elsewhere. FPL's proposal depends on Tetra Tech's model for salinity migration within Biscayne Aquifer; however Tetra Tech's model shows that the retraction wells do not meet their stated objective of retracting the hypersaline plume from west of the CCS footprint, as I have shown in my analysis above.[76] As such, the retraction well component of FPL's proposal is not reasonably effective in retracting the hypersaline plume.

<u>V. EVALUATION OF THE COST ALLOCATION IN THE FPL PROPOSAL</u>

Q. **WHAT DO YOU RECOMMEND TO THE COMMISSION WITH RESPECT TO FPL'S REQUEST TO ALLOCATE 17% OF THE PROJECT AS REMEDIATION AND 83% OF THE PROJECT AS PREVENTION/CONTAINMENT, FOR PURPOSES OF ENVIRONMENTAL COST RECOVERY FROM RATEPAYERS?**

[76] Tetra Tech, 2016c, 2016f.

First, I express no opinion in my testimony regarding whether the proposal or suggested basis to allocate any costs to customers is appropriate. However, if there is to be an allocation between remediation and prevention/containment, it is my opinion that the allocation percentages proposed by FPL are not supported by the evidence.

Tetra Tech conducted an evaluation for allocating a portion of the costs for the recovery system of hypersaline water to retraction, and the remaining to containment.[77] It was proposed from this evaluation that 17% of the project costs should be allocated as retraction or remediation and the remaining 83% of the costs should be allocated as containment/prevention. My recommendation is to reject FPL's suggestion, as there are several deficiencies in the analyses for a 17-83 percentage split between remediation and prevention/containment.

Additionally, the remediation function of the suggested design was only related to hypersaline water, and does not address saline water that was pushed further inland (westward) as a result of the operation of CCS. In fact, the proposed remedial alternative does not consider retraction of saline water further west of the hypersaline plume. In that regard, the remedial wells' impacts were noted to occur mainly in regions where the plume is not hypersaline, as seen in Exhibit SP-3, Demonstratives 25a, 25b, and 22, thus not achieving the stated goal of hypersaline plume retraction.

Also, the cost allocation mass calculations that underlie the suggested 17-83 percentage split between remediation and prevention/containment does not evaluate mass in the entire model. Specifically, "model layers 10 and 11 were omitted from

[77] Tetra Tech, 2016l, 2016m.

hypersaline mass calculations due to suggested uncertainties in hydraulic parameters in the deepest portion of the aquifer along the southwestern border of the CCS."[78] Omitting results from model layers with assumed uncertainties in parameters is not a scientifically valid or accepted methodology for quantifying the impact of uncertainty or variability. The model was calibrated using information from all layers so all of them should all be used in the evaluation. Otherwise, one could omit all results since there is uncertainty in parameter values for all model layers. If there is uncertainty in parameter values for model layers 10 and 11, the appropriate method of evaluating the impact would be, at the least, to bracket the parameter value range and bound the mass removal simulation results accordingly. The objective of the modeling effort of Tetra Tech was to evaluate relative mass recovery amounts between containment versus retraction of the hypersaline plume.[79] It was noted that the "model appears to under-simulate the extraction well influence in the bottom two layers of the model,"[80] therefore, in that case, it would do so for both retraction and containment portions of the hypersaline plume, thus providing similar ratios. For this reason, the cost allocation calculations should have used the entire model results and should not have omitted layers 10 and 11. In this case, the 20-year average split between retraction and containment was noted to be a 26-74 percentage split and not a 17-83 percentage split.

Regarding omitting model layers 10 and 11 in the mass allocation calculations, Tetra Tech suggested that the lower two layers have a low permeability and are not part of the Biscayne Aquifer.[81] Tetra Tech further suggested that the 2015 Consent

[78] Tetra Tech, 2016m.
[79] Tetra Tech, 2016m.
[80] Tetra Tech, 2016.
[81] Tetra Tech 2016m.

Agreement between FPL and Miami-Dade County only required retraction of the contents of the hypersaline plume in the Biscayne Aquifer. I have noted that the lower two layers have hydraulic conductivities in excess of 500 feet/day in the model. This is not a low number and does not reflect confining or aquitard-like conditions. Further, if the model appeared to under-simulate the extraction well influence in the bottom two layers, it is likely that modeled hydraulic conductivities need to be even larger. Hydraulic conductivity values larger than 500 feet/day are reflective of transmissive aquifer conditions.

In addition, the cost allocation and mass reduction computations were averaged over a 20-year period. However, it is noted that the "retraction hypersaline mass to the west and north of the CCS is fully removed after approximately 11 years."[82] Evaluating the results for mass reduction in all model layers for 11 years gives a 35-65 percentage split between retraction and containment (if layers 10 and 11 were omitted, that would yield a 30-70 percentage split averaged over 10 years).

Finally, the mass reduction numbers indicate that the effectiveness of the wells for mass removal diminishes significantly over the years. Demonstrative 27 in Exhibit SP-3, reproduces the annually recovered mass through time for the case where all layers are evaluated.[83] It is noted that mass retraction is almost negligible after year 11. Containment mass is also greatly diminished after year 11. However, operation of the wells was not adjusted to reflect the reduction in mass removal efficiency; instead, the wells are pumped at the same rate for 20 years even though mass removal by the wells

[82] Tetra Tech, 2016m.
[83] Figure 6 of Tetra Tech, 2016m.

is greatly diminished. Simulations that use variable pumping rates to reflect this situation should be conducted to evaluate containment and retraction of the hypersaline plume, and those simulations are more appropriately used to reflect cost allocation, if the Commission authorizes it.

Recovery ratios are also transient, as suggested by FPL's modeling study and shown on Exhibit SP-3, Demonstrative 27. Therefore, the cost should be apportioned, if at all, on a more regular basis, as per the varying ratios. Exhibit SP-3, Demonstrative 28 reproduces the proportions of recovered mass through time for the case where all layers are evaluated. [84] With the currently modeled amounts of pumping for Alternative 3D (the FPL-proposed alternative to retract the hypersaline plume), approximately 41% of the cost should be allocated towards containment and 59% for retraction for the first two years. In my opinion, two years is a reasonable time-frame for monitoring and re-evaluation since the model suggests significant changes in hypersaline mass removal in that time period. Monitoring and additional modeling at that stage can determine success of the strategy, adaptive management of the remedial scheme moving forward, and required associated costs.

Just because the operational life of the remediation wellfield is 20 years does not mean that it has to be operated for 20 years, if the objectives have been achieved earlier than that. Again, an adaptive management plan along with periodic monitoring will help guide long-term efforts and adjust for errors or uncertainties that occur in the current computations. A presentation by Tetra Tech considered 5-year and 10-year

[84] Figure 6 of Tetra Tech, 2016m.

averages, but these were not proposed in the ultimate cost allocation memorandum of Tetra Tech.[85]

Q. **DOES THIS CONCLUDE YOUR DIRECT TESTIMONY?**

A. Yes

[85] Tetra Tech, 2016l; 2016m.

CERTIFICATE OF SERVICE

I HEREBY CERTIFY that a true and correct copy of the foregoing Direct Testimony of Sorab Panday has been furnished by electronic mail on this 23rd day of August, 2017, to the following:

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Background and Experience

I am a groundwater hydrologist and modeler with decades of experience in the groundwater industry. During my 27-year professional career, I have developed expertise in constructing and applying models for evaluating groundwater flow, contaminant species transport, groundwater / surface water interactions, and saltwater intrusion.

I received a Bachelor's Degree in Civil Engineering from the Indian Institute of Technology, Bombay, India, in 1984, an M.S. in Civil Engineering from University of Delaware, Newark, Delaware, in 1986, and a Ph.D. in Civil and Environmental Engineering from Washington State University, Pullman, Washington, in 1989. My undergraduate project and graduate thesis involved development of models for complex subsurface flow and transport processes.

After graduation in 1989, I was employed as a Staff Engineer at HydroGeoLogic Inc. I was a Vice President at HydroGeoLogic Inc. when I left in 2007 to join Geomatrix. In 2009, Geomatrix was acquired by AMEC where I worked till 2013 before joining GSI Environmental Inc. I am currently a Principal Engineer at GSI Environmental Inc. Through the span of my career, many clients have relied on my groundwater modeling expertise, including private companies and government agencies such as the U.S. Environmental Protection Agency, Department of Energy, Department of Defense, the U.S. Army Corps of Engineers (USACE), and various agencies in Florida such as the St. Johns River Water Management District, the Southwest Florida Water Management District, the Northwest Florida Water Management District, Pinellas County Water System, and Seminole County.

I have developed several state-of-the-art groundwater modeling codes and am the lead author of the MODFLOW-USG code, released by the United States Geological Survey

(USGS) in 2013. MODFLOW-USG is an unstructured grid version of the traditional MODFLOW code that uses a finite-volume discretization technique, which provides gridding flexibility as compared to the traditional MODFLOW finite-difference method. I have further enhanced this code to include density dependent transport for evaluation of brackish water resources and saltwater intrusion.

I have worked on several density-dependent saltwater intrusion related projects throughout my career. Most recently, I just finished simulating the effects of brackish water pumping by desalination plants in the Lower Rio Grande Valley, Texas. I have also developed saltwater intrusion models for various Water Management Districts throughout Florida and conducted simulations to evaluate saltwater intrusion hydraulic barriers for the West Basin in California.

I have also worked on several groundwater / surface-water interaction models to evaluate the impact of river and canal systems on groundwater and vice versa. I have conducted modeling of coupled groundwater and surface-water flow and migration of chlorides in the Upper Santa Clara River in California, developed several models that evaluate the impact of drains and dewatering of mines, and developed integrated models of flow and transport for various Water Management Districts in Florida.

I am regularly invited to participate in expert panels and to conduct workshops and webinars on water resources, subsurface flow, and transport modeling. I also frequently publish articles (and peer review submissions made by others) in industry journals, publications, and conferences.

In 2015, the National Ground Water Association awarded me the M. King Hubbert Award for "major science or engineering contributions to the groundwater industry through research, technical papers, teaching, and practical applications." In 2017, I was elected as a member of the National Academy of Engineering for "development of computer codes for solving complex groundwater problems".

GSI ENVIRONMENTAL

July 2017

Sorab Panday, Ph.D.

Biographical Summary

Dr. Sorab Panday is a Principal Engineer at GSI Environmental with over 28 years of experience in directing, managing, developing, troubleshooting and reviewing flow and transport models for subsurface contamination evaluations, groundwater/surface-water interactions, and water resource management. He has worked on hydrologic and hydrogeologic modeling projects spanning a wide range of schedules and budgets. These projects involve multiple spatial and temporal scales; complex geological settings; diverse stakeholder concerns; extreme climatic conditions; unique water/contaminant management issues; and challenging numerical conditions.

Dr. Panday has provided leadership, mentorship, training and guidance on projects for client and staff; executed and managed modeling projects for various industries and government agencies; managed regulator and stakeholder modeling committees; provided expert-witness services; participated in expert panels; conducted workshops and webinars on water resource and subsurface contaminant transport modeling; and maintained effective communication with regulators and clients. He has developed code for several of the industry's state-of-the-art water resource modeling tools and is the lead author on MODFLOW-USG, an unstructured-grid version of MODFLOW released by the USGS. Dr. Panday is also an Adjunct Professor at the University of Waterloo, Canada. He publishes regularly in leading industry journals, and provides review and editorial support to industry publications and conferences.

Dr. Panday is the 2015 recipient of the M. King Hubbert Award, presented by the National Ground Water Association for major science or engineering contributions to the groundwater industry through research, technical papers, teaching, and practical applications. He was also elected as a Member of the National Academy of Engineering (NAE) in 2017 for the development of computer code for solving complex groundwater problems.

Education

Ph.D., Civil & Environmental Engineering, Washington State University, Pullman, Washington, 1989

M.S., Civil Engineering, University of Delaware, Newark, Delaware, 1986

B. Tech., Civil Engineering, Indian Institute of Technology, Bombay, India, 1984

Professional Background

Principal Engineer, GSI Environmental Inc., Herndon, Virginia, 2014-Present

Principal Engineer, AMEC Environment & Infrastructure, Herndon, Virginia, 2008-2013

Principal Engineer, Geomatrix Consultants, Inc., Herndon, Virginia, 2007-2008

Vice President R&D, HydroGeoLogic, Inc., Herndon, Virginia, 1989-2007

Professional Affiliations and Awards

American Geophysical Union; National Ground Water Association; International Association of Hydrogeologists; Groundwater Resources Association of California

M. King Hubbert Award, National Groundwater Association, 2015

Member of the National Academy of Engineering, 2017

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Project Experience

Water Resource Modeling

Groundwater/Surface-Water Interaction Model, Los Angeles County Sanitation Districts, CA. Project manager and principal investigator for developing a flow and transport Groundwater/Surface-Water Interaction Model (GSWIM) of the Upper Santa Clara River watershed to address chloride TMDL issues. Model highlights include use of a curvilinear grid to provide resolution near the river; parameterizing evapotranspiration and land surface properties via temporally varying land use types; and water supply systems that distribute pumped and imported water for outdoor use as per the unit demand of each land use type. The water supply systems further discharge indoor-use water (with or without treatment) to discharge locations in streams or apply it to the land surface as reuse. The model was developed and calibrated to groundwater levels, stream flows, groundwater chloride levels and stream chloride measurements for daily-averaged rainfall stresses over a 31 year period from 1975 through 2005. The model is being applied to examine the effects of various scenarios on chloride levels till 2030 and to examine various alternatives that meet the TMDL limits in an optimal manner. Provided leadership in model conceptualization, development, calibration and application; managed scope, budget and work-plans; prepared reports; provided presentations to staff and stakeholders; and attended stakeholder and technical meetings.

Density-dependent Groundwater Flow and Transport Model of the Lower Rio Grande Valley River Basin, Texas Water Development Board, Austin, TX. Developed a numerical model of the Lower Rio Grande Valley (LRGV) to evaluate the impacts of increased fresh and brackish groundwater pumping in the LRGV, as outlined in the 2016 Region M plan. The model was developed with a density-dependent flow and transport version of MODFLOW-USG and included a quad-patch refined grid around the River and irrigation canals to provide finer resolution in capturing the surface-water interactions. The model was calibrated from 1984 through 2013 using annual stress periods. The model is being used to evaluate the impact of pumping on groundwater and surface-water flows and levels; salinity within the groundwater basin; and salinity of the extracted water for current and planned additional desalination plants in the area. Drawdown computations from the model for planned future desalination operations also provide estimates of compaction stresses to help evaluate the potential for land subsidence. The model was also applied towards evaluating the impact of data gaps and different conceptualizations (e.g., for faulting) within the basin.

Impact of Coal Bed Methane (CBM) Extraction on Regional Groundwater Systems, Department of Natural Resources and Mines, Brisbane, Queensland, Australia. Provided simulation support under a sub-contract from Watermark Numerical Computing, to evaluate the impact of CBM extraction facilities on the regional groundwater system. The gas is adsorbed onto coal bed seams under pressurized conditions. Large quantities of water are extracted to desorb gas from the seams – the operation of several such facilities can have a cumulative impact on the overlying potable water aquifers. The regional nature of the analysis precludes practical use of a multiphase simulator for analysis. Therefore, the multi-phase flow conditions were simplified and the modified equations were implemented into a customized version of the MODFLOW-USG code. Benchmark and verification simulations were conducted to validate the methodology against a rigorous multi-phase simulator. Upscaling procedures and parameterization are being investigated to evaluate large aquifer systems, 10s of thousands of kilometers in size.

Peer Review of Groundwater Flow Model, Ventura County, United Water Conservation District (UWCD), Santa Paula, CA. Reviewer for UWCD's groundwater flow model development. UWCD is developing a numerical groundwater flow model of portions of Ventura County in support of efforts to estimate basin-specific sustainable yields and evaluate overdraft mitigation measures. The model is being used to support potential future groundwater extraction, recharge, and other management scenarios within the Basins. Provided review of the model development effort and continuing with ongoing, long-term guidance and review of the model for conducting predictive simulations for basin management and planning.

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Review of Regional Groundwater Flow Model at Aerojet Superfund Site, Carmichael Water District, Carmichael, CA. Review regional groundwater flow model at Aerojet Superfund Site and evaluate current remediation performance as it relates to the Carmichael Water District. Identified areas of limited data and specified model improvements. Present findings to client in technical memorandum.

Modeling Dissolution Behavior of DNAPL at the Ironton Coke Plant Site, Subcontract through AMEC for Honeywell International Inc., Golden Valley, MN. Principal Investigator for modeling conducted to support EPA's 5-year efficiency evaluation for remedial operations at the Ironton Coke Plant Site in Ironton, Ohio. DNAPL removal efforts at the site to date, have not resulted in significant decrease of the measurable subsurface DNAPL mass or of dissolved concentrations of the DNAPL components. The study evaluated the dissolution behavior of major components of a DNAPL pool at the site and compared results with simulations initiated with only residual DNAPL (assuming all mobile DNAPL could be removed). Results from the study indicated that the more soluble components would dissolve and be removed from the system with groundwater migration for both cases. However, the more insoluble components would persist as a source of downstream contamination for over 100 years even if all mobile DNAPL were instantly removed. Therefore, groundwater plume control and monitoring, as is being performed at the site, is an effective strategy and removal of the mobile DNAPL with associated treatment does not provide any significant gains over the 100 year analysis period.

Simulation of Seep and Remedial Alternatives at the Former Invista North Terminal Site, Koch Remediation & Environmental Services, Wilmington, SC. Principal Investigator for developing a groundwater flow model to evaluate and address a low-volume seep of water containing low concentrations of para-xylene. A steady-state groundwater flow model was developed and calibrated to current site conditions, and various alternative remedial measures were evaluated for effectiveness in addressing the issue. Simulations indicated that the preferred French-drain design alternative may not be effective due to low conductivity soils down-gradient from the site; however, backfilling or capping would reliably eliminate the seep even under wet weather conditions.

City of Flagstaff 100-year Water Supply Investigation, City of Flagstaff, AZ. Principal Modeler for construction and calibration of a groundwater model for simulating the 100-year water supply for the City as per ADWR's Adequate Supply Program and proposed Hydrologic Guidelines and Proposed Rulemaking Changes. The modeled scenarios consider a mixed use of surface water, groundwater and reuse to meet its projected requirements.

Groundwater Modeling Impact Analysis at Red Gap Ranch (RGR), City of Flagstaff, AZ. Principal Modeler for construction and calibration of a groundwater model simulating various groundwater pumping scenarios from future wells in the C-Aquifer at RGR. The evaluations also considered impacts of pumping on adjacent Native American lands. Unsaturated Zone Recharge Modeling, GSI Water Solutions Inc., Portland, OR. Modeling Consultant for simulating vadose zone injection to investigate design and operational goals for injection wellfields for a large-scale Aquifer Storage and Recovery (ASR) project at Jeju Island, in Korea. Assisted with conceptualization of the system and preliminary model simulations and provided modeling staff with training and QA. The model was used to evaluate and optimize the number of wells, spacing, and well depth for injection of 6 MGD during the wet season, including maintaining perched water columns for well rehabilitation.

Unsaturated Zone Recharge Modeling, GSI Water Solutions Inc., Portland, OR. Modeling Consultant for vadose zone injection simulation used to investigate design and operational goals of injection wellfields during a large-scale Aquifer Storage and Recovery (ASR) project at Jeju Island, South Korea. Assisted with conceptualization of the system and preliminary model simulations, and provided modeling staff with training and QA. The model was used to evaluate and optimize the number of wells, spacing, and well depth for injection of 6 MGD during the wet season, including maintaining perched water columns for well rehabilitation.

Saltwater Intrusion Hydraulic Barrier Evaluation and Resource Management, West Coast Regional Water Supply Authority, West Basin, CA. Directed and conducted updating of an existing groundwater flow and transport model of the West Coast Basin Barrier Project in Los Angeles, California from SUTRA to the SEAWAT code. The model was calibrated and used to assess movement of tertiary treated wastewater injected as saltwater intrusion barriers.

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Model for 5-Year Dewatering Plan, Bingham Canyon Mine Kennecott Utah Copper, Utah. Under subcontract from Montgomery and Associates, assisted with model development, review and troubleshooting support for evaluating dewatering and mine planning at the mine pit using the unstructured grid code MODFLOW-USG. The groundwater model will ultimately be used to support geotechnical analyses conducted in support of ongoing mine planning and to assist in optimization of the mine dewatering system and will replace the 3-D regional model in conjunction with 2-D cross-sectional models being used for planning. Vertically and horizontally nested grids provide resolution and conduit flow mechanisms move water within the workings to simulate regional conditions and required details with one model.

Model for Mine Dewatering at the Antamina Mine, Peru. Provided model development, review and troubleshooting support for modeling of mine dewatering to estimate pumping and treatment infrastructure requirements, and the impact of dewatering to nearby surface water bodies. The model covers the entire watershed and includes linear conduit elements to evaluate fracture flow in the region. A nested grid was developed with MODFLOW-USG to provide resolution in the vicinity of the mine workings. Steady-state and transient simulations were conducted to evaluate seepage under various weather conditions to assist in mine development planning. A modeling seminar was also conducted in Peru to present the MODFLOW-USG code and provide technology transfer.

Model of Tailings Impoundments, British Columbia, Canada. Senior Reviewer for various finite element and finite difference models constructed to evaluate containment systems to prevent tailings effluents from entering the regional groundwater system. The project locations were across British Columbia and included gold mines and sulfide deposit mines.

Brighton and Worthing Groundwater Flow Model, London, UK. Provided modeling support and review for development of a MODFLOW-USG model to simulate well and adit yields in the Chalk of the South Downs. The model is being applied in conjunction with climate models to provide predictions of future yields under changing precipitation patterns.

Integrated Surface and Subsurface Flow and Transport Modeling, National Parks Service (NPS), Everglades, FL. Project manager and principal investigator for developing a surface/subsurface flow and transport model to evaluate the Marsh Driven Operations Plan (MDOP) for the Rocky Glades, as part of the multi-billion dollar Comprehensive Everglades Restoration Program (CERP). The MDOP is developed to manage pumping operations from the L-31N canal into adjacent detention areas to minimize drainage of the Everglades to the canal without introducing high levels of phosphorous into the Everglades ecosystem. The model was developed using MODHMS and calibrated to daily water levels at over 40 wells and gauge stations over a 3-year period. Phosphorous transport in the surface and subsurface domains was also evaluated. The model was to be used further to evaluate other MDOP systems which may be more effective in achieving several conflicting objectives including flood prevention, drought maintenance, and ecosystem restoration. Provided technical input and supervision, managed project tasks and budgets, provided presentations and technical training to NPS staff.

Integrated Surface Water-Groundwater Model, St. Johns River Water Management District, Western Orange and Seminole Counties, Palatka, FL. Project manager and principal investigator for development and application of an integrated surface-water/subsurface water model in East-Central Florida. Performed integration of complex surface and subsurface data into a comprehensive model to investigate various conjunctive issues, including recharge areas, water movement in the system of interconnected ponds and lakes, and effects of groundwater pumping on surface-water bodies. Additional modules were developed within the MODFLOW framework of MODHMS to include the complexity of the system. Predictive analyses were conducted for transient conditions starting in 1999 and will continue through 2025, with current pumping and increased pumping estimates used to observe the effect of pumping on various lakes, wetlands, surface water bodies, spring flows and stream flows. Provided leadership to a team of hydrologists, hydrogeologists, engineers and scientists in conducting this project, including assimilating vast quantities of information and data for model development. Managed project progress and budgets; provided technical direction; prepared reports, presentations; conducted training sessions; and communicated progress and issues regularly with the client.

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Integrated Groundwater, Surface Water Modeling of Flow and Transport, U.S. EPA Gulf of Mexico Programs, Stennis Space Center, MS. Principal Investigator for conjunctive surface/ subsurface modeling study of the Mobile River Basin, LA. A MODHMS model was conceptualized and constructed for the approximately 3,000 square mile area of Hydrologic Unit Catalog (HUC) 204 and 205 surrounding and including Mobile Bay. Data for the system was obtained electronically in ArcView coverages of topography (DEMs), Land Use/Land Cover, and STATGO Soils databases which were translated appropriately for the subsurface, overland flow, and channel flow models. Simulations were performed to examine various hazard scenarios including heavy local rainfall, and effects of floods propagating down the Mobile River. Transport simulations included point and non-point of contaminants in upstream regions of the model. This model was further coupled with a coastal model to predict the associated impacts on Mobile Bay.

Integrated Tiger Bay, Bennett Swamp Model, St. Johns River Water Management District, Western Orange and Seminole Counties, Palatka, FL. Project manager for conversion of a MIKE SHE model into the MODHMS framework. The model included complex surface and subsurface interactions to determine recharge and runoff, as well as surface-water bodies such as canals, lakes, and ponds that discharge water from the domain. A comparison study was then performed between MODHMS and MIKE SHE by evaluating simulation results from both codes for the 1985 through 1999 time period. The models give comparable results, though the MODHMS model provided additional flexibility for handling operations of structures.

East-Central Florida Groundwater Modeling, St. Johns River Water Management District, Palatka, FL. Lead modeler for development and application of MODFLOW and DSTRAM regional flow and sub-regional saltwater intrusion models at several locations within the District, to meet various objectives of the District. Tasks have included conceptual model development, model calibration (manual adjustments with automatic refinement of parameters using PEST), sensitivity analyses, uncertainty analyses, predictions with uncertainty of alternate demand scenarios, and safe-yield determination. Provided hands-on training on the set-up and application of these models, as well as QA and trouble-shooting support to District staff in model evaluation of groundwater withdrawal impacts for water-supply development, consumptive use permitting and minimum flows and levels development.

Regional Groundwater Modeling for Water Supply Planning, Northwest Florida Water Management District, Havana, FL. Project manager and principal investigator for development and application of density-dependent saltwater intrusion models. Two models – an Eastern Domain and a Western Domain – were developed covering Escambia, Santa Rosa, Okaloosa and Walton Counties, to address concerns of up-coning of deeper saline waters and of saltwater intrusion from the Gulf of Mexico. The District-wide MODFLOW model was translated onto the local grids and the complexities of chloride intrusion were subsequently introduced. Calibration was performed for steady-state pre-development and transient post-development conditions. Sensitivity analyses have been performed on various parameters, with model application for predictive simulations of various future scenarios.

Evaluation of Streamflow Reductions due to Pumping, Northwest Florida Water Management District, Havana, FL. Principal investigator for a modeling evaluation of groundwater flow and surface-water interactions in the Apalachicola-Chattahoochee-Flint River Basin. The USGS finite-element code, MODFE, was applied for simulating the basin to estimate transient streamflow reduction due to pumping, for various alternative scenarios. Sensitivity analyses were also conducted to determine the range of streamflow reductions subject to parameter uncertainty.

Review, Training, and Support Services, St. Johns River Water Management District, Palatka, FL. Reviewer and instructor. Reviewed the ECF model of McGurk and Presley, and the Volusia County model of Williams. Reviewed the drafts and final reports for these studies. Conducted an in-depth examination of the data files for the respective models, for further QA of the report and modeling effort. Provided 3-day training on conjunctive surface/subsurface modeling using MODHMS to 12 staff members of the District. The theory and application of MODHMS were discussed, proceeding in complexity from the MODFLOW framework to include the unsaturated zone, and the surficial domain (overland flow and channel flow). Density-dependent solute transport was also detailed. Hands-on exercises were conducted to exemplify the theory and familiarize staff with the processing involved with conducting complex simulations that include density processes and surface/subsurface interactions.

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Saltwater Intrusion Model of the Geneva Freshwater Lens, St. Johns River Water Management District, Palatka, FL. Primary modeler for numerical modeling of saltwater intrusion. Activities involved development of the model using the finite-element density-dependent flow and solute transport code, DSTRAM, with further application for understanding the freshwater lens response to various ambient and groundwater development conditions for withdrawal permitting.

Consumptive Use Permit Consolidation, Seminole County Water Supply, Seminole County, FL. Principal investigator for developing and applying models towards evaluation of the impacts of various alternatives to current groundwater supplies including impacts of land-use changes, surface-water withdrawals, waste-water reuse for irrigation and artificial recharge via rapid infiltration basins. The East-Central Florida groundwater flow model was examined and used to evaluate the maximum groundwater withdrawals achievable without adverse impacts and that meet the growing needs of the county in conjunction with surface water supplies.

Saltwater Intrusion Study, Southwest Florida Water Management District, Brooksville, FL. Principal investigator for the Southern Water Use Caution Area (SWUCA) density-dependent saltwater intrusion modeling project. The project used the Southern District groundwater MODFLOW model already developed by the District as a starting point for the local, refined density-dependent saltwater intrusion model developed with MODHMS. The conceptual regional model was translated onto the local grid, and the complexities of chloride intrusion were successively introduced to the model, which was then calibrated for steady-state pre-development, and transient post-development conditions. Also developed the local scale model; guided calibration, sensitivity and model applications for predictive simulations; provided training on use of the model and on the theory and application of the software; and provided quality assurance oversight during application of the model by District staff.

Model Investigations for Consumptive use Permit Applications, Southwest Florida Water Management District, Brooksville, FL. Project manager responsible for the development and application of cross-sectional and 3-D DSTRAM finite-element models for predicting groundwater flow and saltwater intrusion in the Eastern Tampa Bay WUCA. Also assisted in reviewing previous MODFLOW regional and subregional groundwater modeling studies as part of the consumptive use permit (CUP) applications.

Water Resources Assessment Program HCWRAP2, Southwest Florida Water Management District, Brooksville, FL. Directed the development of MODFLOW-based regional groundwater flow and saltwater intrusion models that were used in conjunction with management optimization techniques to determine optimal locations of wells to minimize their impacts on lakes and wetlands and on the movement of the saltwater/freshwater interface. Several models were developed and calibrated which were then used with the well optimization simulations to investigate various objectives of the District.

Safe Yield Analysis of County Wellfields, Pinellas County Water System, Pinellas County, FL. Project manager for the development of a safe yield analysis model for the Eldridge-Wilde and East Lake Road wellfields operated by the County. Water management concerns included drying up of lakes and wetlands, and saltwater intrusion from the Gulf of Mexico and Tampa Bay. Developed a finite-element model using DSTRAM to investigate the effects of pumping on saltwater intrusion and the surface water impacts. Performed safe yield analyses to optimize operation with minimal intrusion of saltwater or degradation of wetlands and lakes.

Contaminant Transport Modeling

Estimation of the Volumes, Mobility, Recoverability, and Natural Depletion of LNAPL Plumes, Papa John's Cardinal Stadium Property, Louisville, Kentucky, Louisville, Kentucky. Co-principal investigator for estimating product volumes, mobility, recoverability and natural depletion of LNAPL plumes. A GIS based mobility and volume approach was used to model LNAPL plumes in a heterogeneous aquifer setting, using the American Petroleum Institute's LNAPL Distribution and Recovery Model equation in multiple dimensions. Volumes of LNAPL were compared with the mobile volumes and the readily recoverable volumes. Mobility distributions were also evaluated to determine optimal site operations. Recoverability estimates were computed for skimming which was the most effective method at the site.

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Flow and Transport Modeling of Trichloroethene (TCE) to Support Remedial and Containment Design, Confidential Client, Goodyear, AZ. Principal investigator for development, calibration, and application of groundwater flow and transport models to evaluate remedial and containment designs for pump and treat systems. The MODFLOW and MT3DMS models were used to evaluate pumping rates and well locations for effective containment, capture, and treatment of the TCE plume under various changes in aquifer recharge, municipal pumping and other operations adjacent to the site. The models are still being used to evaluate the impacts of any major hydrogeological decision at the site and in the vicinity and will be further used to evaluate source zone remediation. The models were developed and applied in an open forum that included technical representatives from stakeholders and regulators and were an important component of the remedial and containment plan.

Development of a Site-Specific Impact to Groundwater Soil Remediation Standard, Confidential Client, Roseland, NJ. Principal investigator for the development of site specific soil standards for TCE underneath the site. A SESOIL vadose zone model with normalized soil loading inputs was used to provide input to an AT123D groundwater flow model at various locations to evaluate cleanup objectives for various depths of vadose zone contamination. The site specific objectives guided soil clean-up levels and locations required for groundwater compliance.

Flow and Transport Modeling of Perchlorate to Support Cost Allocations and Remedial Design, Confidential Client, Rialto, CA. Principal investigator for the development, calibration, and application of a groundwater flow and transport model to assess source conditions from munitions and fireworks manufacturing and storage facilities, and to assist with remedial design for perchlorate and trichloroethene (TCE) plumes emanating from the former bunker and storage facilities. The model was used in mediation/litigation to address cost allocation disputes as well as to evaluate pumping rates and well locations for effective containment and treatment of the perchlorate plume.

Remedial Design Modeling, U.S. Army Corps of Engineers, Fort Ord, CA. Principal investigator for modeling remedial design of the contaminated site at the Fort Ord facility. A local model around the benzene plume was developed and calibrated for flow and transport conditions at the site using MODFLOW-SURFACT. The model was used to evaluate various design alternatives for pump-and-treat of the contaminant, with predictive sensitivity analysis providing uncertainty bounds on the results. Well locations were constrained to avoid drilling in adjacent ecologically sensitive areas, and well pumping was optimized to meet regulatory requirements within a period of six years of operation. Modeling served as a design guide for the project throughout the multi-year cleanup effort.

Flow and Transport Modeling for Massachusetts Military Reservation, U.S. Air Force Center for Environmental Excellence, Cape Cod, MA. Project manager responsible for leading a team of personnel in the development, calibration, and application of MODFLOW-based regional and plume-specific groundwater flow, particle tracking and contaminant transport models for examination of alternative remedial strategies and optimization of pump and treat systems at the site. Managed the development of appropriate modules to MODFLOW for stable solution to drying/re-wetting situations and for analyzing contaminant transport. Also provided support for preparation of presentation materials, and participated in technical and public meetings at this highly visible DOD site.

Peer Review of Modeling for Riverbed Water Quality, Fluor Hanford. Served on expert panel convened to evaluate Hanford groundwater issues related to chromium contamination within the hyporheic zone, groundwater surface water interactions, and modeling. Reviewed required reading materials, participated in a three day technical workshop, prepared presentations and reports of findings.

Flow and Transport Modeling, U.S. EPA Office of Radiation Programs, Carlsbad, NM. Project scientist for providing flow and transport modeling analyses support for the Waste Isolation Pilot Plant (WIPP) project. Evaluated BRAGFLOW, TOUGH2, MAGNAS, STAFF3D, and SECCO (various flow and transport codes) to analyze multi-phase flow, fracture flow and transport; provided EPA personnel training and expert support on model applications to the WIPP site; conducted independent verification of modeling investigations conducted by Sandia National Laboratory for the Performance Assessment (PA); provided other technical assistance and expertise in reviewing PA reports and models; and provided relevant EPA personnel training in principles and numerical implementation of multiphase and fracture flow and transport models for the subsurface.

Flow and Transport Modeling for Niagara Falls Storage Site, U.S. Army Corps of Engineers, Buffalo District, Buffalo, NY. Technical supervisor for vadose zone and groundwater modeling of radionuclides at the Niagara Falls Storage Site. One-dimensional unsaturated zone flow and transport models were coupled with a three-dimensional groundwater flow and transport model to analyze the fate of various radionuclides originating from the storage facility under various future scenarios. The modeling was conducted to evaluate potential migration to the river.

Flow and Contaminant Transport Investigations, U.S. Air Force Center for Environmental Excellence, Beale Air Force Base, CA. Technical supervisor for groundwater modeling project involving regional and sub-regional model calibration using Data Fusion Modeling (DFM) for flow and contaminant transport investigations within the subsurface and their interactions with adjacent streams periodically backed up by beaver dams. Provided model conceptualization, development and calibration guidance, numerical troubleshooting, report review, and quality control reviews. The model was subsequently used to evaluate site remedial operations.

Groundwater Flow Models using Data Fusion Modeling (DFM), Westinghouse Savannah River Company, Savannah River Site, SC. Project engineer for development of a groundwater flow model using Data Fusion Modeling (DFM) for the A/M Area of the Savannah River Site (SRS). Provided troubleshooting for variably-saturated flow simulations using the finite-element VAM3DF code in conjunction with DFM to calibrate a flow model, quantify its uncertainties, perform transport calibration of source area and strength, and then quantify uncertainty in transport of contaminants using Monte Carlo simulations. The modeling was part of a program aimed at better understanding the radionuclide contamination at the site and associated risk by using all available soft and hard information.

Z-area Flow and Transport Modeling of Containment System Design for Low-level Nuclear Wastes, Westinghouse Savannah River Company, Savannah River Site, SC. Co-investigator involved in performance assessment and migration potential modeling of low-level nuclear waste in the Z-area at the SRS. Performed 2-D cross-sectional and 3-D analyses of potential contaminant fate and transport from a containment system design located in the unsaturated zone above the groundwater system using a finite-element saturated/unsaturated flow and transport code VAM3D. The simulations were aimed at assessing effectiveness of a cap-and-drain system of waste burial above the water table.

Groundwater Flow and Waste Migration Modeling, Westinghouse Hanford Company, Hanford, WA. Principal investigator responsible for conducting modeling studies of the groundwater flow and waste migration in support of RI/FS activities at the 200 West area of the DOE Hanford site. The model was used to evaluate the potential migration of several contaminants at the site. Also provided training and troubleshooting of model applications.

Flow and Transport Model Development, Westinghouse Hanford Company, Hanford, WA. Project engineer involved in modeling the migration of low-level nuclear waste at the Hanford site. Tasks included developing and calibrating local and site wide models to assess the extent of contamination, evaluating proposed cleanup strategies, conceptualizations, and problem setups, and analyzing other regional and local-scale models developed by Hanford personnel. Provided training sessions to Westinghouse Hanford personnel on use of the finite-element saturated/unsaturated flow and transport code, VAM3DCG. Provided guidance and troubleshooting support to personnel applying these models for examining a variety of transport related issues.

Flow and Transport Model Applications, Bechtel Hanford Company, Hanford, WA. Project manager responsible for modeling the migration of low-level nuclear waste at the Hanford site. A site-wide model was developed to assess the extent of contamination and to evaluate proposed cleanup strategies. The transport of tritium, nitrate, iodine-129, carbon tetrachloride, TCE, chloroform, uranium, and technetium-99 was simulated using VAM3DCG. Model sensitivity was investigated and the transport model was validated using current monitoring well concentrations. A 200-year predictive simulation was performed for all eight contaminants. Two pump-and-treat scenarios were modeled to predict the effect on future contaminant migration.

Multi-phase Modeling of Cleanup and Containment of LNAPLs at a Refinery Site, Confidential Oil Company, CA. Project manager and principal investigator responsible for conducting large-scale 3-D simulations of LNAPL contaminant movement under a refinery site. Tasks involved detailed literature searches and analysis of available data, model development and parameter estimation from various data sources, model simulations for history-matching at different time periods through several years, sensitivity analyses, and development of optimal remediation and containment strategies for free product and dissolved contaminants. The model illustrated that aggressive technologies were not better at removing LNAPL from the silty soils and that containment strategies such as skimming were the more effective.

Saturated/Unsaturated Modeling for Landfill Liner Design, EPA Office of Solid Waste, Washington, D.C. Project engineer. Performed modeling investigations of synthetic and natural landfill liner materials and designs in support of drafting guidelines for landfill liner designs.

Hazardous Waste Identification Rule (HWIR) Modeling Support, U.S. EPA Office of Solid Waste, Washington, D.C. Task manager for RCRA support contract. Responsible for conducting land disposal and oily waste data surveys, developing composite vadose-saturated zone models for performance assessment of landfills and surface impoundments under RCRA subtitles C and D, and conducting modeling analyses and risk assessment support of the Hazardous Waste Identification Rule (HWIR).

Regulatory Modeling Support, U.S. EPA Office of Solid Waste, Washington, D.C. Project engineer. Conducted a quick-response risk evaluation for the Cement Kiln Dust Rule. Conducted several simulations using the EPACMTP code to examine migration through the groundwater pathway for exposure to various metals.

Multiphase Air-Sparging Remedial Modeling, Texaco, Inc. Loma Linda, CA. Project engineer for UST site remediation project. Performed modeling analyses of pilot field study to estimate the outcome of air sparging at a service station. Responsibilities included site data collection and interpretation, multiphase model development and application, and parameter sensitivity analyses. The strategies that were evaluated showed that air sparging could spread contamination to other parts of the aquifer, and sufficient control could not be exerted by the vacuum extraction wells.

<u>Software Development</u>

Lead Developer of the MODFLOW-USG Groundwater Flow Model, U.S. Geological Survey, Reston, VA. Co-investigator for development of the MODFLOW-USG code which is an enhancement of MODFLOW to use unstructured grids. Version 1 of the code has been released by the USGS in May 2013 with several enhancements planned for version 2 including turbulent fracture flow, contaminant transport, and saltwater intrusion simulation capabilities.

Co-Developer of the MODFLOW-NWT Groundwater Flow Model, U.S. Geological Survey, Reston, VA. Co-investigator for development of the MODFLOW-NWT code which is an enhancement of MODFLOW that overcomes drying and rewetting difficulties of unconfined solutions. The code uses an upstream-weighting formulation with a Newton Raphson linearization and other robust schemes to provide robust solutions to highly nonlinear problems. MODFLOW-NWT is gaining in popularity since its recent release and is being used throughout the world.

Principal Developer of MODFLOW-SURFACT and MODHMS Codes till 2007, HydroGeoLogic Inc, Reston, VA. Principal Developer of the popular commercial MODFLOW-SURFACT and MODHMS suite of codes from inception through 2007. The USGS groundwater simulation code, MODFLOW, was greatly enhanced to increase functionality and improve simulation capabilities and speed for large, complex problems.

Co-Developer of the HydroGeoSphere Integrated Groundwater, Surface Water Model, U.S. Bureau of Reclamation, Sacramento, CA. Co-investigator for development of the HydroGeoSphere code for physically-based, spatially-distributed modeling of scale-dependent investigations on agricultural plots, small watersheds, and large basins. The code is developed as an extension to the FRAC3DVS model developed at the University of Waterloo. Responsibilities included definition, design, interface, coding, testing and documentation of surface-water flow and transport modules, and modules for interaction between the subsurface and surface systems.

Development of Multi-Phase, Non-Isothermal Model, U.S. National Science Foundation, Washington, D.C. Principal investigator on SBIR grant for development of CAMFACT, a compositional, multi-phase, non-isothermal model for NAPL contamination and remediation investigations. Tasks included delineation of required functionality and objectives, development of a robust formulation, code development, verification, benchmarking, documentation, and examination of steam injection and venting processes for remediation of LNAPL contaminants. The code handles up to seven component species that exist in one or all of up to three fluid phases in the domain. Robust nodal column assembly schemes for the Jacobian, block Orthomin solution routines, adaptive time-stepping, under relaxation formulas, and orthogonal curvilinear grid geometry were incorporated to enable solutions of field scale problems on workstations or minicomputers.

Development of a 3-D Multiphase Flow and Transport Simulator, Los Alamos National Laboratory, Los Alamos, NM. Project engineer with team for the development of MAGNAS, a 3-D multiphase flow and transport simulator. Involvement included providing input on the governing equations and code structure, coding of non-linear modules, interfacing the solver, finalizing the document, and preparing manuscripts for publication in refereed technical journals.

Development of a Finite-Element 3-D Fracture Flow and Transport Code, Sandia National Laboratory, City, NM. Co-developer of STAFF3D, a finite-element, 3-D fracture flow and transport code. A 3-component decay chain and density dependent flow and transport can be handled by the code. Dual porosity as well as discrete fracture options were provided. Orthogonal curvilinear elements and transition elements were implemented to provide a natural discretization for layered systems, irregular boundaries, and nested grids in regions of interest. Various lattice connectivity options, adaptive time-stepping and under relaxation formulas, and robust Orthomin solution schemes were used in the code to provide efficient solutions to large-scale field problems. The model was benchmarked and a documentation and user's guide was prepared. The code primarily was developed for Sandia National Laboratories for their investigation of the Yucca Mountain site, NV. Responsibilities included code design, numerical algorithm development, and implementation, benchmarking, and documentation.

3-D Density-Dependent Flow and Transport Code Development, St. Johns River Water Management District, Palatka, FL. Co-developer of DSTRAM, a 3-D density-dependent flow and transport code intended for saltwater intrusion investigations. Responsibilities included code development, verification, validation, benchmarking, and documentation.

Saturated and Unsaturated Zone Flow and Transport Model Development, Westinghouse Savannah River Company, Savannah River Site, SC. (Prior to AMEC) Co-developer of VAM3DCG, a 3-D saturated/unsaturated zone flow and transport model. Implemented state-of-the-art techniques including curvilinear elements, transition elements (for creating nested grids), various lattice connectivity options, Newton-Raphson linearization, and robust Orthomin solution schemes. Rigorously modeled unsaturated zone physical processes such as recharge, evaporation, and plant root uptake. Assisted in algorithm development, coding, benchmarking, and documentation of the model and disseminating the effort through referred technical publications.

Litigation Support

Impact of Groundwater Pumping on Flow to Rivers and Streams in the Apalachicola, Chattahoochee, Flint (ACF) River Basin, State of Georgia, Atlanta, GA. Expert Witness in a court case concerning State of Florida v. State of Georgia, in the Supreme Court of the United States, Case No. 142, Original. Provided support to Georgia for delineating the impact of pumping within the Basin from weather related impacts to flow at the Florida-Georgia Stateline. Evaluated the weather, streamflow, and hydrogeologic data in the basin and modeled the impact of groundwater pumping on unimpaired flows (UIFs) to the rivers and streams. The UIFs for various pumping and non-pumping cases were also provided to the surface-water testifying expert for calculations that evaluated flow into Florida, considering storage in reservoirs and operations of dams within the Basin regulated by the United States Army Corps of Engineers (USACE). Plaintiff's modeling efforts and investigations were also reviewed and critiqued. Provided three full days of depositions and testified before the Special Master appointed by the Supreme Court. The Special Master has ruled in Georgia's favor.

GIS-Based Mobility Modeling for LNAPL at an Oil Terminal Site, BP Products North America, Inc., Green Bay, WI property. Expert witness in court case Tilot Oil, LLC v. BP Products North America, in the United States District Court Eastern District of Wisconsin, Case No. 09-C-0210. Provided two depositions on NAPL mobility modeling that was conducted in a GIS setting to provide NAPL flux estimates across the property boundary of an Oil Terminal site in support of litigation. The American Petroleum Institute's LNAPL Distribution and Recovery Model equation representing multiphase flow of LNAPL was integrated in the vertical direction over the free product thickness and applied spatially in a GIS environment to provide mobility estimates for free product in an areally distributed manner throughout the area of investigation and specifically, across the property boundary. Plaintiff's modeling efforts were also reviewed and critiqued. The analysis and subsequent report resulted in an undisclosed settlement in the client's favor.

Model Reviews, St Johns River Water Management District, Titusville, Florida. Provided review support for models developed by all parties in this case concerning permit application for pumping from the Area IV well field in Titusville, Florida. MODFLOW and SEAWAT models were developed by the permit applicants and parties opposing the permitted withdrawals. The reviews were provided to allow the District to be unbiased in the permit application process, and to enable the District to defend their position in court.

Litigation Support, Santa Maria Valley Water Conservation District, Santa Maria, CA. (Prior to AMEC) Expert witness for use of MODFLOW-SURFACT in case concerning Santa Maria Valley Water Conservation District V. City of Santa Maria, et al., Santa Clara County Superior Court Case No. CV 70214. Provided deposition for this case, for which the judge later requested the parties to come to an understanding out of court.

Training and Support

MODFLOW-USG Training, Various Clients. Conduct training courses and webinars on fundamentals and application of MODFLOW-USG with various organizations including the California Groundwater Resource Association (GRA), the National Groundwater Association (NGWA), and with developers of commercial interface codes such as Groundwater Vistas, GMS and Visual MODFLOW.

Code Training and Support, HydroGeoLogic Inc, Reston, VA. Provided modeling support and training nationally and internationally, for users of MODHMS, MODFLOW-SURFACT, DSTRAM, STAFF3D, MAGNAS3D and VAM3D.

U.S. EPA Office of Radiation Programs, Carlsbad, NM. Conducted two, week-long training sessions on principles of modeling multiphase flow and transport through porous media, and on the fundamentals of fracture flow and transport.

Washington State University, Pullman, WA. Research and teaching assistant. Assisted in conducting a short course on the application of MOC, MODFLOW, PLASM, and other public domain groundwater flow and transport codes. Conducted classroom, laboratory, and tutorial sessions for first fluid mechanics course (Fundamentals of Fluid Mechanics) for 4 semesters.

University of Delaware, Newark, DE. Research and teaching assistant. Assisted in conducting NATO-ASI (Advanced Study Institute) seminars and short courses on the application of MOC, MODFLOW, PLASM, and other public domain groundwater flow and transport codes. Assisted in conducting short courses on fundamentals of modeling.

Invited Talks

Groundwater Modelers Forum, *"Pushing the Boundaries – New Issues and Applications in Groundwater Modelling,"* Birmingham, UK. May, 2014

"What's New in Groundwater Modeling?" NGWA, Pillars of Groundwater Innovation Conference, Phoenix, Arizona, November 2013MODFLOW and More, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, Technical Committee Member, 2006 to 2015

MODFLOW and More, International Groundwater Modeling Center, Colorado School of Mines, Golden, Colorado, Technical Committee Member, 2006 to 2015

NGWA Conference, *"Modeling for Groundwater Management and Sustainability,"* Garden Grove, CA, May, 2012

Select Publications

“Incorporating the effect of gas in modelling the impact of CBM extraction on regional groundwater systems”, D. Herckenrath, J. Doherty, and S. Panday, Journal of Hydrology 523, 587–60, 2015.

“A method for estimating spatially variable seepage and hydraulic conductivity in channels with very mild slopes”, M. Shanafield, R.G. Niswonger, D. E. Prudic, G. Pohll, R. Susfalk and S. Panday, Hydrological Processes, DOI: 10.1002/hyp.9545, 2014.

“MODFLOW-USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation”, Panday, Sorab, Langevin, C.D., Niswonger, R.G., Ibaraki, Motomu, and Hughes, J.D., U.S. Geological Survey Techniques and Methods, book 6, chap. A45, 66 p, May 2013.

“Future of Groundwater Modeling”, C. D. Langevin, and S. Panday, Invited article for Column Theme: 50th Year Tribute to Modeling: Past, Current, and Future, Groundwater, Vol. 50, No. 3, p. 333-339, doi: 10.1111/j.1745-6584.2012.00937.x, May-June 2012.

“Improving sub-grid scale accuracy of boundary features in regional finite-difference models”, S. Panday and C. D. Langevin, Advances in Water Resources, Volume 41, pages 65-75, June 2012.

“Dynamic Subtiming-Based Implicit Nonoscillating Scheme for Contaminant Transport Modeling”, Misra, C., S. T. Manikandan, S. M. Bhallamudi, and S. Panday, Journal of Hydrologic Engineering, Vol. 17, No. 6, June 1, 2012. ©ASCE, ISSN 1084-0699/2012/6-0–0/$25.00, 2012.

“Impact of Sea Level Rise on Groundwater Salinity in a Coastal Community of South Florida”, Guha, H., and S. Panday, Journal of the American Water Resources Association 1-19. DOI: 0.1111/j.1752-1688.2011.00630.x, 2012.

“Approaches to the Simulation of Unconfined Flow and Perched Groundwater Flow in MODFLOW”, Bedekar, V., Niswonger, R. G., Kipp, K., Panday, S. and Tonkin, M., Ground Water, 49: no. doi: 10.1111/j.1745-6584.2011.00829.x, 2012.

“MODFLOW-NWT, A Newton formulation for MODFLOW-2005”. Niswonger, R.G., S. Panday, and Ibaraki, Motomu, U.S. Geological Survey Techniques and Methods 6–A37, 44 p. 2011.

“An Un-Structured Grid Version of MODFLOW”, Panday, S., R.G. Niswonger, C.D. Langevin, M. Ibaraki. MODFLOW and MORE 2011 Conference, Golden, CO. 2011.

“Local Grid Refimement with an Unstructured Grid Version of MODFLOW”, Langevin C.D., S. Panday, R.G. Niswonger, M. Ibaraki, S. Mehl. MODFLOW and MORE 2011 Conference, Golden, CO. 2011.

“Simulating Dynamic Water Supply Systems in a Fully Integrated Surface–Subsurface Flow and Transport Model.” S. Panday, N. Brown, T. Foreman, V. Bedekar, J. Kaur, and P. S. Huyakorn. Vadose Zone Journal. 8: 858-872. Nov. 1 2009.

“Implicit Subtime Stepping for Solving Nonlinear Flow Equations in an Integrated Surface–Subsurface System.” Young-Jin Park, E. A. Sudicky, S. Panday, and G. Matanga. Vadose Zone Journal. 8: 825-836. Nov. 1 2009.

“A Spatially Distributed Hydroeconomic Model to Assess the Effects of Drought on Land Use, Farm Profits, and Agricultural Employment.” M.P. Maneta, M.O. Torres, W.W. Wallender, S. Vosti, R. Howitt, L. Rodrigues, L.H. Bassoi and S. Panday. Water Resources Research, Vol. 45, W11412, doi:10.1029/2008WR007534. November, 2009.

“CHyMP Workshop: The Community Hydrologic Modeling Platform.” S. Panday. The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) Conference, Memphis, TN. March 30 – April 1, 2009.

“Managing Salinity in the Upper Santa Clara River System of California.” Brown, N., B.Louie, F.Guerrero, T.Foreman, S.Panday, V.Bedekar, and J.Kaur. Proceedings of the World Environmental and Water Resources Congress 2009: Great Rivers. May 17-21, 2009. Kansas City, Missouri, 2009.

“Calibration of an Evapotranspiration Model to Simulate Soil Water Dynamics in a Semiarid Rangeland.” M. P. Maneta, S. Schnabel, W. W. Wallender, S. Panday, and V. Jetten. Hydrological Processes. 2008.

“Application of Implicit Sub-time Stepping to Simulate Flow and Transport in Fractured Porous Media.” Y.-J. Park, E.A. Sudicky, S. Panday, J.F. Sykes, V. Guvanasen. Advances in Water Resources. Vol. 31, pp. 995-1003. 2008.

“MODFLOW SURFACT: A State-of-the-Art Use of Vadose Zone Flow and Transport Equations and Numerical Techniques for Environmental Evaluations.” S. Panday and P. S. Huyakorn. Vadose Zone Journal. Vol. 7, No. 2, pp. 610-631. May 2008.

“Solubility-limited transport of radionuclides through the unsaturated zone using MODHMS”, Scott, M., D. Demarco, S. Panday, and E. Evans, Proceedings of the MODFLOW-2008 Conference, Golden, Colorado, 2008.

“Modeling the surface-water groundwater interactions in the Peace River Basin, Florida using MODHMS”, Khambhammettu, P., J. Kool, M-S. Tsou, S. Panday, M. Beach, Proceedings of the MODFLOW-2008 Conference, Golden, Colorado, 2008.

“Modeling shallow water table evaporation in irrigated regions”, Young, C.A. , W.W. Wallender, G. Schoups, G. Fogg, B. Hanson, T.H. Harter, J.W. Hopmans, R. Howitt, T. Hsiao, S. Panday, K.K. Tanji, S. Ustin, K. Ward, Irrigation and Drainage Systems, 21(2), 119-132, 2007.

“Sustainability of irrigated agriculture in the San Joaquin Valley, California.” Schoups, G., Hopmans, J.W., Young, C.A., Vrugt, J.A., Wallender, W.W., Tanji, K.K., and Panday, S. Proceedings of the National Academy of Sciences of the United States of America, 2005.

“On the Challenge of Integrated Surface - Subsurface Flow and Transport Modeling at Multiple Catchment Scales, Innovations and New Frontiers in Hydrologic Modeling.” E. A. Sudicky, R. Therrien, Y. J. Park, R. G. McLaren, J. P. Jones, J. M. Lemieux, A. E. Brookfield, D. Colautti, S. Panday, and V. Guvanasen. GSA Annual Meeting, Salt Lake City, UT, 2005.

“A Fully Coupled Physically-Based Spatially-Distributed Model for Evaluating Surface/Subsurface Flow.” Panday, S. and P.S. Huyakorn. Advances in Water Resources. Vol. 27, pp. 361 – 382, 2004.

“Effect of Permeability and Porosity Conditioning on the Prediction of Dense Chlorinated Solvent Migration Patterns in a Highly Characterized Fluvial Aquifer.” Maji, R., Sudicky, E.A., Panday, S. and Teutsch, G., Geological Society of America Annual Meeting, Proceedings, Seattle, Washington, November, 2003.

“MODFLOW-Based Tools for Simulation of Variable-Density Groundwater Flow.” Langevin, C., Oude Essink, G., Panday, S., Bakker, M., Prommer, H., Swain, E., Jones, W., Beach, M., Barcelo, M. Coastal Aquifer Management-Monitoring, Modeling, and Case Studies. Cheng, Alexander H.D. and D. Ouazar, CRC Press. 2003.

“Sub-timing in Fluid Flow and Transport Simulations.” Bhallamudi, S. M., Panday, S., and P.S. Huyakorn, Advances in Water Resources. Vol. 26, pp. 477 - 489. 2003.

“Multi-Scale Conjunctive Modeling of Surface and Subsurface Flow.” S. Panday, MODFLOW-2003 Conference, Golden, CO, 2003.

“Conditional Stochastic Analysis of DNAPL Migration Patterns and Aqueous-phase Plume Transport in a Highly Characterized Fluvial Aquifer.” Maji, R., E. A. Sudicky, S. Panday, and G. Teutsch. Proceedings of the MODFLOW-2003 Conference, Golden, CO, 2003.

“Simulation of Dissolution and Vapor Partitioning from LNAPL using a MODFLOW-Compatible Transport Code.” Young, S. C., T. Budge, S. Panday, D. Van Winkle, D. Huntley, and R. Frank. Proceedings of the MODFLOW-2003 Conference, Golden, CO, 2003.

“Surface/Subsurface Modeling of Western Orange and Seminole Counties of Florida.” Jones, W., S. Panday, S. Frost, and B. McGurk. Proceedings of the MODFLOW-2003 Conference, Golden, CO, 2003.

GSI ENVIRONMENTAL

“Comparisons of Linked and Fully Coupled Approaches to Simulating Conjunctive Surface/Subsurface Flow and Their Interactions.” Fairbanks, J., S. Panday, and P.S. Huyakorn, Proceedings of the MODFLOW-2001 Conference, Golden, CO, 2001.

“Rigorous Coupling of Surface Water and Vadose Zone Flow with MODFLOW.” Panday, S., and P.S. Huyakorn. Proceedings of the MODFLOW-98 Conference, Golden, CO, 1998.

"A Comprehensive Three-Dimensional Numerical Model for Predicting the Transport and Fate of Petroleum Hydrocarbons in the Subsurface." Huyakorn, P.S., Y.S. Wu, and S. Panday, Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Groundwater Conference, Houston, TX, 1992.

“Air Sparging: A case study in characterization, field testing, and modeling design.” Beckett, G.D., D. Huntley, and S. Panday. Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection and Remediation Conference and Exposition, Houston, TX, 1995.

“A Mathematical Model of Ground Movement Due to Thaw Action in Unsaturated Soils.” Corapcioglu, M.Y., and S. Panday. Proceedings of the Fourth International Symposium on Ground Freezing, Sapporo, Japan, 1985.

“Thawing in Permafrost - Simulation and Verification.” Corapcioglu, M.Y., and Panday, S. Proceedings of the Fifth International Conference on Permafrost, Trondheim, Norway, 1988.

“Sensitivity of a Thaw Model to Various Frozen Soil Parameters.” Corapcioglu, M.Y., and Panday, S. Proceedings of the Fifth International Symposium on Ground Freezing, Nottingham, England, 1988.

“MODFLOW Enhancements for Robust, Reliable Simulations of Complex Environmental Flow and Contaminant Transport Situations.” Panday, S., and P.S. Huyakorn. Advances in Porous Media. Corapcioglu, M.Y. Volume 4, pp. 1-84, 2001.

“DSTRAM - Density-dependent Subsurface Transport Analysis Model.” Huyakorn, P.S., and Panday, S. Sea Water Intrusion in Coastal Aquifers - Concepts, Methods and Practices. J. Bear, A. H-D. Cheng, S. Sorek, I. Herrera, and D. Ouazar, Kluwer Academic Publishers, Chapter 10. pp. 407-409, 1999.

“A Composite Numerical Model for Assessing Subsurface Transport of Oily Wastes and Chemical Constituents.” Panday, S., Wu, Y.S., Huyakorn, P.S., Wade, S.C. and Saleem, Z.A. Journal of Contaminant Hydrology. Vol. 25, pp. 36-62, 1997.

“Considerations for Robust Compositional Simulations of Subsurface NAPL Contamination and Remediation.” Panday, S., Forsyth, P.A., Falta, R.W., Wu, Y.S., and Huyakorn, P.S. Water Resources Research. Vol. 31, No. 5, pp. 1273-1289, 1995.

“Multiphase Approach to Thaw Subsidence of Unsaturated Frozen Soils: Equation Development.” Panday, S., and Corapcioglu, M.Y. Journal of Engineering Mechanics. Vol. 123, No. 3, pp. 448-459, 1995.

“Solution and Evaluation of Permafrost Thaw-Subsidence Model.” Panday, S., and Corapcioglu, M. Y. Journal of Engineering Mechanics. Vol. 121, No. 3, pp. 460-471, 1995.

“A Three-Dimensional Multiphase Flow Model for Assessing NAPL Contamination in Porous and Fractured Media: I Formulation.” Huyakorn, P.S., Panday, S. and Wu, Y.S. Journal of Contaminant Hydrology. Vol. 16, pp. 109-130, 1994.

“A Three-Dimensional Multiphase Flow Model for Assessing NAPL Contamination in Porous and Fractured Media: II Porous Medium Simulation Examples.” Panday, S., Wu, Y.S., Huyakorn, P.S., Springer, E.P. Journal of Contaminant Hydrology. Vol. 16, pp.131-156, 1994.

“Theory of Phase-Separate Multicomponent Contaminant Transport in Frozen Soils.” Panday, S., and Corapcioglu, M.Y. Journal of Contaminant Hydrology. Vol. 16, pp. 235-269, 1994

“Improved Three-Dimensional Finite Element Techniques for Field Simulation of Variably Saturated Flow and Transport.” Panday, S., Huyakorn, P.S., Therrien, R., Nichols, R.L. Journal of Contaminant Hydrology, Vol. 12, pp. 3-33, 1993.

“Simulation of Hydrocarbon Spills in Permafrost.” Corapcioglu, M.Y., and Panday, S. Permafrost. Vol.1, pp.100-104, 1993.

"Compositional Multiphase Flow Models." Corapcioglu, M.Y. and S. Panday. Advances in Porous Media. M. Y. Corapcioglu Vol. 1, pp. 1-59, 1991.

"Numerical Analysis of the Effects of Groundwater Development in the Geneva Area, Seminole County, Florida." Panday, S., P.S. Huyakorn, J.B. Robertson, B. McGurk. Journal of Contaminant Hydrology. Vol. 12, pp. 329-354, 1991.

"Solute Rejection in Freezing Saline Soils." Panday, S. and M.Y. Corapcioglu. Water Resources Research. Vol. 27, No. 1, p. 99-108, 1991.

"A FORTRAN Microcomputer Program for Heat and Mass Transfer in Frozen Soils." Panday, S. and M.Y. Corapcioglu. Computers and Geosciences. Vol 15, No. 5, pp. 709-726, 1989.

"Reservoir Transport Equations by Compositional Approach." Panday, S. and M.Y. Corapcioglu. Transport in Porous Media. Vol. 4, pp. 369-393, 1989.

"Fundamental Equations for Transport Processes in Storage Reservoirs." Corapcioglu, M.Y., and S. Panday, Underground Storage of Natural Gas Theory and Practice, edited by M.R. Tek, Kluwer Academic Publishers, Proceedings of the NATO Advanced Study Institute, Ankara, Turkey, 2-10 May 1988.

TABLE 1

DATA AND STUDIES REGARDING SALINITY WITHIN THE TPCCS AND ITS EFFECTS ON GROUNDWATER

Ref No.	Year	Reference Abbreviation	Reference
1	2016	Chin, 2016	Chin, David A., 2016, The Cooling-Canal System at the FPL Turkey Point Power Station (Chin, 2016).
2	1978	Dames & Moore, 1978	Dames & Moore, 1978, Salinity Evaluation, Turkey Point Cooling Canal System, Florida Power & Light Company, January 5 (Dames & Moore, 1978).
3	1990	Dames & Moore, 1990	Dames & Moore, 1990, Annual Report, August 1990, Ground-Water Monitoring Program, Florida Power & Light Company Turkey Point Plant, August 30 (Dames & Moore, 1990).
4	1992	Dames & Moore, 1992	Dames & Moore, 1992, Annual Report, August 1992, Ground-Water Monitoring Program, Florida Power & Light Company Turkey Point Plant, Date County, Florida, August 31 (Dames & Moore, 1992).
5	2011	Ecology and Environment, 2011a	Ecology and Environment, Inc., 2011, Turkey Point Plant, Semi-Annual Monitoring Report, Units 3 & 4 Uprate Project, February 15 (Ecology and Environment, 2011a).
6	2011	Ecology and Environment, 2011b	Ecology and Environment, Inc., 2011, Turkey Point Plant, Annual Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2011b).
7	2011	Ecology and Environment, 2011c	Ecology and Environment, Inc., 2011, Turkey Point Plant, Appendices - Annual Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2011c).
8	2012	Ecology and Environment, 2012a	Ecology and Environment, Inc., 2012, Turkey Point Plant, Semi-Annual Monitoring Report, Units 3 & 4 Uprate Project, March 28 (Ecology and Environment, 2012a).
9	2012	Ecology and Environment, 2012b	Ecology and Environment, Inc., 2012, Turkey Point Plant, Initial Ecologic Condition Characterization Report, June (Ecology and Environment, 2012b).
10	2012	Ecology and Environment, 2012c	Ecology and Environment, Inc., 2012, Turkey Point Plant, Comprehensive Pre-Uprate Monitoring Report, Units 3 & 4 Uprate Project, October 31 (Ecology and Environment, 2012c).
11	2014	Ecology and Environment, 2014	Ecology and Environment, Inc., 2014, Turkey Point Plant, Annual Post-Uprate Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2014).
12	2016	Ecology and Environment, 2016a	Ecology and Environment, Inc., 2016, Florida Power & Light Company, Turkey Point Power Plant, Cooling Canal System (CCS) Freshening Effectiveness Report, January 29 (Ecology and Environment, 2016a).
13	2016	Ecology and Environment, 2016b	Ecology and Environment, Inc., 2016, Turkey Point Plant, Comprehensive Post-Uprate Monitoring Report, Units 3 and 4 Uprate Project, March 31 (Ecology and Environment, 2016b).

SECTION II - HISTORY OF WATER FLOW AND SALINITY IN AND AROUND THE TPCCS

Ref No.	Year	Reference Abbreviation	Reference
14	2016	Enercon, 2016	Enercon Services Inc., 2016, PTN Cooling Canal System, Electromagnetic Conductance Geophysical Survey, Final Report, Florida Light & Power (FPL) Turkey Point Plant, May (Enercon, 2016).
15	1972	FCD, 1972	Central and Southern Florida Flood Control District, Agreement with FPL, dated February 2nd, 1972 (FCD, 1972).
16	2003	FPL, 2003	FPL, 2003, Annual Report - 2003, Ground-Water Monitoring Program, Turkey Point Plant, Dade County, Florida, September 9 (FPL, 2003).
17	2005	FPL, 2005	FPL, 2005, Annual Report - 2004, Ground-Water Monitoring Program, Turkey Point Plant, Dade County, Florida, February 28 (FPL, 2005).
18	2016	FPL, 2016a	FPL, 2016, Response to Chin, 2016, and Technical Addendum, March 18 (FPL, 2016a).
19	2010	GeoTrans, 2010a	GeoTrans, Inc., 2010, Technical Memorandum, Water/Salt Balance Model of Turkey Point Cooling Canal System, August 4 (GeoTrans, 2010a).
20	2010	GeoTrans, 2010b	GeoTrans, Inc., 2010, Feasilibity Study to Assess Engineerring Options for Stopping Westward Migration of Saline Water and Decreasing Cooling Canal System Concentrations, Turkey Point Plant, Florida, August 11 (GeoTrans, 2010b).
21	2008	Golder, 2008a	Golder Associates, Inc., 2008, 2005 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, June 13 (Golder, 2008a).
22	2008	Golder, 2008b	Golder Associates, Inc., 2008, 2006 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, July 9 (Golder, 2008b).
23	2008	Golder, 2008c	Golder Associates, Inc., 2008, 2007 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, July 14 (Golder, 2008c).
24	2008	Golder, 2008d	Golder Associates, Inc., 2008, 2008 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, August 28 (Golder, 2008d).
25	2009	Golder, 2009	Golder Associates, Inc., 2009, 2009 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, September 16 (Golder, 2009).
26	2010	Golder, 2010	Golder Associates ,Inc., 2010, 2010 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, August 30 (Golder, 2010).

Ref No.	Year	Reference Abbreviation	Reference
27	2011	Golder, 2011a	Golder Associates, Inc., 2011, Appendix A of 2011 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida (Golder, 2011a).
28	2011	Golder, 2011b	Golder Associates ,Inc., 2011, 2011 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, August 31 (Golder, 2011b).
29	2009	Hughes et al., 2009	Hughes, Joseph D., Langevin, Christian D., Brakefield-Goswami, Linzy, 2009, Effect of Hypersaline Cooling Canals on Aquifer Salinization, U.S. Geological Survey, (Hughes et al., 2009).
30	2010	JLA Geosciences, 2010	JLA Geosciences, Inc., 2010, Geology & Hydrogeology Report for FPL, Turkey Point Plant, Groundwater, Surface Water, & Ecological Monitoring Plan, FPL, Turkey Point Plant, Homestead, Florida, October (JLA Geosciences, 2010).
31	2015	Miami-Dade Co., 2015a	Miami-Dade County, 2015, Consent Agreement between Miami-Dade County, Division of Environmental Resources Management and FPL, dated October 7, 2015 (Miami-Dade Co., 2015a).
32	2009	SFWMD, 2009	South Florida Water Management District, 2009, FPL Turkey Point Power Plant, Groundwater, Surface Water, and Ecological Monitoring Plan, Exhibit B, October 14 (SFWMD, 2009).
33	2010	SFWMD, 2010	South Florida Water Management District, 2010, Response to the Florida Power and Light 2008 and 2009 Annual Reports, Ground-Water Monitoring Program, August 3 (SFWMD, 2010).
34	2013	SFWMD, 2013	South Florida Water Management District, 2013, Consultation Pursuant to the October 14, 2009 Fifth Supplemental Agreement between the South Florida Water Management District and Florida Power & Light, April 16 (SFWMD, 2013).
35	2013	Tetra Tech, 2013	Tetra Tech, 2013, Technical Memorandum, Cross-Sectional Model of Turkey Point Cooling Canal System, July 15 (Tetra Tech, 2013).
36	2014	Tetra Tech, 2014a	Tetra Tech, 2014, Technical Memorandum, Evaluation of Required Floridan Water for Salinity Reduction in the Cooling Canal System, May 9 (Tetra Tech, 2014a).
37	2014	Tetra Tech, 2014b	Tetra Tech, 2014, Technical Memorandum, Evaluation of Drawdown in the Upper Floridan Aquifer Due to Proposed Salinity Reduction-based Withdrawals, May 13 (Tetra Tech, 2014b).
38	2014	Tetra Tech, 2014c	Tetra Tech, 2014, Technical Memorandum, Evaluation of Drawdown in the Upper Floridan Aquifer Due to Proposed Salinity Reduction-based Withdrawals, December 3 (Tetra Tech, 2014c).

Ref No.	Year	Reference Abbreviation	Reference
39	2015	Tetra Tech, 2015	Tetra Tech, 2015, Technical Memorandum, Evaluation of Alternative Measures for Cooling Canal System Salinity Reduction, January 29 (Tetra Tech, 2015).
40	2016	Tetra Tech, 2016a	Tetra Tech, 2016, A Groundwater Flow and Salt Transport Model of the Biscayne Aquifer, June (Tetra Tech, 2016a).
41	2016	Tetra Tech, 2016b	Tetra Tech, 2016, Addendum to Regional Biscayne Aquifer Groundwater Model Report (Tetra Tech, 2016b).
42	2016	Tetra Tech, 2016c	Tetra Tech, 2016, Application of Parameter Estimation Techniques to Simulation of Remedial Alternatives at the FPL Turkey Point Cooling Canal System, July 20 (Tetra Tech, 2016c).
43	2016	Tetra Tech, 2016d	Tetra Tech, 2016, Powerpoint Presentation: Allocation of Costs for CCS Remediation and Improvement, Methodology and Results, December 7 (Tetra Tech, 2016d).
44	2016	Tetra Tech, 2016e	Tetra Tech, 2016, Determination of Allocation of Costs for CCS Recovery and Improvement, December 21 (Tetra Tech, 2016e).
45	1971	US District Court, 1971	United States District Court for the Southern District of Florida, 1971, United States v. Florida Power & Light Co., September 10, 1971, Civ. A. No. 70-328 (US District Court, 1971).
46	2014	USGS, 2014	USGS, 2014, Origins and Delineation of Saltwater Intrusion in the Biscayne Aquifer and Changes in the Distribution of Saltwater in Miami-Dade County, Florida, Scientific Investigations Report 2014-5025 (USGS, 2014).
47	1978	USNRC, 1978	United States Office of Nuclear Reactor Regulation, 1978, Environmental Impact Appraisal by the Office of Nuclear Reactor Regulation Supporting Amendment Nos. 41 and 33 to Facility License Nos. DPR-31 and DPR-41, Florida Power and Light Company, Turkey Point Plant, Units 3 and 4, Docket Nos. 50-250 and 50-251 (USNRC, 1978).

TABLE 2

ANALYSES CONDUCTED BY OR ON BEHALF OF FPL SINCE 1978 TO EVALUATE SALTWATER MIGRATION

Ref No.	Year	Reference Abbreviation	Reference
1	1978	Dames & Moore, 1978	Dames & Moore, 1978, Salinity Evaluation, Turkey Point Cooling Canal System, Florida Power & Light Company, January 5 (Dames & Moore, 1978).
2	1990	Dames & Moore, 1990	Dames & Moore, 1990, Annual Report, August 1990, Ground-Water Monitoring Program, Florida Power & Light Company Turkey Point Plant, August 30 (Dames & Moore, 1990).
3	1992	Dames & Moore, 1992	Dames & Moore, 1992, Annual Report, August 1992, Ground-Water Monitoring Program, Florida Power & Light Company Turkey Point Plant, Date County, Florida, August 31 (Dames & Moore, 1992).
4	2011	Ecology and Environment, 2011a	Ecology and Environment, Inc., 2011, Turkey Point Plant, Semi-Annual Monitoring Report, Units 3 & 4 Uprate Project, February 15 (Ecology and Environment, 2011a).
5	2011	Ecology and Environment, 2011b	Ecology and Environment, Inc., 2011, Turkey Point Plant, Annual Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2011b).
6	2011	Ecology and Environment, 2011c	Ecology and Environment, Inc., 2011, Turkey Point Plant, Appendices - Annual Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2011c).
7	2012	Ecology and Environment, 2012a	Ecology and Environment, Inc., 2012, Turkey Point Plant, Semi-Annual Monitoring Report, Units 3 & 4 Uprate Project, March 28 (Ecology and Environment, 2012a).
8	2012	Ecology and Environment, 2012b	Ecology and Environment, Inc., 2012, Turkey Point Plant, Initial Ecologic Condition Characterization Report, June (Ecology and Environment, 2012b).
9	2012	Ecology and Environment, 2012c	Ecology and Environment, Inc., 2012, Turkey Point Plant, Comprehensive Pre-Uprate Monitoring Report, Units 3 & 4 Uprate Project, October 31 (Ecology and Environment, 2012c).
10	2014	Ecology and Environment, 2014	Ecology and Environment, Inc., 2014, Turkey Point Plant, Annual Post-Uprate Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2014).

SECTION II - HISTORY OF WATER FLOW AND SALINITY IN AND AROUND THE TPCCS

Ref No.	Year	Reference Abbreviation	Reference
11	2016	Ecology and Environment, 2016a	Ecology and Environment, Inc., 2016, Florida Power & Light Company, Turkey Point Power Plant, Cooling Canal System (CCS) Freshening Effectiveness Report, January 29 (Ecology and Environment, 2016a).
12	2016	Ecology and Environment, 2016b	Ecology and Environment, Inc., 2016, Turkey Point Plant, Comprehensive Post-Uprate Monitoring Report, Units 3 and 4 Uprate Project, March 31 (Ecology and Environment, 2016b).
13	2016	Enercon, 2016	Enercon Services Inc., 2016, PTN Cooling Canal System, Electromagnetic Conductance Geophysical Survey, Final Report, Florida Light & Power (FPL) Turkey Point Plant, May (Enercon, 2016).
14	2003	FPL, 2003	FPL, 2003, Annual Report - 2003, Ground-Water Monitoring Program, Turkey Point Plant, Dade County, Florida, September 9 (FPL, 2003).
15	2005	FPL, 2005	FPL, 2005, Annual Report - 2004, Ground-Water Monitoring Program, Turkey Point Plant, Dade County, Florida, February 28 (FPL, 2005).
16	2016	FPL, 2016a	FPL, 2016, Response to Chin, 2016, and Technical Addendum, March 18 (FPL, 2016a).
17	2010	GeoTrans, 2010a	GeoTrans, Inc., 2010, Technical Memorandum, Water/Salt Balance Model of Turkey Point Cooling Canal System, August 4 (GeoTrans, 2010a).
18	2010	GeoTrans, 2010b	GeoTrans, Inc., 2010, Feasilibity Study to Assess Engineerring Options for Stopping Westward Migration of Saline Water and Decreasing Cooling Canal System Concentrations, Turkey Point Plant, Florida, August 11 (GeoTrans, 2010b).
19	2008	Golder, 2008a	Golder Associates, Inc., 2008, 2005 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, June 13 (Golder, 2008a).
20	2008	Golder, 2008b	Golder Associates, Inc., 2008, 2006 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, July 9 (Golder, 2008b).

SECTION II - HISTORY OF WATER FLOW AND SALINITY IN AND AROUND THE TPCCS

Ref No.	Year	Reference Abbreviation	Reference
21	2008	Golder, 2008c	Golder Associates, Inc., 2008, 2007 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, July 14 (Golder, 2008c).
22	2008	Golder, 2008d	Golder Associates, Inc., 2008, 2008 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, August 28 (Golder, 2008d).
23	2009	Golder, 2009	Golder Associates, Inc., 2009, 2009 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, September 16 (Golder, 2009).
24	2010	Golder, 2010	Golder Associates ,Inc., 2010, 2010 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, August 30 (Golder, 2010).
25	2011	Golder, 2011a	Golder Associates, Inc., 2011, Appendix A of 2011 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida (Golder, 2011a).
26	2011	Golder, 2011c	Golder Associates ,Inc., 2011, 2011 Annual Report, Ground-Water Monitoring Program, Florida Power & Light Company, Turkey Point Plant, Miami-Dade County, Florida, August 31 (Golder, 2011c).
27	2010	JLA Geosciences, 2010	JLA Geosciences, Inc., 2010, Geology & Hydrogeology Report for FPL, Turkey Point Plant, Groundwater, Surface Water, & Ecological Monitoring Plan, FPL, Turkey Point Plant, Homestead, Florida, October (JLA Geosciences, 2010).
28	2013	Tetra Tech, 2013	Tetra Tech, 2013, Technical Memorandum, Cross-Sectional Model of Turkey Point Cooling Canal System, July 15 (Tetra Tech, 2013).
29	2014	Tetra Tech, 2014a	Tetra Tech, 2014, Technical Memorandum, Evaluation of Required Floridan Water for Salinity Reduction in the Cooling Canal System, May 9 (Tetra Tech, 2014a).

Ref No.	Year	Reference Abbreviation	Reference
30	2014	Tetra Tech, 2014b	Tetra Tech, 2014, Technical Memorandum, Evaluation of Drawdown in the Upper Floridan Aquifer Due to Proposed Salinity Reduction-based Withdrawals, May 13 (Tetra Tech, 2014b).
31	2014	Tetra Tech, 2014c	Tetra Tech, 2014, Technical Memorandum, Evaluation of Drawdown in the Upper Floridan Aquifer Due to Proposed Salinity Reduction-based Withdrawals, December 3 (Tetra Tech, 2014c).
32	2015	Tetra Tech, 2015	Tetra Tech, 2015, Technical Memorandum, Evaluation of Alternative Measures for Cooling Canal System Salinity Reduction, January 29 (Tetra Tech, 2015).
33	2016	Tetra Tech, 2016a	Tetra Tech, 2016, A Groundwater Flow and Salt Transport Model of the Biscayne Aquifer, June (Tetra Tech, 2016a).
34	2016	Tetra Tech, 2016b	Tetra Tech, 2016, Addendum to Regional Biscayne Aquifer Groundwater Model Report (Tetra Tech, 2016b).
35	2016	Tetra Tech, 2016c	Tetra Tech, 2016, Application of Parameter Estimation Techniques to Simulation of Remedial Alternatives at the FPL Turkey Point Cooling Canal System, July 20 (Tetra Tech, 2016c).
36	2016	Tetra Tech, 2016d	Tetra Tech, 2016, Powerpoint Presentation: Allocation of Costs for CCS Remediation and Improvement, Methodology and Results, December 7 (Tetra Tech, 2016d).
37	2016	Tetra Tech, 2016e	Tetra Tech, 2016, Determination of Allocation of Costs for CCS Recovery and Improvement, December 21 (Tetra Tech, 2016e).

TABLE 3

ANALYSES TO WHICH FPL HAD ACCESS

Ref No.	Year	Reference Abbreviation	Reference
1	2016	Chin, 2016	Chin, David A., 2016, The Cooling-Canal System at the FPL Turkey Point Power Station (Chin, 2016).
2	2009	Hughes et al., 2009	Hughes, Joseph D., Langevin, Christian D., Brakefield-Goswami, Linzy, 2009, Effect of Hypersaline Cooling Canals on Aquifer Salinization, U.S. Geological Survey, (Hughes et al., 2009).
3	2016	Miami-Dade Co., 2016	Miami-Dade County, 2016, Report on Recent Biscayne Bay Water Quality Observations associated with Florida Power and Light Turkey Point Cooling Canal System Operations - Directive 152884, March 7 (Miami-Dade Co., 2016).
4	2009	SFWMD, 2009	South Florida Water Management District, 2009, FPL Turkey Point Power Plant, Groundwater, Surface Water, and Ecological Monitoring Plan, Exhibit B, October 14 (SFWMD, 2009).
5	2010	SFWMD, 2010	South Florida Water Management District, 2010, Response to the Florida Power and Light 2008 and 2009 Annual Reports, Ground-Water Monitoring Program, August 3 (SFWMD, 2010).
6	2013	SFWMD, 2013	South Florida Water Management District, 2013, Consultation Pursuant to the October 14, 2009 Fifth Supplemental Agreement between the South Florida Water Management District and Florida Power & Light, April 16 (SFWMD, 2013).
7	2016	USGS, 2014	USGS, 2014, Origins and Delineation of Saltwater Intrusion in the Biscayne Aquifer and Changes in the Distribution of Saltwater in Miami-Dade County, Florida, Scientific Investigations Report 2014-5025 (USGS, 2014).

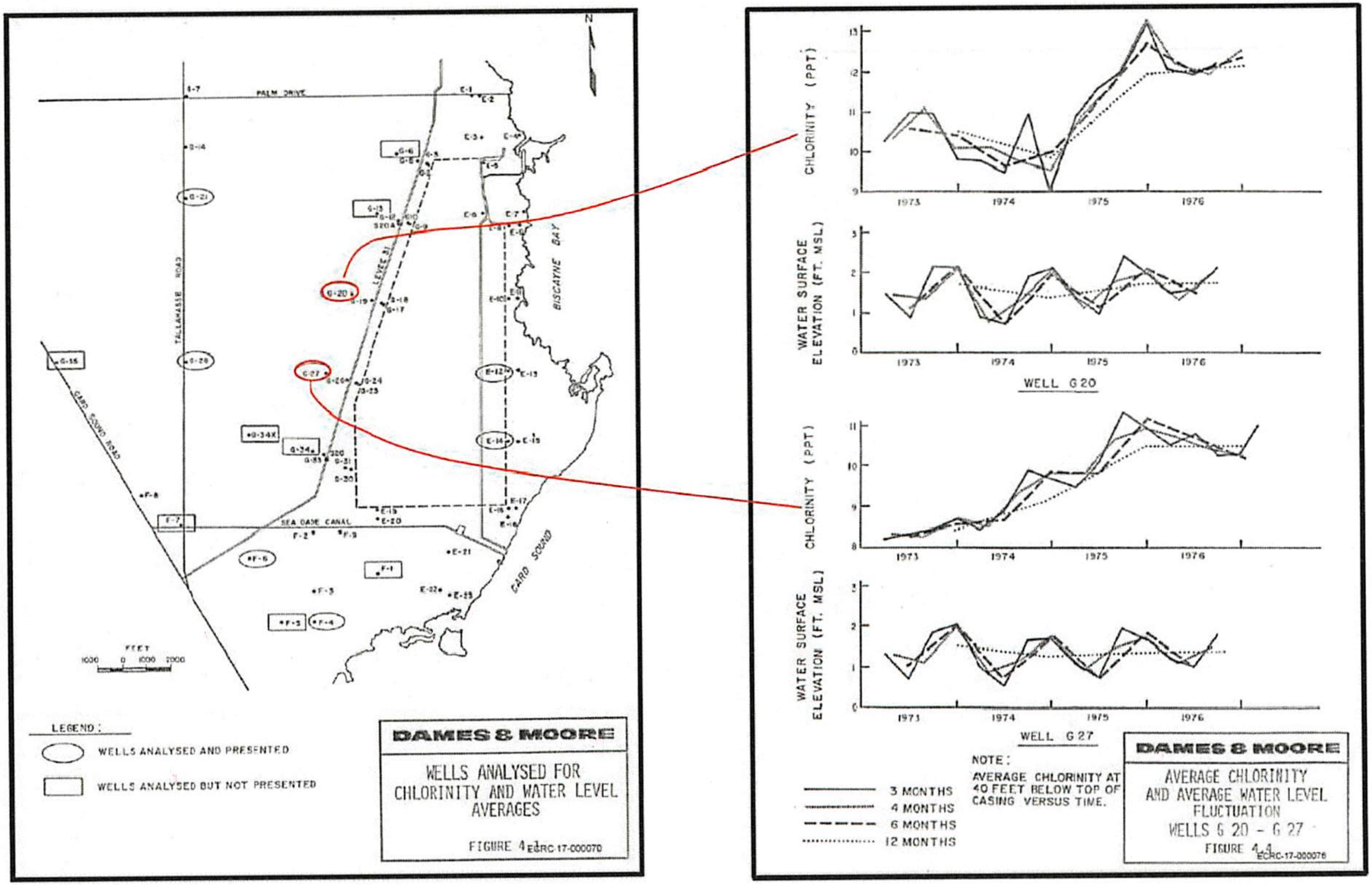
TABLE 4

ANALYSES CONDUCTED BY OR ON BEHALF OF FPL TO MEASURE THE EFFECT OF EFFORTS TO REDUCE SALINITY

Ref No.	Year	Reference Abbreviation	Reference
1	2011	Ecology and Environment, 2011a	Ecology and Environment, Inc., 2011, Turkey Point Plant, Semi-Annual Monitoring Report, Units 3 & 4 Uprate Project, February 15 (Ecology and Environment, 2011a).
2	2011	Ecology and Environment, 2011b	Ecology and Environment, Inc., 2011, Turkey Point Plant, Annual Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2011b).
3	2011	Ecology and Environment, 2011c	Ecology and Environment, Inc., 2011, Turkey Point Plant, Appendices - Annual Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2011c).
4	2012	Ecology and Environment, 2012a	Ecology and Environment, Inc., 2012, Turkey Point Plant, Semi-Annual Monitoring Report, Units 3 & 4 Uprate Project, March 28 (Ecology and Environment, 2012a).
5	2012	Ecology and Environment, 2012b	Ecology and Environment, Inc., 2012, Turkey Point Plant, Initial Ecologic Condition Characterization Report, June (Ecology and Environment, 2012b).
6	2012	Ecology and Environment, 2012c	Ecology and Environment, Inc., 2012, Turkey Point Plant, Comprehensive Pre-Uprate Monitoring Report, Units 3 & 4 Uprate Project, October 31 (Ecology and Environment, 2012c).
7	2014	Ecology and Environment, 2014	Ecology and Environment, Inc., 2014, Turkey Point Plant, Annual Post-Uprate Monitoring Report, Units 3 & 4 Uprate Project, August (Ecology and Environment, 2014).
8	2016	Ecology and Environment, 2016a	Ecology and Environment, Inc., 2016, Florida Power & Light Company, Turkey Point Power Plant, Cooling Canal System (CCS) Freshening Effectiveness Report, January 29 (Ecology and Environment, 2016a).
9	2016	Enercon, 2016	Enercon Services Inc., 2016, PTN Cooling Canal System, Electromagnetic Conductance Geophysical Survey, Final Report, Florida Light & Power (FPL) Turkey Point Plant, May (Enercon, 2016).
10	2010	GeoTrans, 2010a	GeoTrans, Inc., 2010, Technical Memorandum, Water/Salt Balance Model of Turkey Point Cooling Canal System, August 4 (GeoTrans, 2010a).

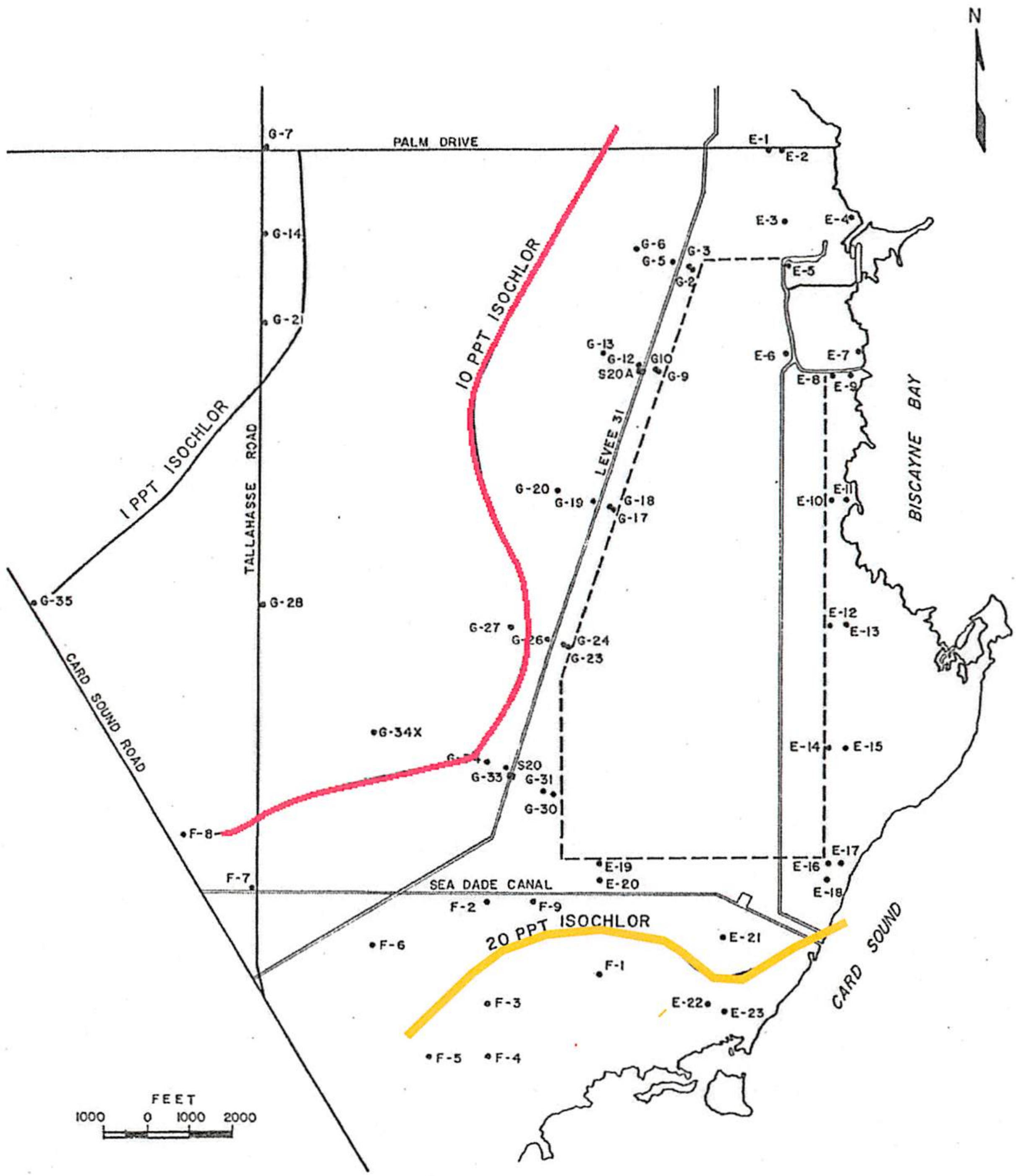
Ref No.	Year	Reference Abbreviation	Reference
11	2010	GeoTrans, 2010b	GeoTrans, Inc., 2010, Feasibility Study to Assess Engineerring Options for Stopping Westward Migration of Saline Water and Decreasing Cooling Canal System Concentrations, Turkey Point Plant, Florida, August 11 (GeoTrans, 2010b).
12	2013	Tetra Tech, 2013	Tetra Tech, 2013, Technical Memorandum, Cross-Sectional Model of Turkey Point Cooling Canal System, July 15 (Tetra Tech, 2013).
13	2014	Tetra Tech, 2014a	Tetra Tech, 2014, Technical Memorandum, Evaluation of Required Floridan Water for Salinity Reduction in the Cooling Canal System, May 9 (Tetra Tech, 2014a).
14	2015	Tetra Tech, 2015	Tetra Tech, 2015, Technical Memorandum, Evaluation of Alternative Measures for Cooling Canal System Salinity Reduction, January 29 (Tetra Tech, 2015).
15	2016	Tetra Tech, 2016a	Tetra Tech, 2016, A Groundwater Flow and Salt Transport Model of the Biscayne Aquifer, June (Tetra Tech, 2016a).
16	2016	Tetra Tech, 2016b	Tetra Tech, 2016, Addendum to Regional Biscayne Aquifer Groundwater Model Report (Tetra Tech, 2016b).
17	2016	Tetra Tech, 2016e	Tetra Tech, 2016, Determination of Allocation of Costs for CCS Recovery and Improvement, December 21 (Tetra Tech, 2016e).

Demonstrative 1



Demonstrative 1. Dames & Moore, 1978, Figure 4.1: Wells Analyzed for Chlorinity and Water Level Averages; and Dames & Moore, 1978, Figure 4.4: Average Chlorinity and Average Water Level Fluctuation, Wells G-20 – G-27.

Demonstrative 2
(1 of 2)



DAMES & MOORE

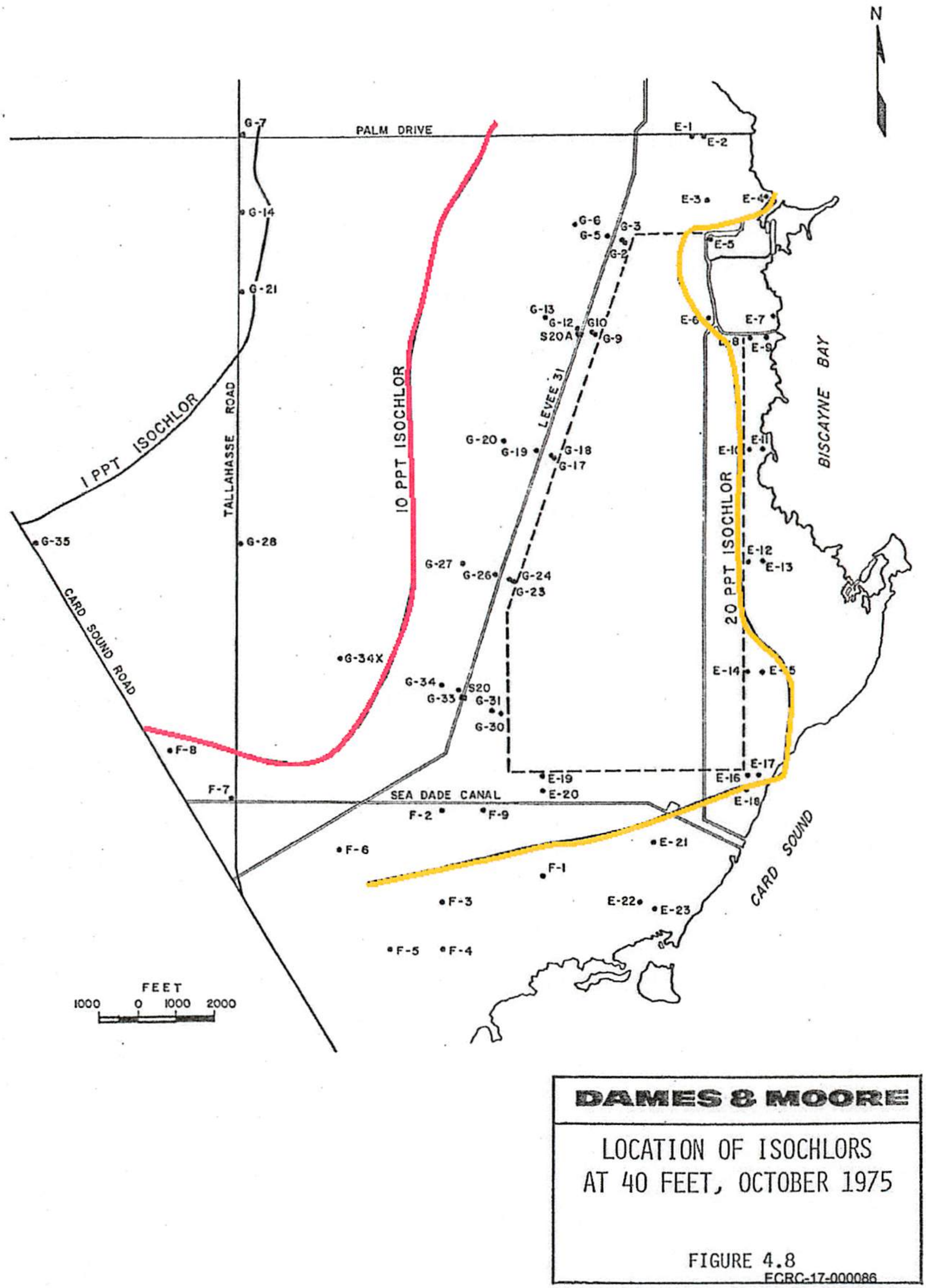
LOCATION OF ISOCHLORS AT 40 FEET, OCTOBER 1972

FIGURE 4.7

ECRC-17-000085

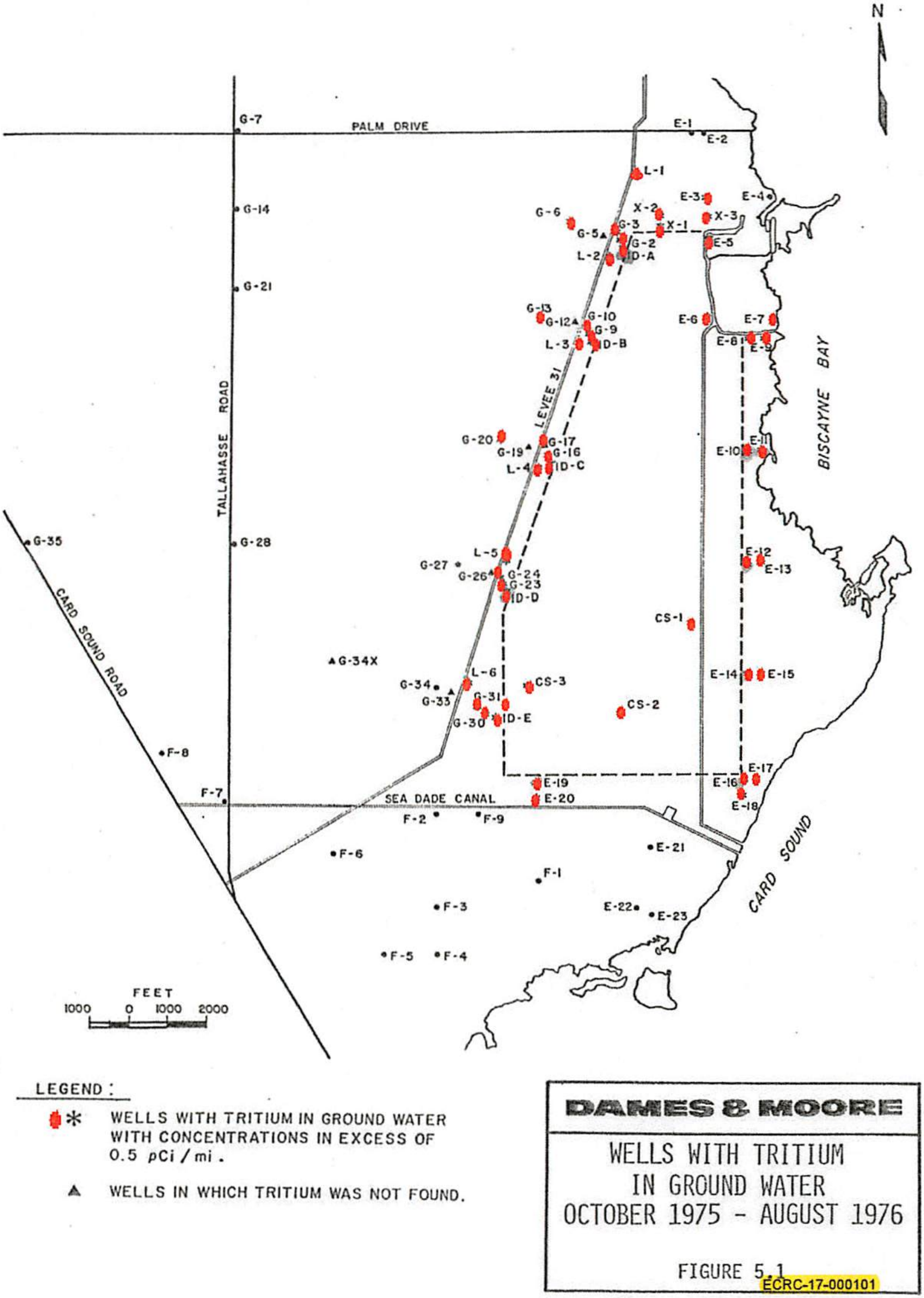
Demonstrative 2. Dames & Moore, 1978, Figure 4.7: Location of Isochlors at 40 Feet, October 1972

Demonstrative 2
(2 of 2)



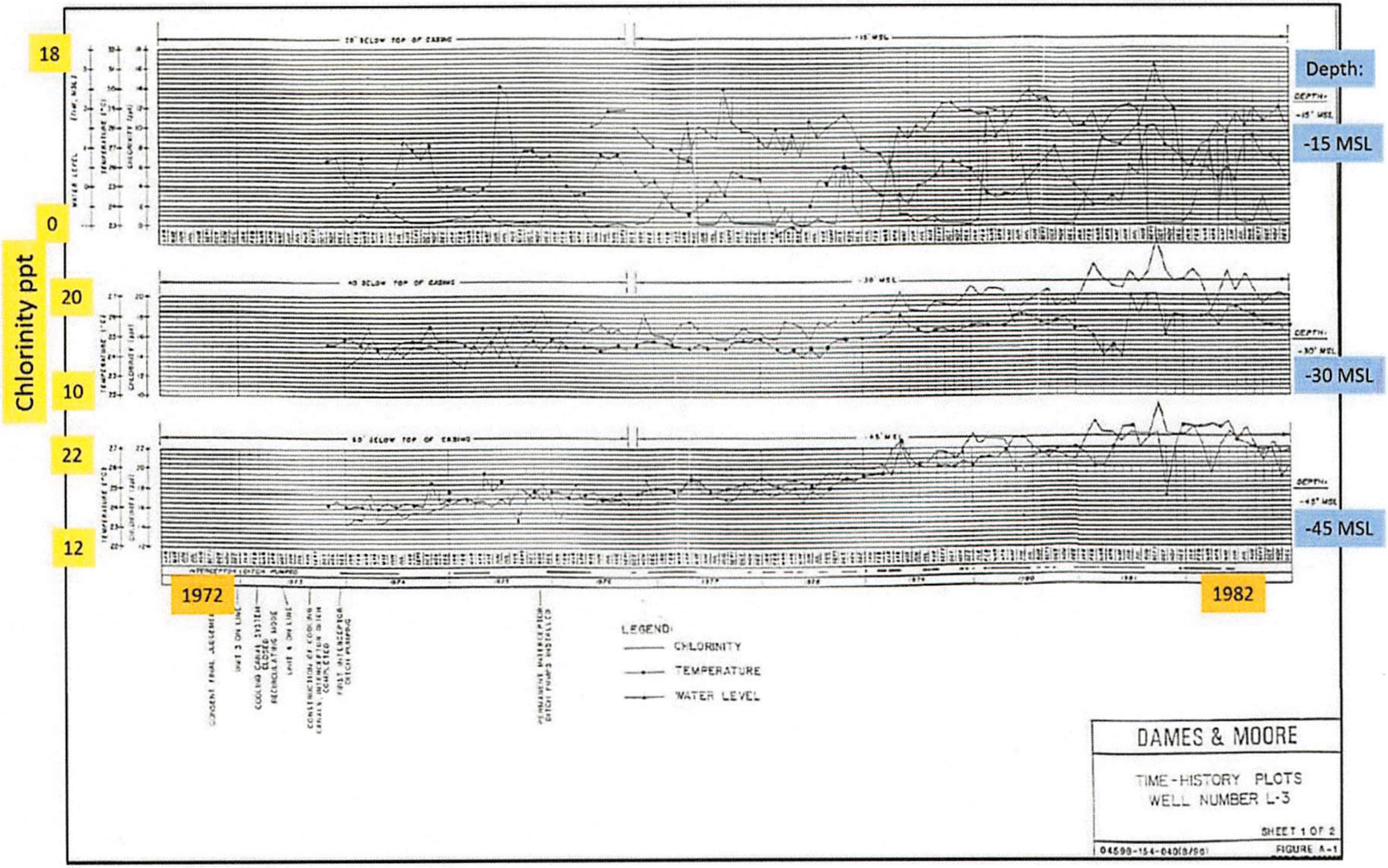
Demonstrative 2. Dames & Moore, 1978, Figure 4.8: Location of Isochlors at 40 Feet, October 1975

Demonstrative 3



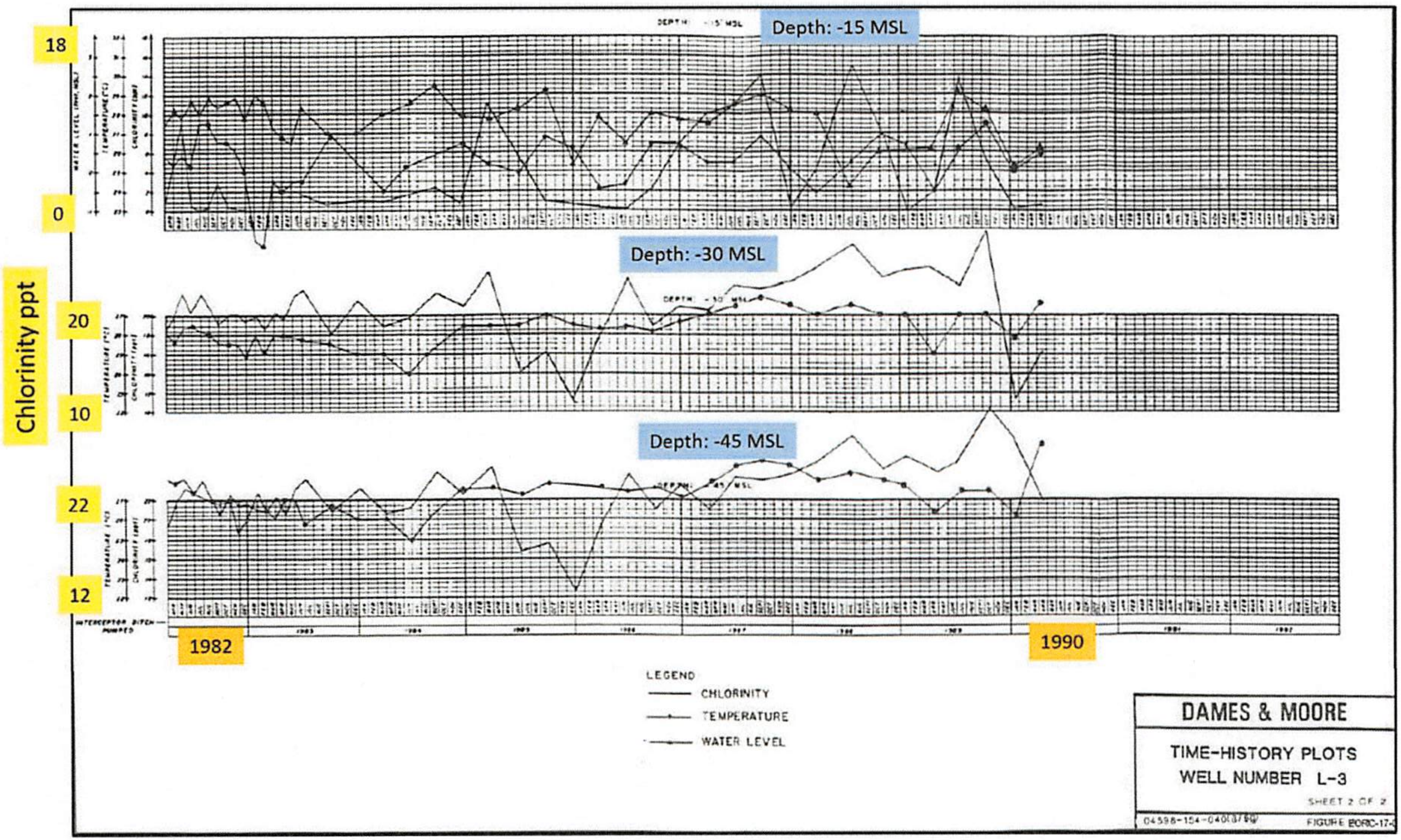
Demonstrative 3. Dames & Moore, 1978, Figure 5.1: Wells with Tritium in Groundwater

Demonstrative 4
(1 of 2)



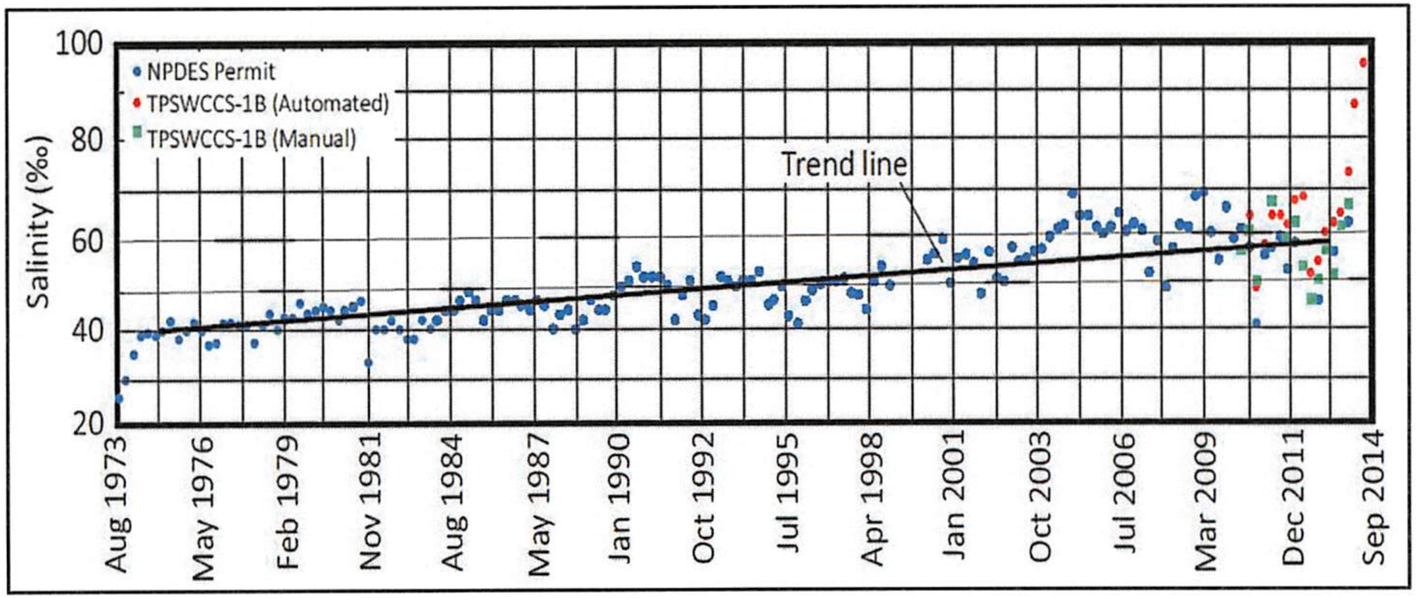
Demonstrative 4. Dames & Moore, 1990, Appendix A: Time-History Plots, Well Number L-3, sheet 1 of 2

Demonstrative 4
(2 of 2)



Demonstrative 4. Dames & Moore, 1990, Appendix A: Time-History Plots, Well Number L-3, sheet 2 of 2.

Demonstrative 5



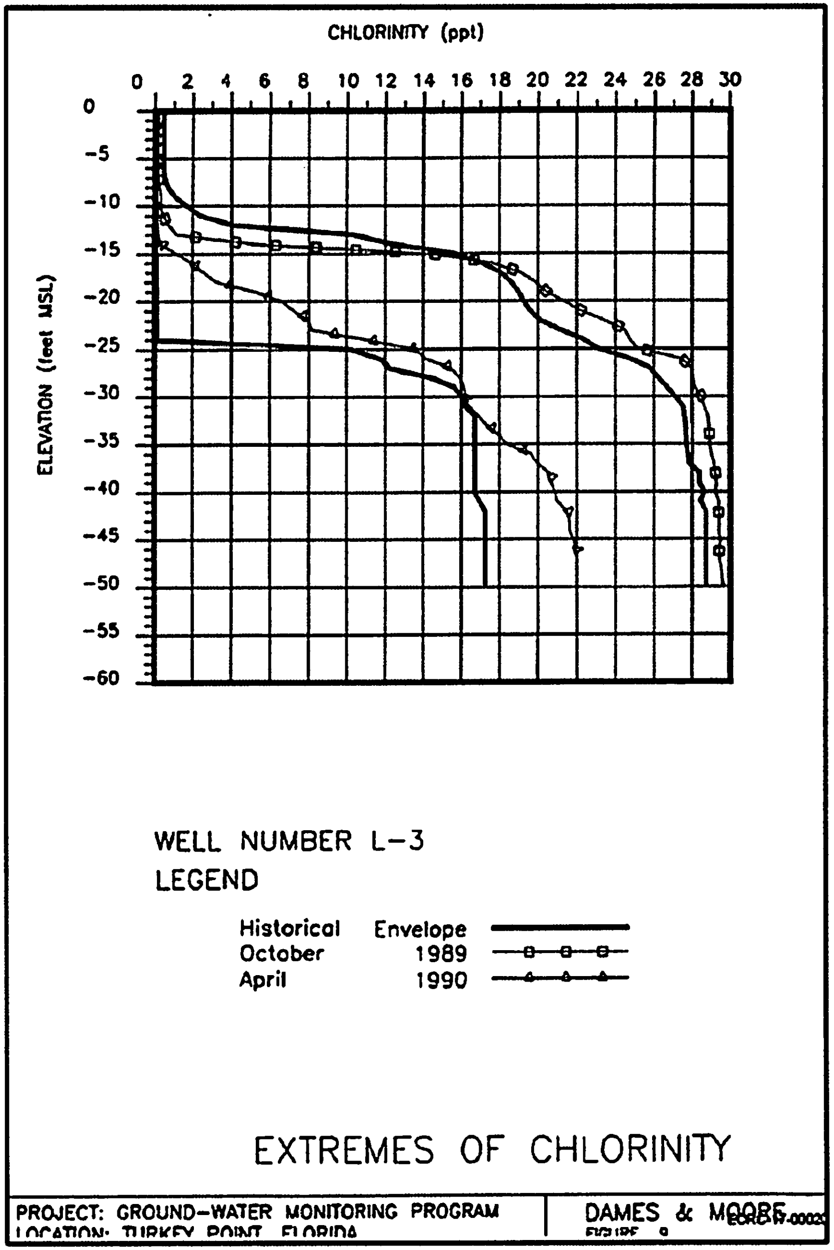
Demonstrative 5. Chin, 2016, Figure 10: Maximum observed salinities in the CCS since initial operation.

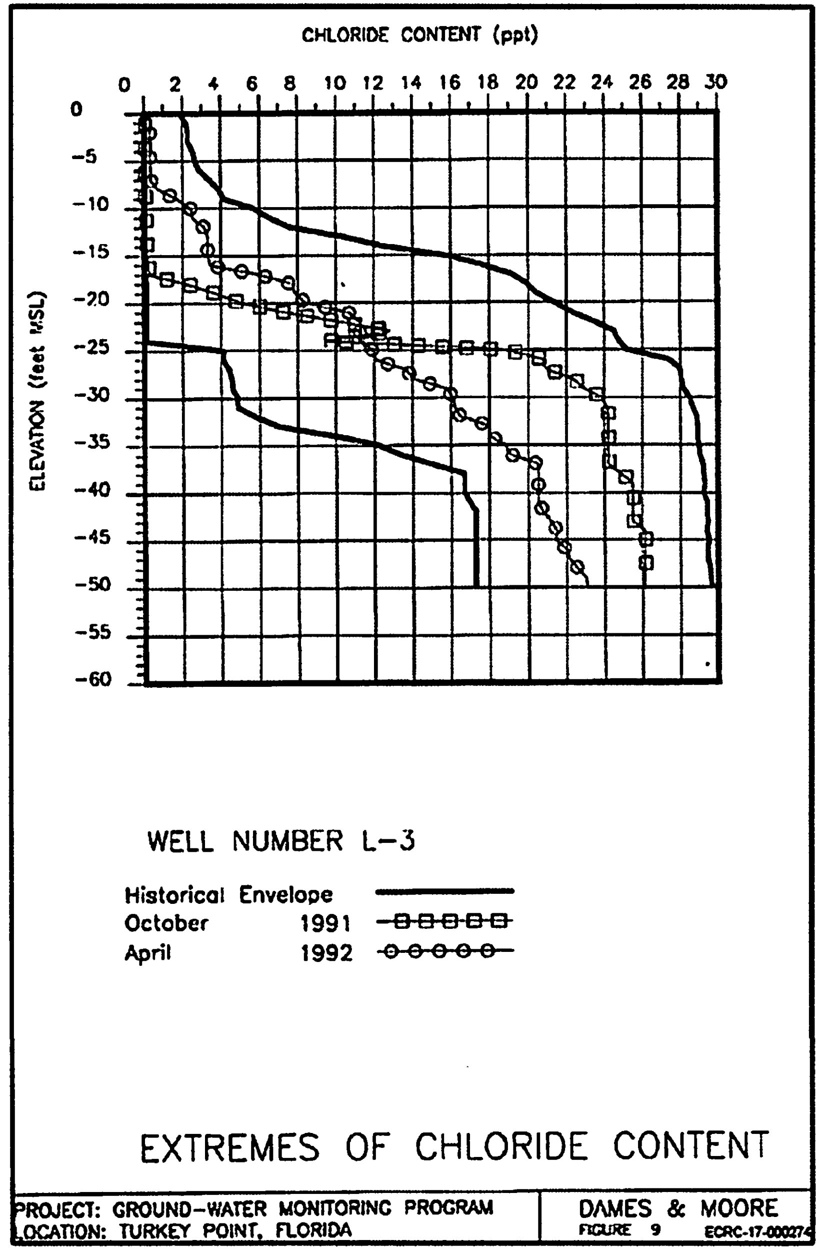
Demonstrative 6

Year	CCS Ave. Salinity (SU)	Year	CCS Ave. Salinity (SU)	Year	CCS Ave. Salinity (SU)	Year	CCS Ave. Salinity (SU)
1980	41.4	1990	47.0	2000	51.7	2010	54.4
1981	38.6	1991	48.3	2001	50.9	2011	54.7
1982	37.7	1992	45.5	2002	51.2	2012	50.4
1983	36.2	1993	48.8	2003	54.2	2013	54.5
1984	41.4	1994	45	2004	60.2	2014	74.8
1985	45.0	1995	41	2005	59.4	2015	75.6
1986	45.2	1996	46.3	2006	62.0	2016	52.2
1987	41.1	1997	46.8	2007	54.9		
1988	39.3	1998	47.3	2008	60.9		
1989	42.4	1999	50	2009	62.2		

Demonstrative 6. Response to Staff's First Set of Interrogatories, Interrogatory No. 2. Average Annual Salinity of CCS from 1980 through 2016

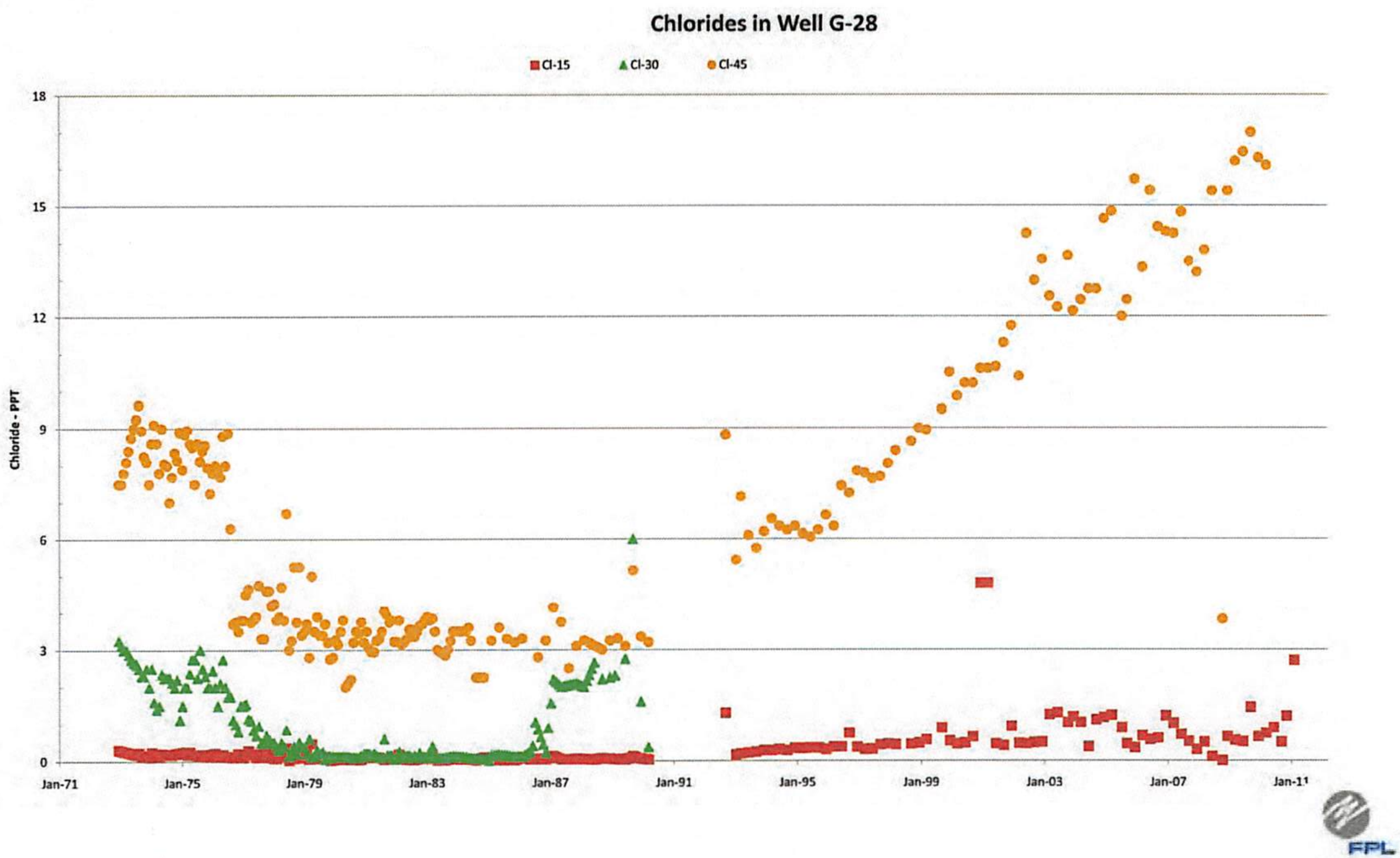
Demonstrative 7





Demonstrative 7. Dames & Moore, 1990, Figure 9: Extremes of Chlorinity; and Dames & Moore, 1992, Figure 9: Extremes of Chloride Content

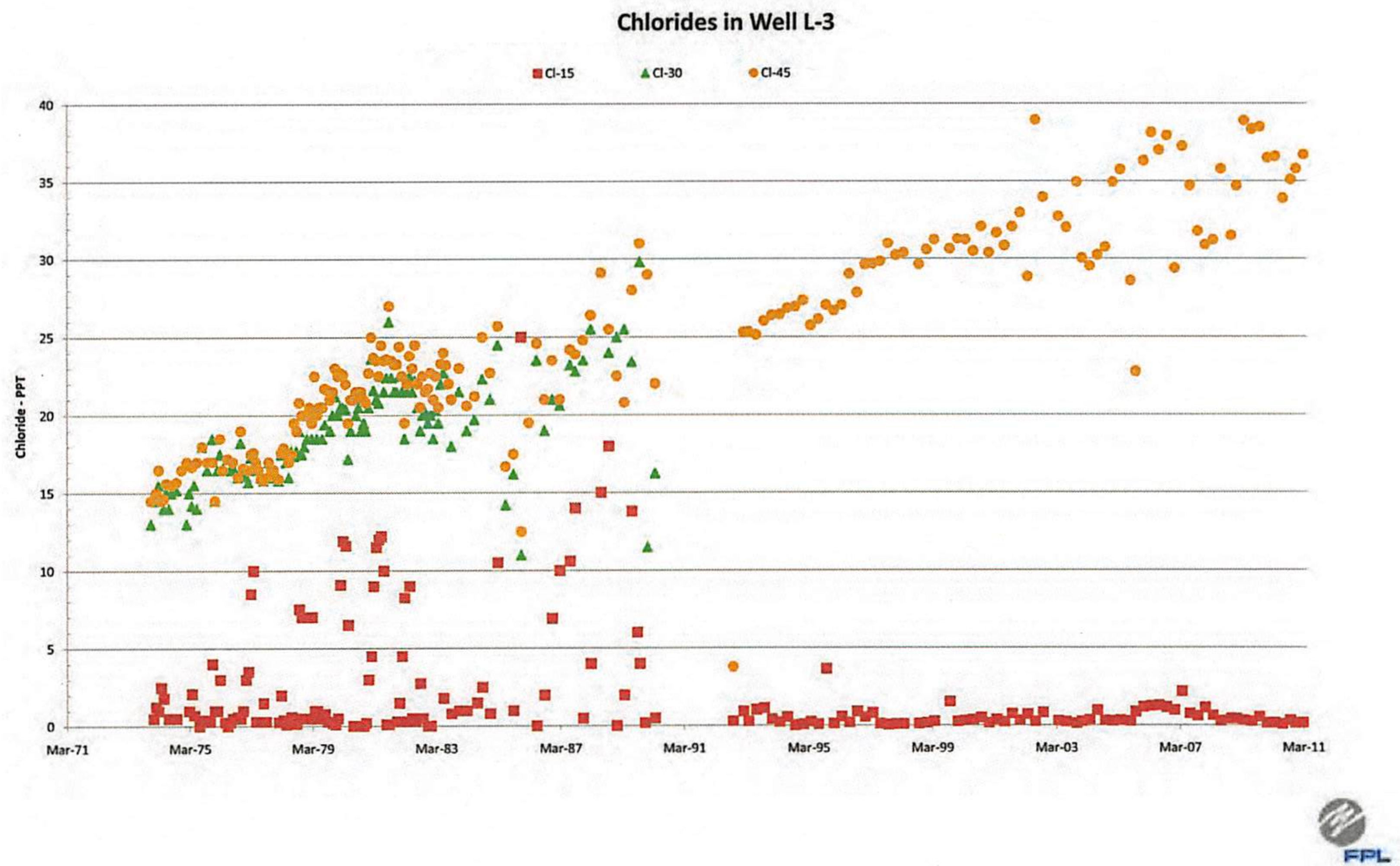
Demonstrative 8



Golder Associates Atlanta, Georgia		TITLE Time-History Plots Well Number G-28		
CLIENT/PROJECT FPL/2011 Annual Report Groundwater Monitoring Program/FL	DRAWN MAT	DATE 7/12/11	JOB NO. 10390308	
	CHECKED SM	SCALE NTS	DWG. NO.	REV. NO.
	REVIEWED HF	FILE NO. 10390308 Fig A4-1	SUBTITLE	FIGURE NO. A-4 1 of 3

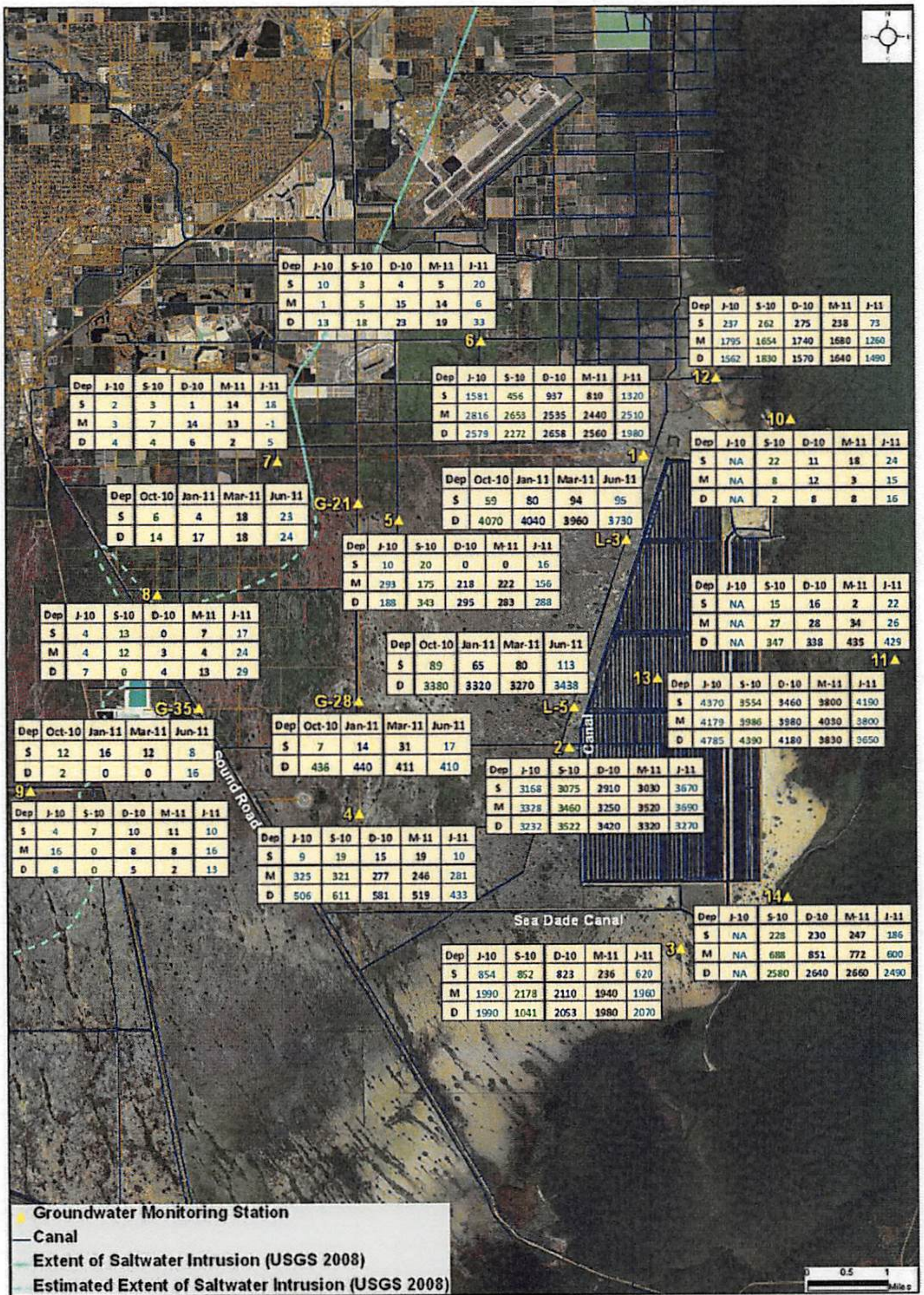
Demonstrative 8 Golder, 2011c, Appendix A, Figure A-4, Time-History Plots Well Number G-28.

Demonstrative 9



Golder Associates — Atlanta, Georgia	TITLE: Time-History Plots Well Number L-3		
CLIENT/PROJECT: FPL/2011 Annual Report Groundwater Monitoring Program/FL	DRAWN: MAT	DATE: 7/12/11	JOB NO.: 10390308
	CHECKED: SM	SCALE: NTS	DWG. NO.: / REV. NO.:
	REVIEWED: HF	FILE NO.: 10390308 Fig A1-1	SUBTITLE: / FIGURE NO.: A-1 1 of 3

Demonstrative 9. Golder, 2011c, Appendix A, Figure A-1, Time-History Plots Well Number L-3.



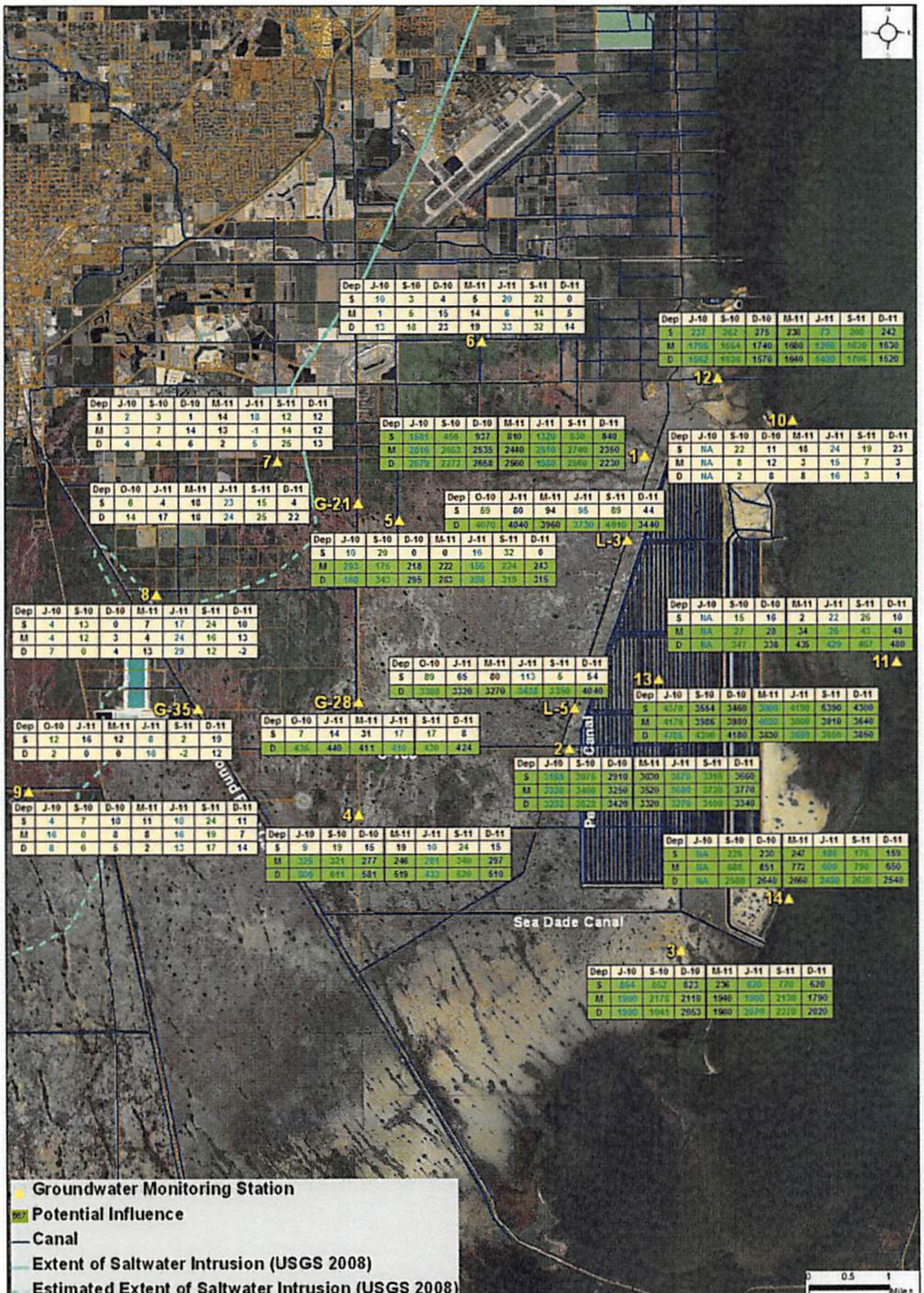
Note: 1) J-10: Jun-2010; S-10: Sep-2010; D-10: Dec-2010; M-11: Mar-2011; J-11: Jun-2011: S-11: Sep-2011.
2) Samples for wells L-5, L-31, G-21, G-28, and G-35 were taken at depths of 18 ft and 58 ft.
3) NA: Not Available.

3-2012

Tritium values (pCi/L) for Groundwater stations. Quarterly samples collected at 3 depths (S: shallow; M: intermediate; D: deep) in 2010 and 2011 (Maximum contaminant level per Florida Drinking Water Standards = 20,000 pCi/L)

Figure 3.1-6. Tritium Concentrations in Groundwater for All Quarters.

Demonstrative 10. Ecology and Environment, 2012a, Figure 3.1-6: Tritium Concentration in Groundwater for All Quarters.



Note: 1) J-10: Jun-2010; S-10: Sep-2010; D-10: Dec-2010; M-11: Mar-2011; J-11: Jun-2011; S-11: Sep-2011; D-11: Dec-2011.
2) Samples for wells L-5, L-31, G-21, G-28, and G-35 were taken at depths of 18 ft and 58 ft.
3) NA: Not Available.

9-2012

Tritium Samples Taken at 3 Depths (S: shallow; M: intermediate; D: deep)

Figure 5.2-35. FPL Monitoring Wells Potentially Influenced by CCS Water.

Demonstrative 11. Ecology and Environment, 2012c, Figure 5.2-35: FPL Monitoring Wells Potentially Influenced by CCS Water.

Demonstrative 12

Table 5.2-5. Estimated Percent CCS Water Based on Chloride Concentrations

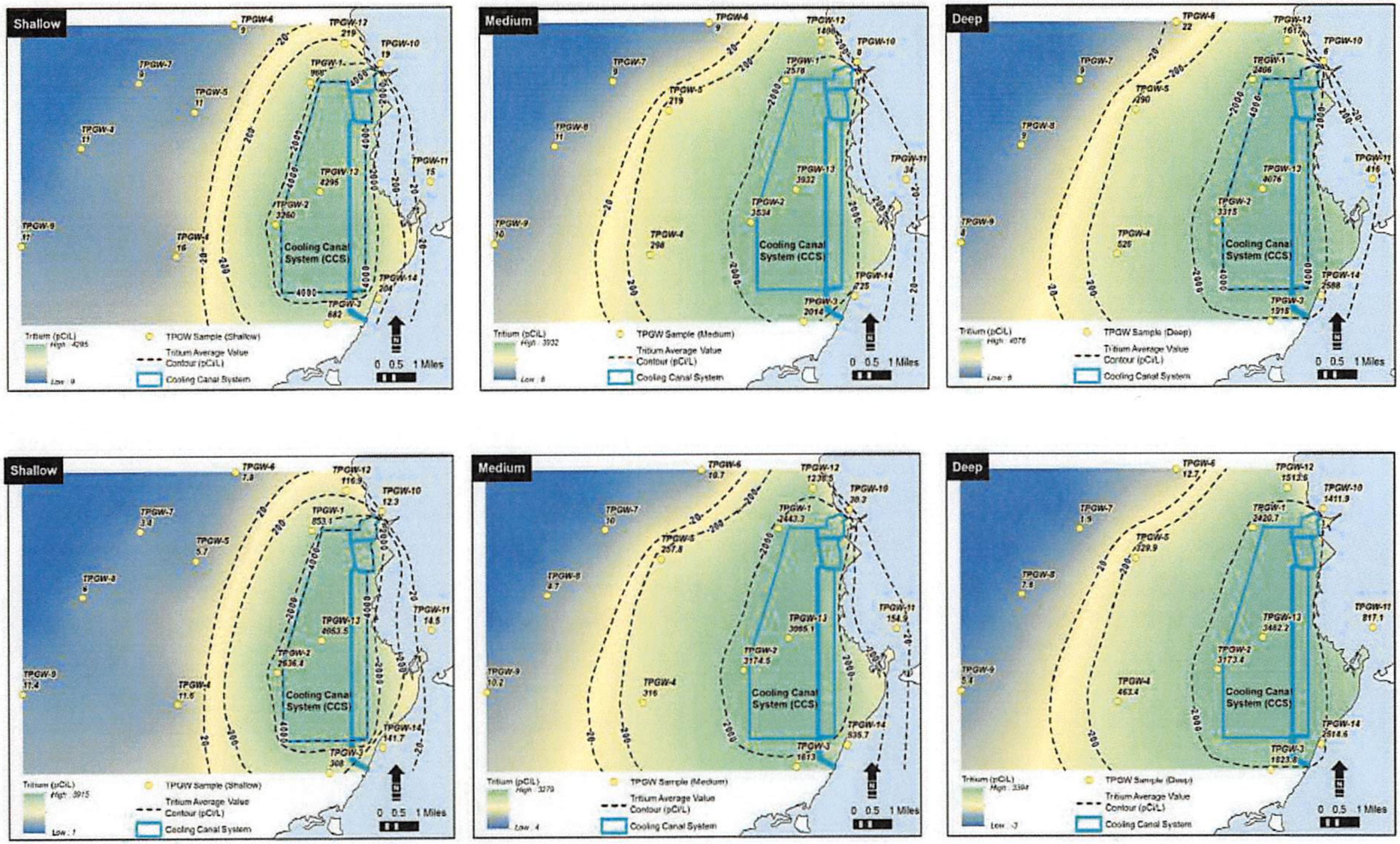
Well	Average Current Tritium Concentration (pCi/L)	Cl_{well}: Average Current Chloride Concentration (mg/L)	Cl_{CCS}: Assumed CCS Chloride Concentration (mg/L)	$Cl_{background}$: Estimated Pre-CCS Chloride Concentration (mg/L)	% CCS Water: Calculated Percent CCS Water
1S	968	17,714	34,000	6,483	41%
1M	2,578	28,571	34,000	14,607	72%
1D	2,406	28,000	34,000	21,667	51%
2S	3,260	30,143	34,000	5,987	86%
2M	3,534	31,286	34,000	10,748	88%
2D	3,315	31,571	34,000	15,447	87%
3S	682	25,000	34,000	18,384	42%
3M	2,014	27,429	34,000	20,804	50%
3D	1,918	27,571	34,000	21,529	48%
4M	298	13,857	24,000	2,941	52%
4D	526	15,429	24,000	8,095	46%
5M	219	10,171	24,000	32	42%
5D	290	11,286	24,000	318	46%
11M	34	22,000	34,000	21,667	3%
11D	416	22,333	34,000	21,667	5%
12S	219	15,143	34,000	14,879	1%
12M	1,408	24,429	34,000	17,894	41%
12D	1,617	25,429	34,000	18,635	44%
14S	204	22,833	34,000	21,667	9%
14M	725	24,167	34,000	21,667	20%
14D	2,588	30,167	34,000	21,667	69%
L3-58	3,938	32,625	34,000	16,594	92%
L5-58	3,364	30,750	34,000	11,103	86%
G28-58	421	14,375	24,000	11,313	24%

Notes: Wells with average current tritium concentrations below 20 pCi/L (+/- 1 sigma 5 piC/L) not shown.

Key:
Approx. = Approximate.
CCS = Cooling Canal System.
Cl = Chloride.
ft = Feet.
mg/L = Milligram(s) per liter.
NA = Not available.
pCi/L = Picocuries per liter.
yr = Year(s).

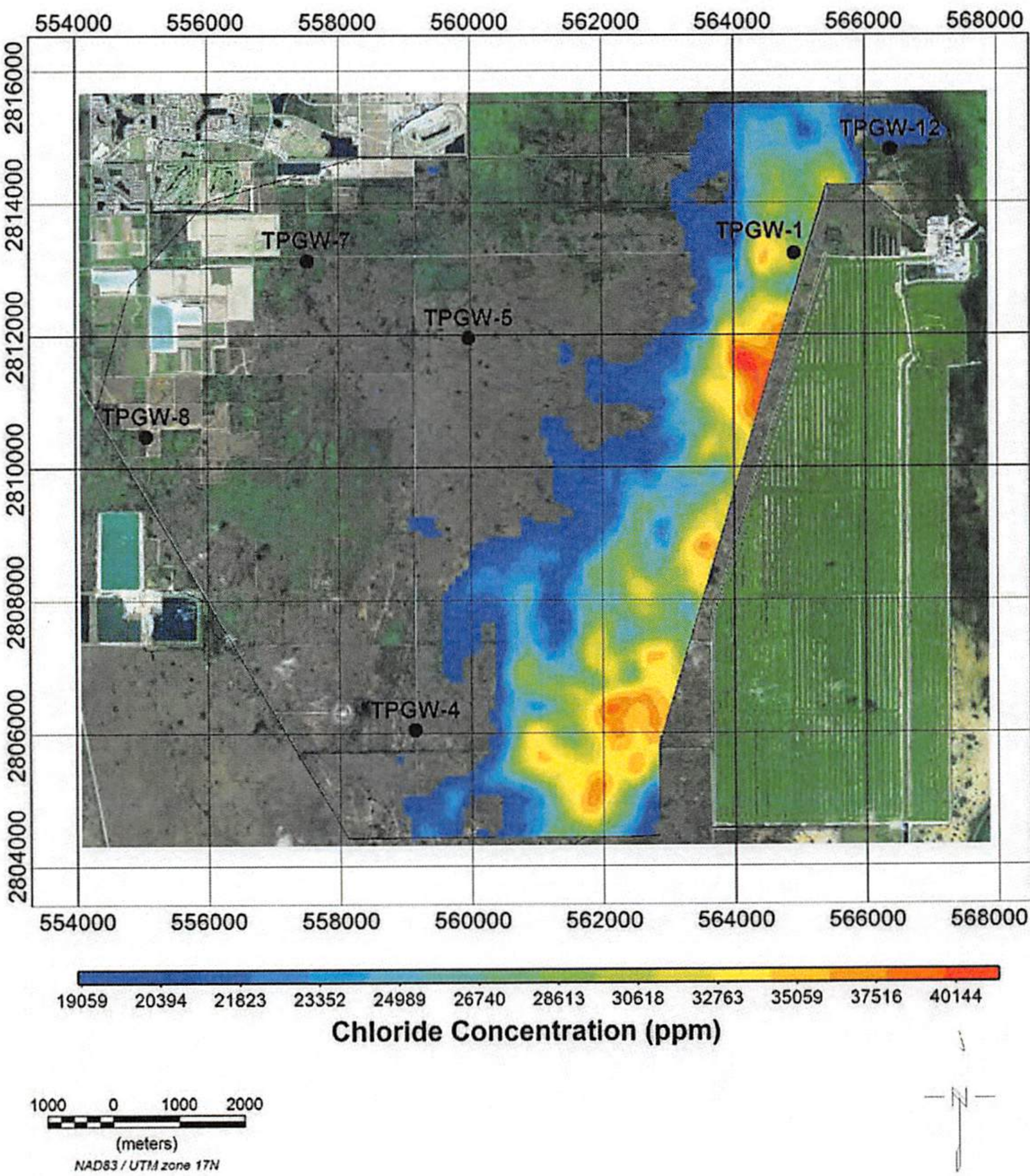
Demonstrative 12. Ecology and Environment, 2012c, Table 5.2-5: Estimated Percent CCS Water Based on Chloride Concentration.

Demonstrative 13



Demonstrative 13. Ecology and Environment, 2016b, Figure 5.2-7: Pre-Uprate (Top) and Post-Uprate (Bottom) Average Tritium Isopleths for Shallow, Medium, and Deep Wells.

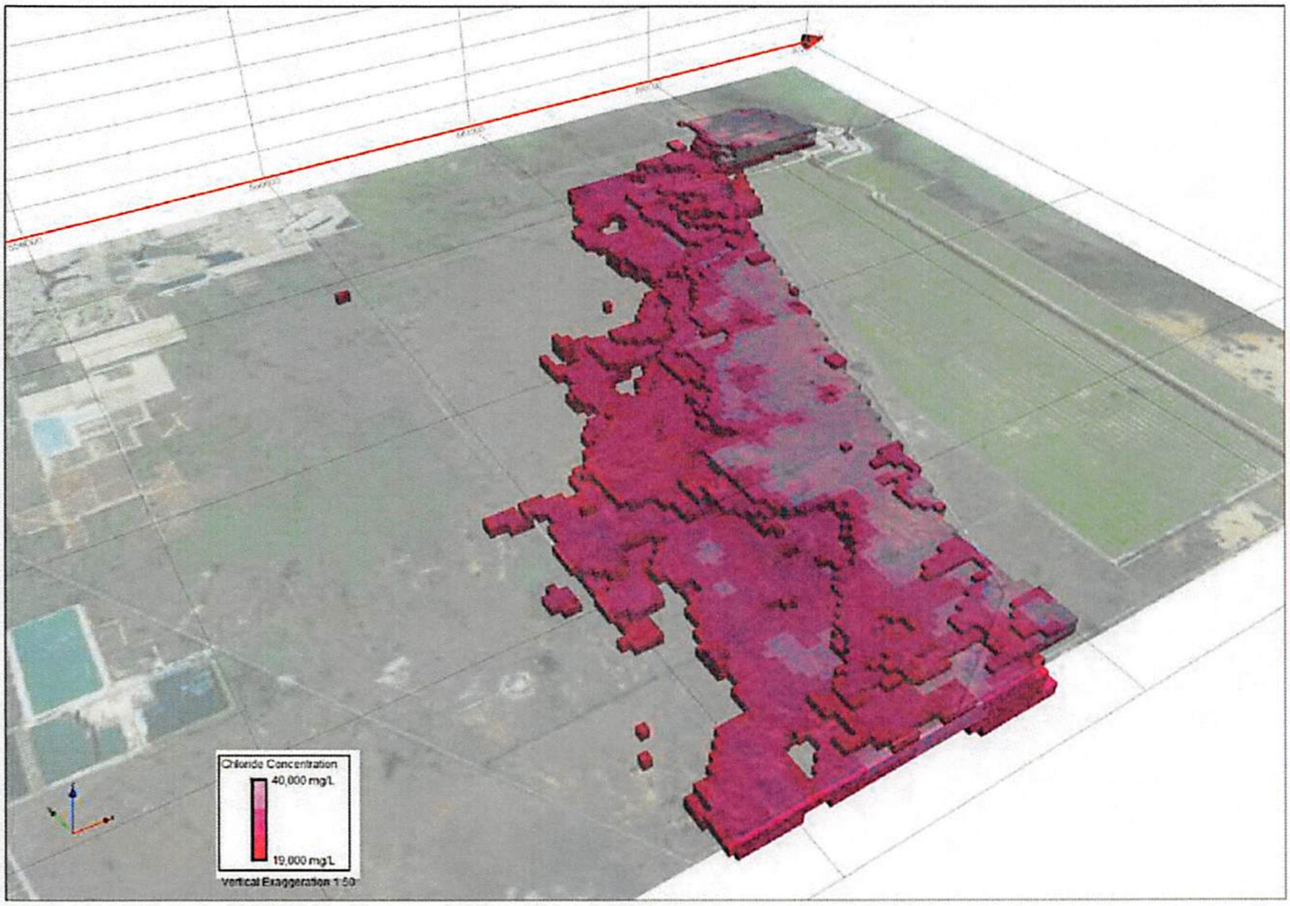
Demonstrative 14a



Prepared for: **Florida Power & Light** **Subject Property:** Turkey Point Nuclear Generating Station Homestead, Florida	ENERCON **Figure 16: Chloride Concentration Depth-Slice from Layer 11, 55 to 65 feet below land surface (16.8 to 19.7m)** Reproduced from: "Report on Advanced Processing and Inversion of AEM Survey Data and Derived Chloride Concentrations near the TurkeyPoint Power Plant, Southern Florida. Aqua Geo Frameworks, Inc. 2016" *Prepared by: E. Dare; April 28, 2016*

Demonstrative 14. Enercon, 2016, Figure 16: Chloride Concentration Depth-Slice from Layer 11, 55 to 65 feet below land surface (16.8 to 19.7 m).

Demonstrative 14b



Prepared for:
Florida Power & Light

Subject Property:
Turkey Point Nuclear Generating Station
Homestead, Florida

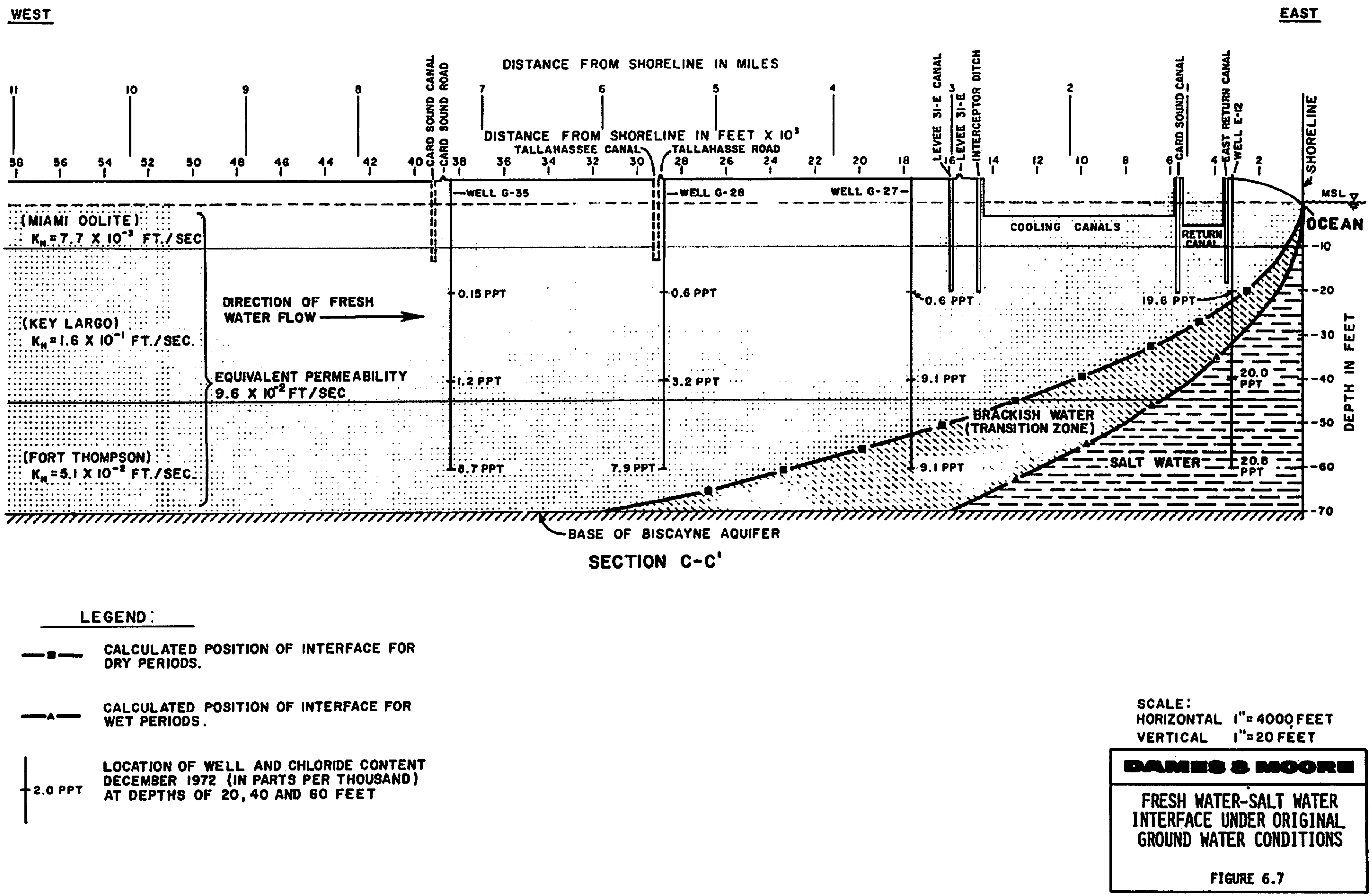
ENERCON

Figure 14: 3D View of AEM Chloride Concentrations Greater than 19,000 mg/L (View to the Northeast)
Reproduced from: "Report on Advanced Processing and Inversion of AEM Survey Data and Derived Chloride Concentrations near the TurkeyPoint Power Plant, Southern Florida. Aqua Geo Frameworks, Inc. 2016"

Prepared by: E. Dare; April 28, 2016

Demonstrative 14. Enercon, 2016, Figure 14: 3D View of AEM Chloride Concentrations Greater than 19,000 mg/L (View to the Northeast)

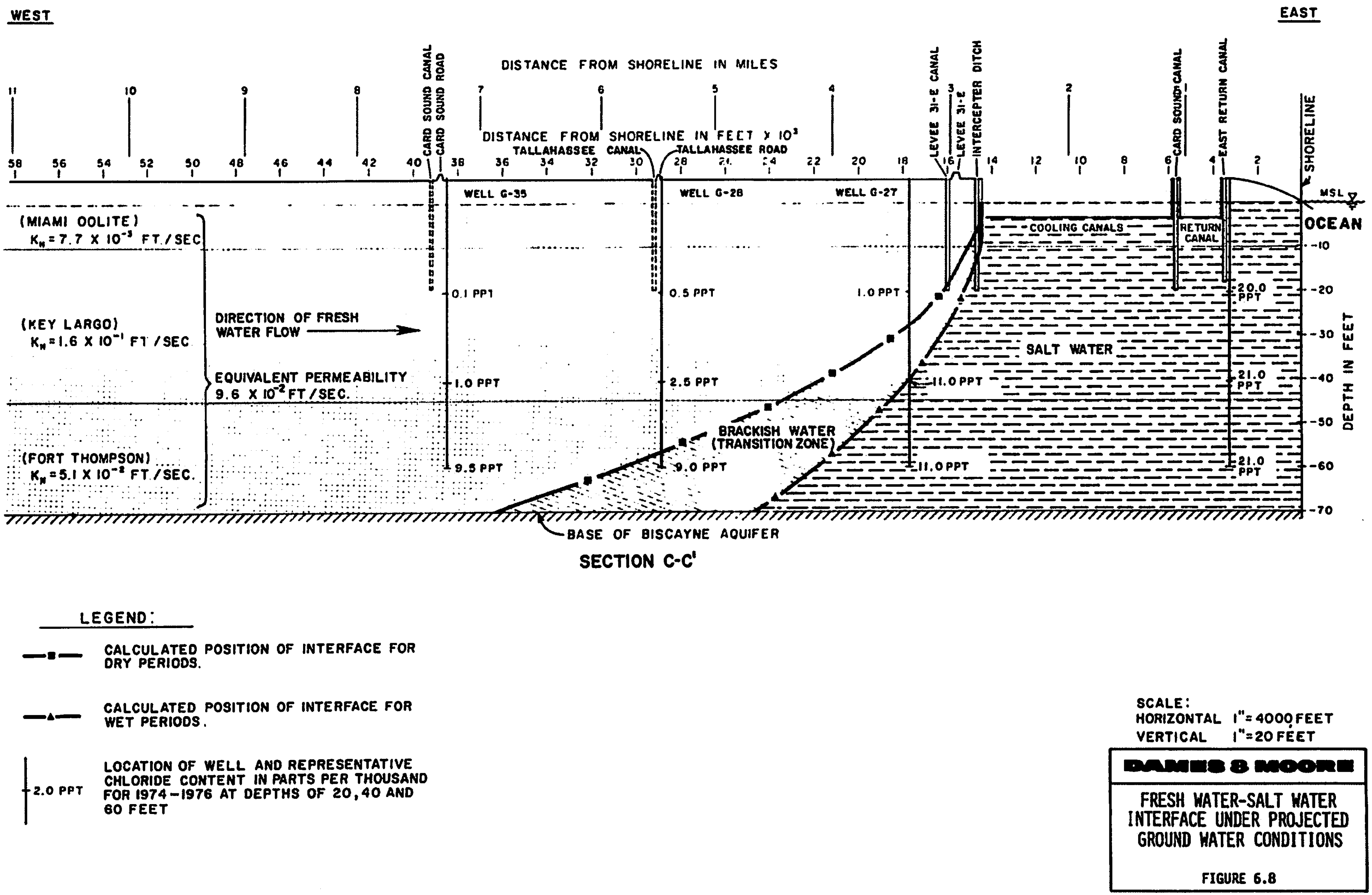
Demonstrative 15
(1 of 2)



ECRC-17-000126

Demonstrative 15. Dames & Moore, 1978, Figure 6.7: Fresh Water-Salt Water Interface under Original Ground Water Conditions

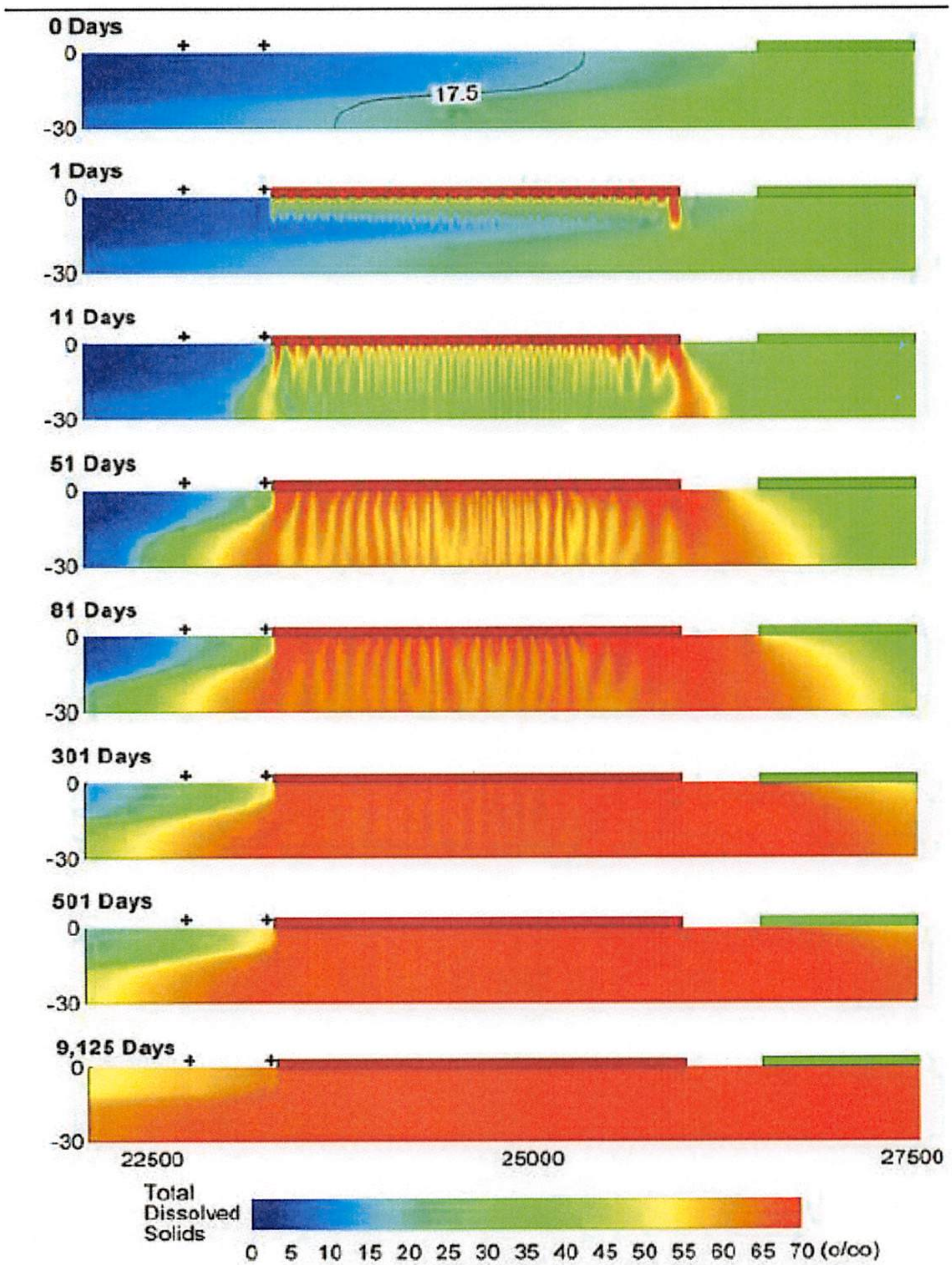
Demonstrative 15
(2 of 2)



ECRC-17-000127

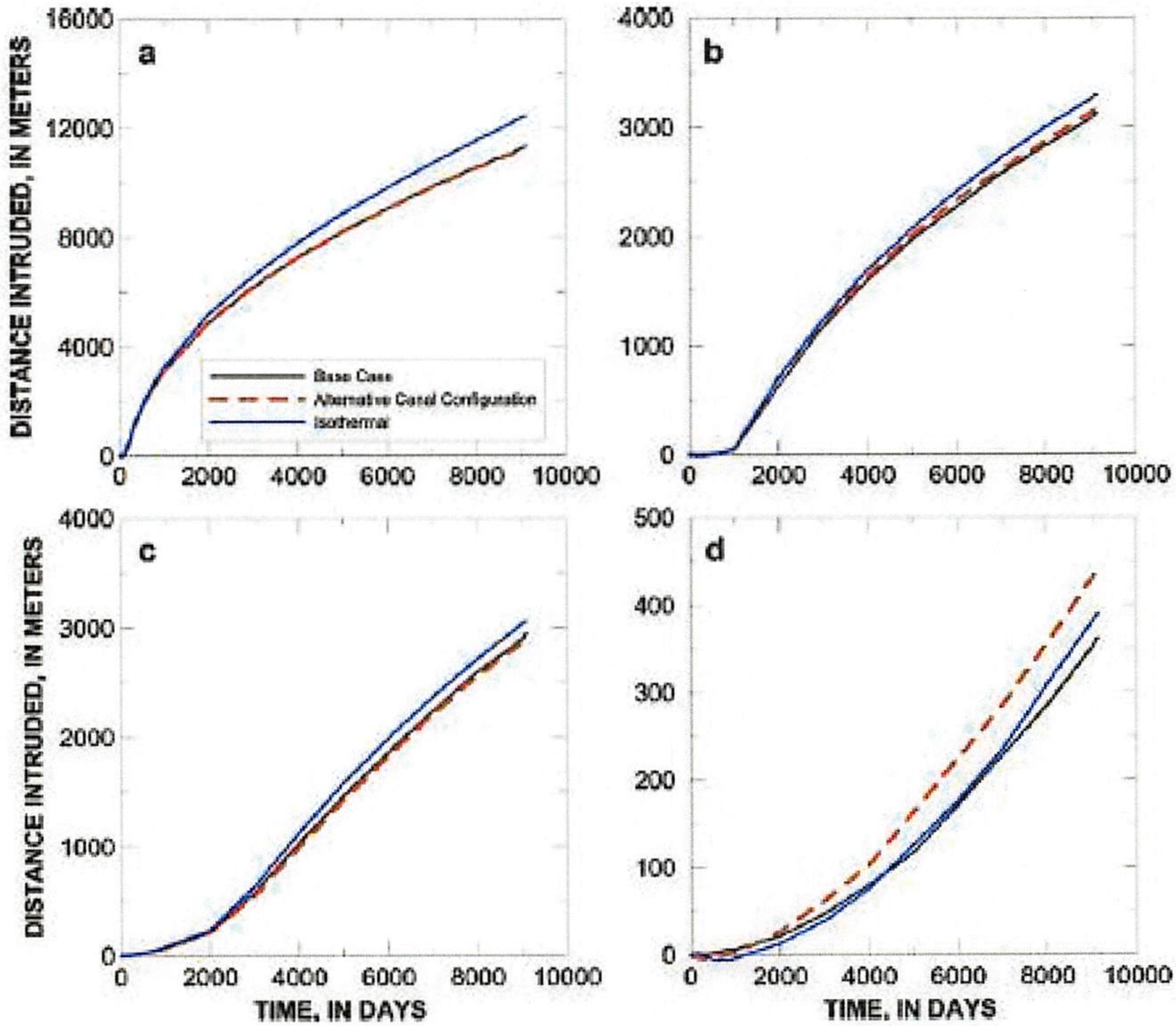
Demonstrative 15. Dames & Moore, 1978, Figure 6.8: Fresh Water-Salt Water Interface Under Projected Ground Water Conditions.

Demonstrative 16



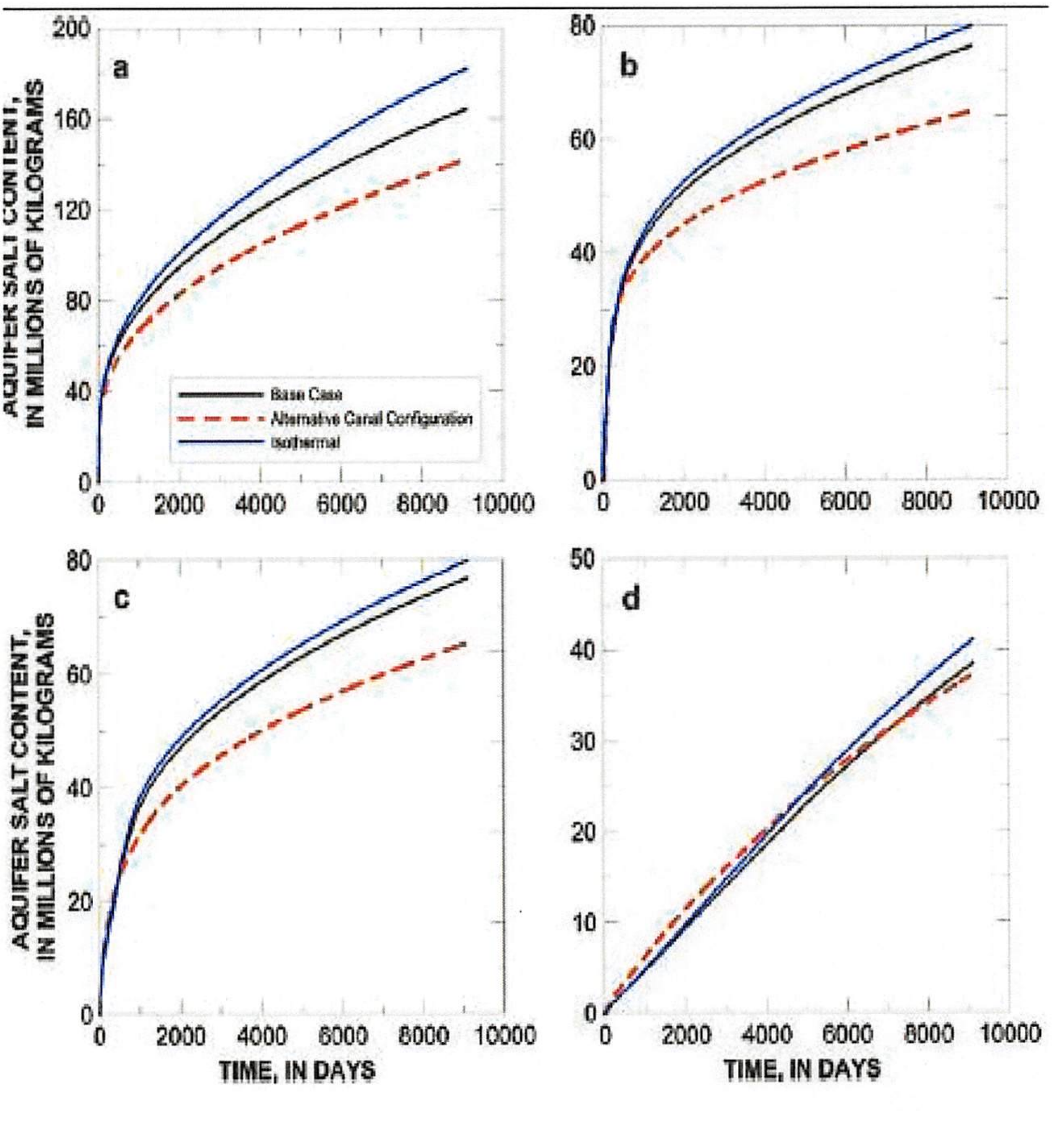
Demonstrative 16. Hughes et al (2009), Figure 4a: Simulated TDS concentrations for base simulation case A after specified days since cooling canal system construction.

Demonstrative 17



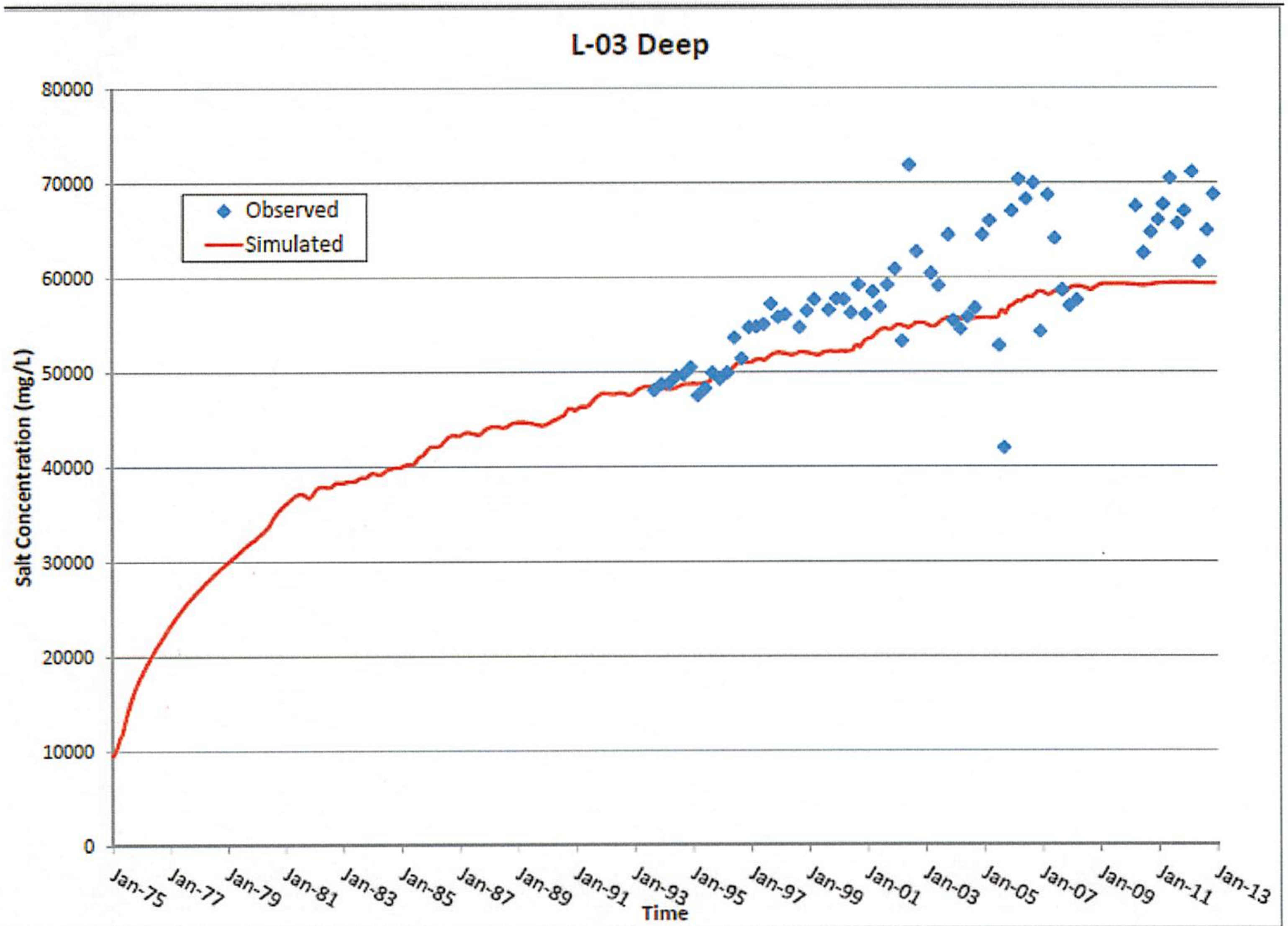
Demonstrative 17. Hughes et al (2009), Figure 7: Simulated movement of the 1‰ TDS concentration at the base of the aquifer

Demonstrative 18



Demonstrative 18. Hughes et al (2009), Figure 6: Simulated increases in salt content of the aquifer as a result of CCS seepage.

Demonstrative 19



Demonstrative 19. Tetra Tech (2013b), Figure 4a: Salinity Concentration Changes in Monitoring Well L-03 (deep).

Demonstrative 20

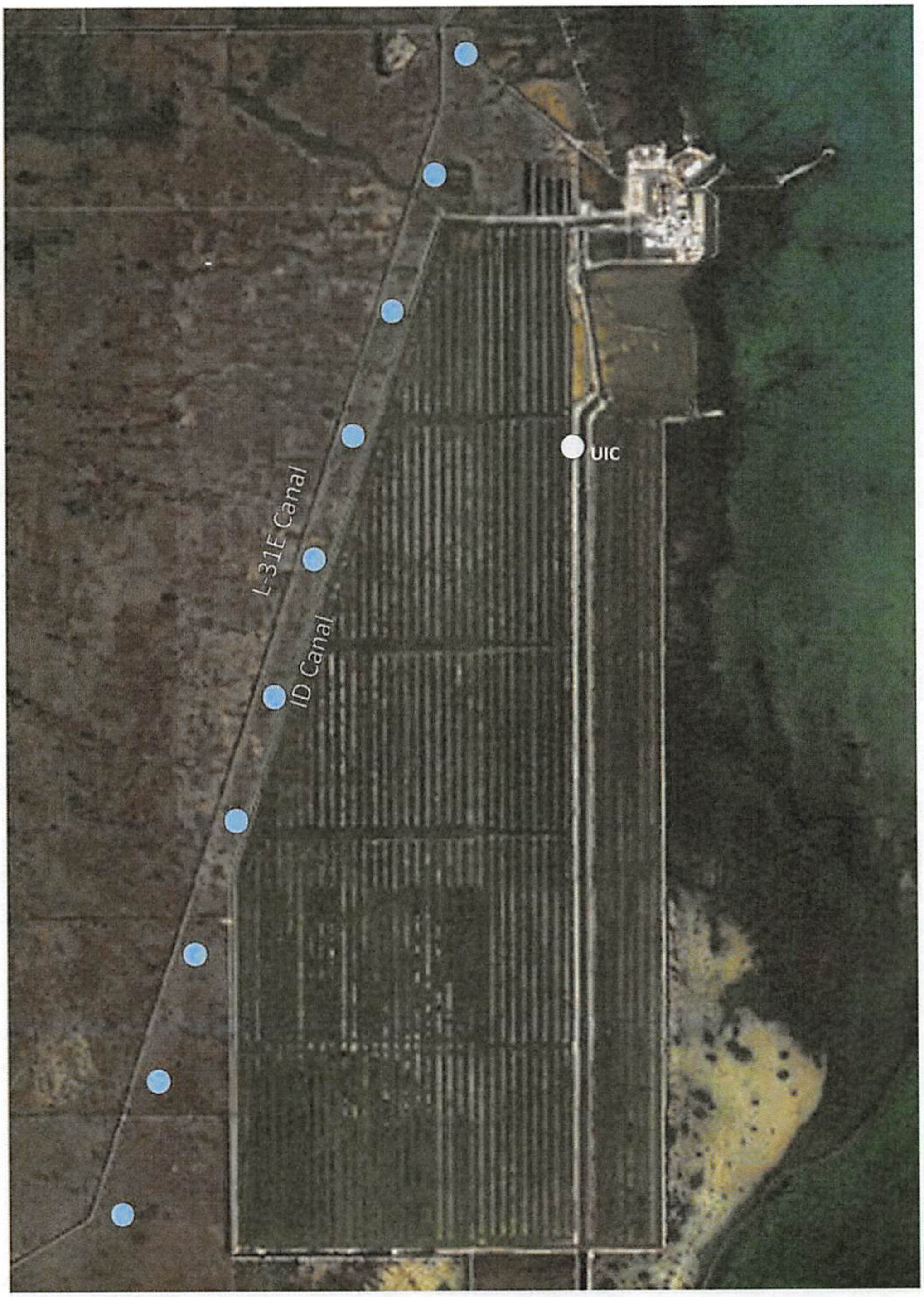


Figure 19. Configuration of extraction wells (blue dots) for Alternative 3D

Demonstrative 20. Tetra Tech, 2016c, Figure 19: Configuration of Extraction Wells (blue dots) for Alternative 3D.

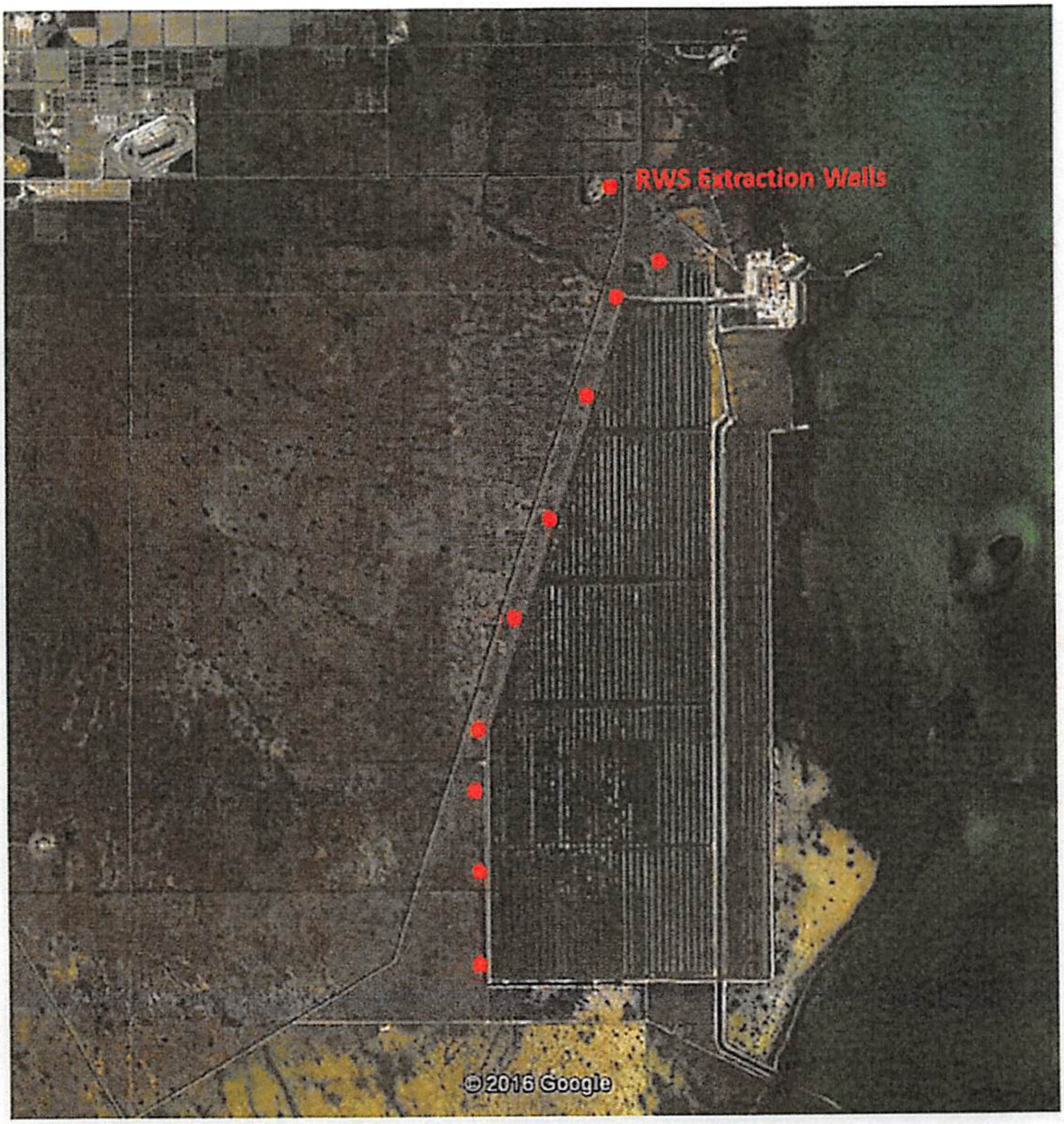
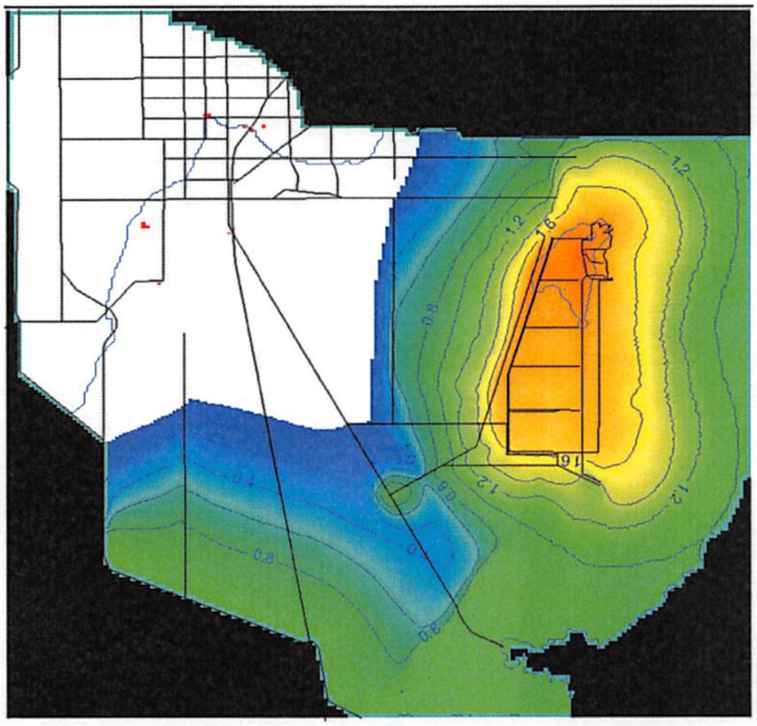


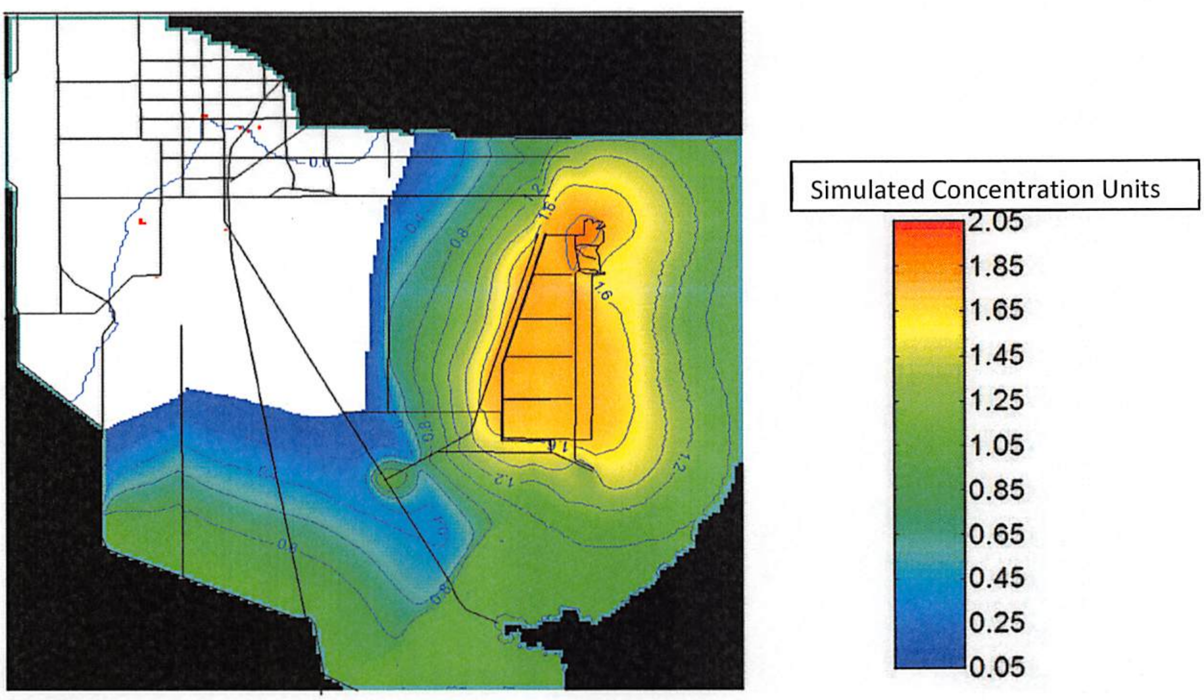
Figure 1. Approximate location of extraction wells associated with the selected RWS alternative

Demonstrative 21 Tetra Tech, 2016m, Figure 1: Approximate location of extraction wells associated with the selected RWS alternative.

Demonstrative 22



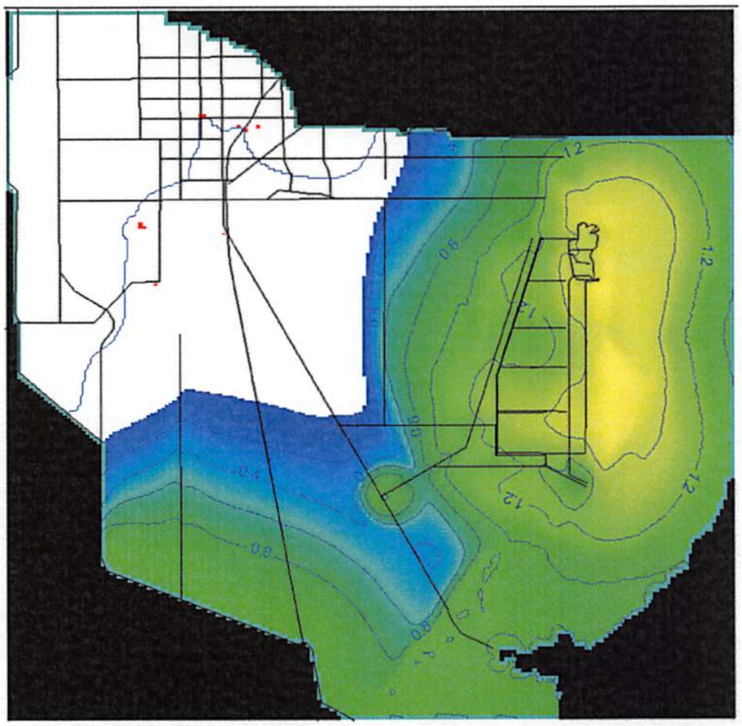
22a. Without pumping of retraction wells



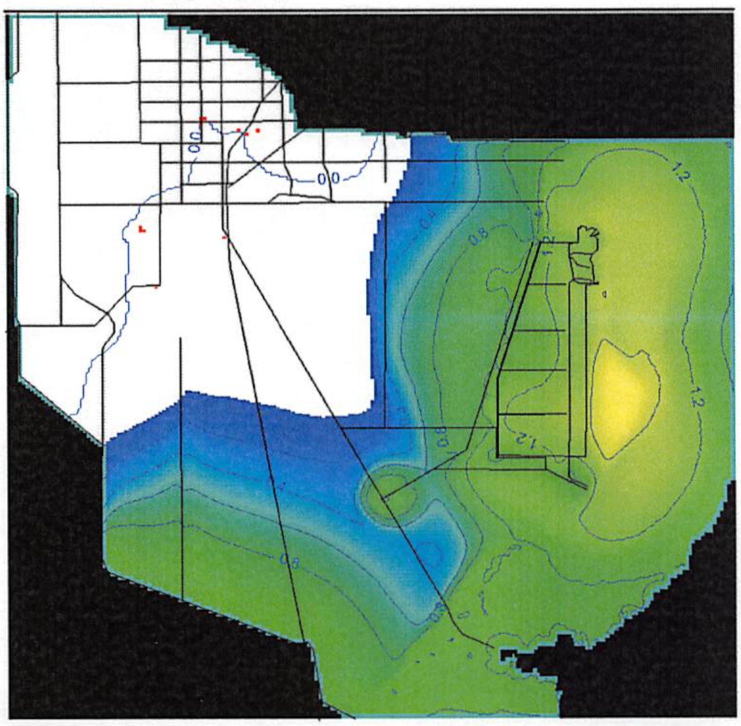
22b. With pumping of retraction wells

Demonstrative 22. Simulated Concentration Distribution in Layer 8 after 1 year

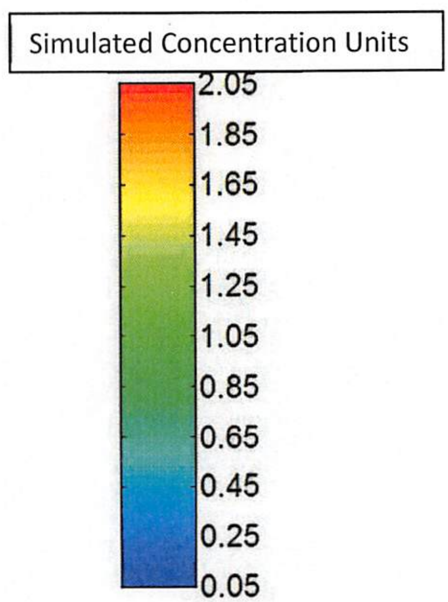
Demonstrative 23



23a. Without pumping of retraction wells

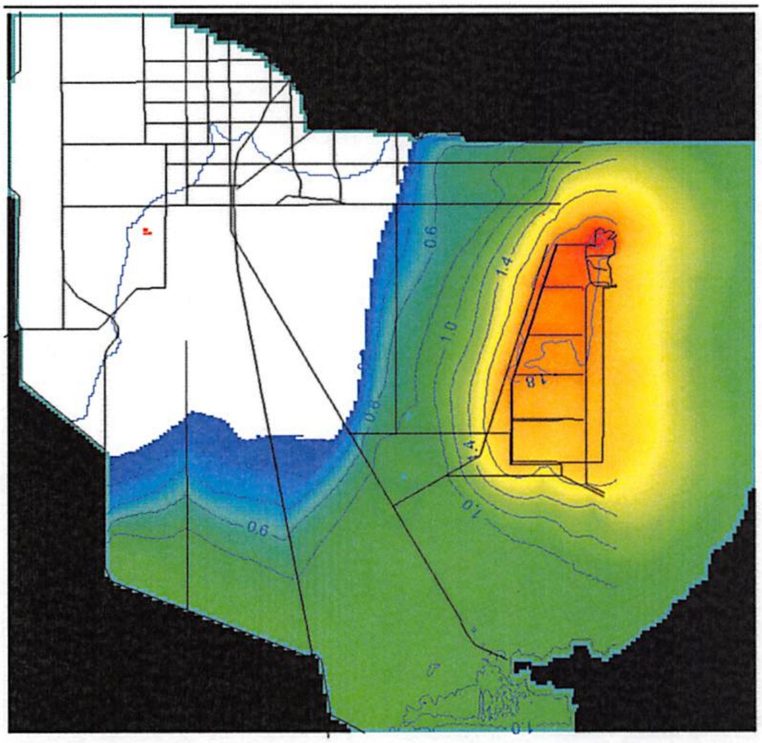


23b. With pumping of retraction wells

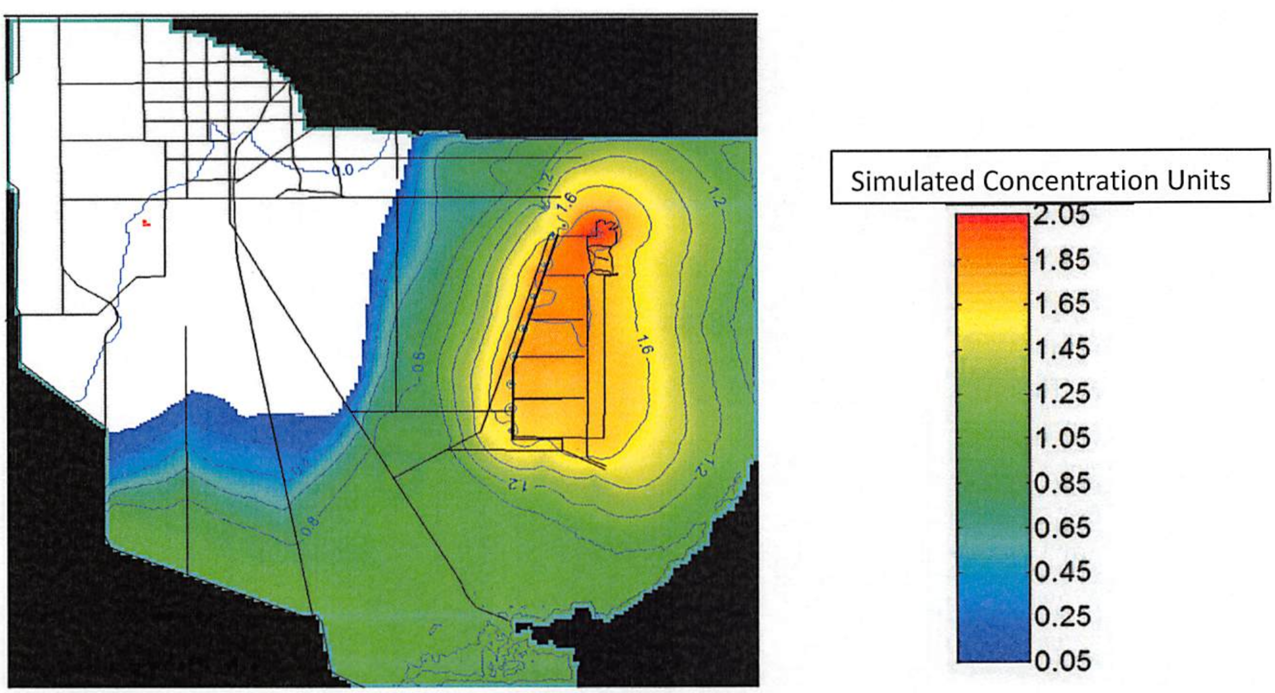


Demonstrative 23. Simulated Concentration Distribution in Layer 8 after 10 years

Demonstrative 24



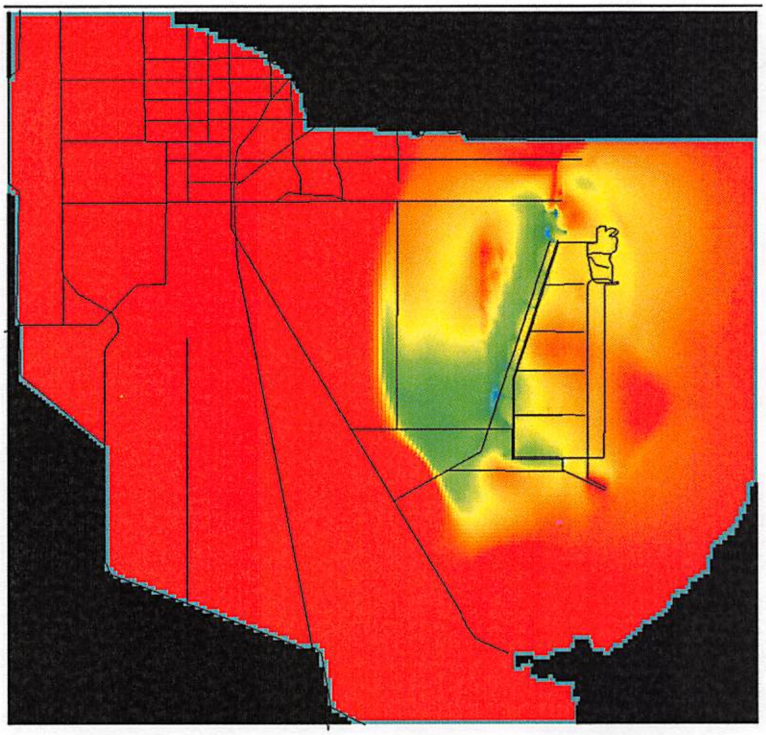
24a. Without pumping of retraction wells



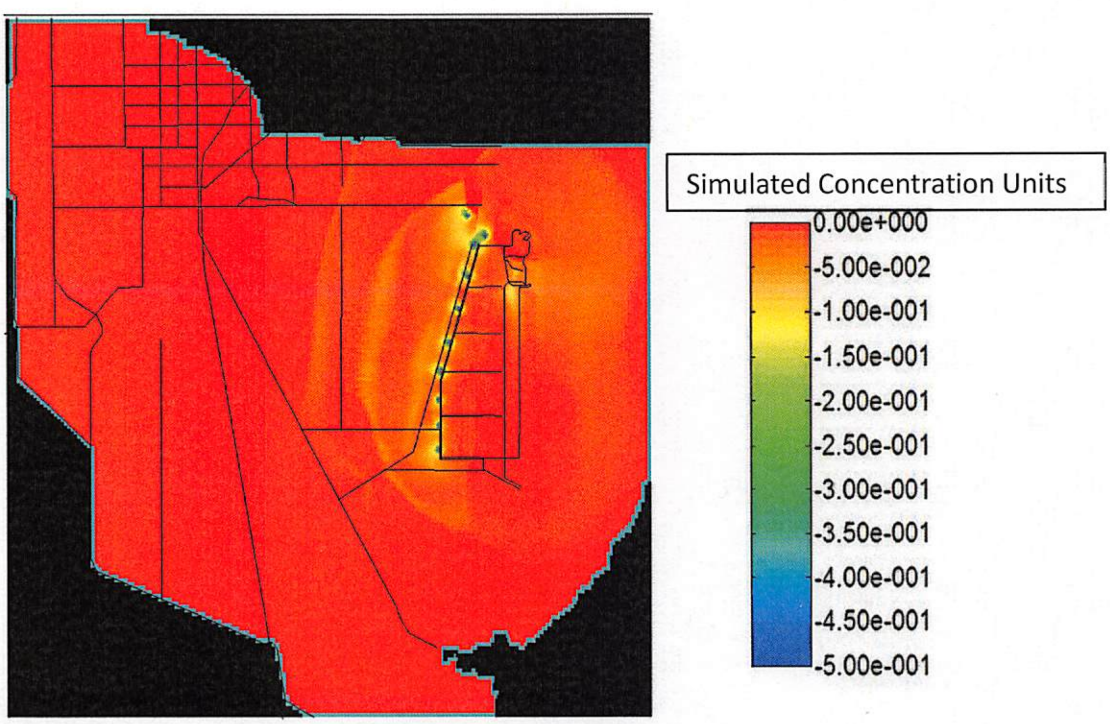
24b. With pumping of retraction wells

Demonstrative 24. Simulated Concentration Distribution in Layer 11 after 10 years

Demonstrative 25



25a. Layer 8



25b. Layer 11

Demonstrative 25. Difference in Simulated Concentrations between the Retraction Well Pumping and No-Pumping Cases after 10 years

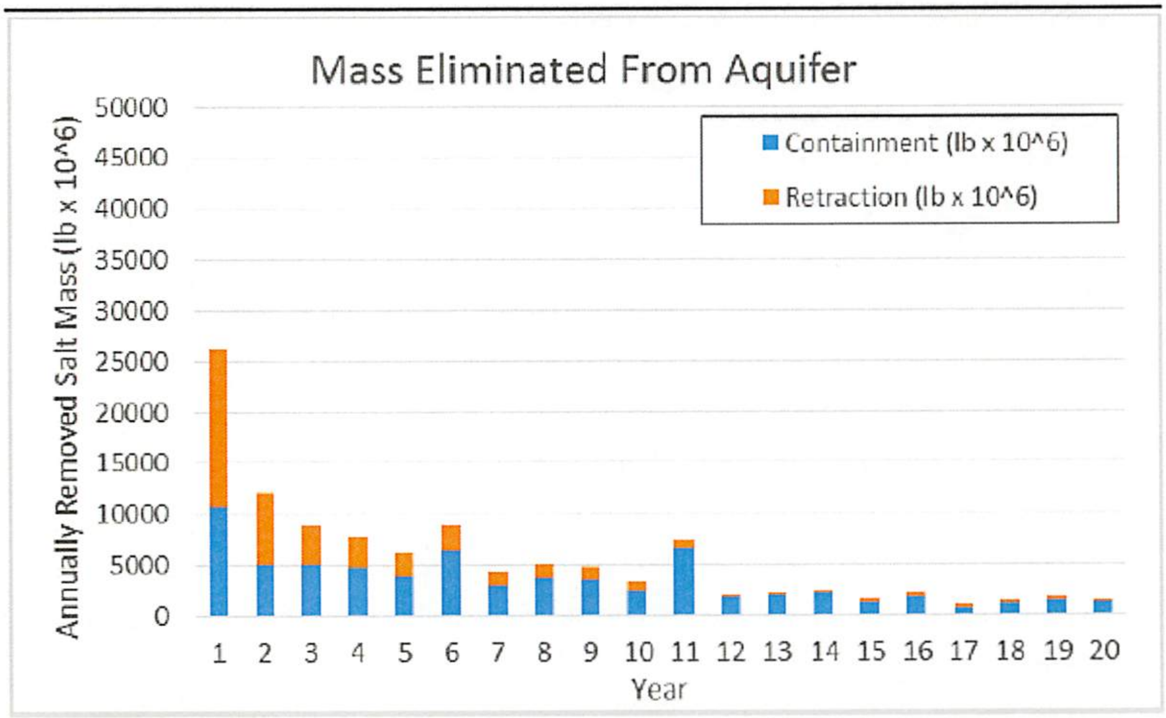
Demonstrative 26

Inflow	Flow (MGD)	Salinity (g/L)
Precipitation	24.7	0.0
Blowdown	7.9	7.0
GW inflow to CCS	28.9	55.0
Added Water	31	2.0
TOTAL	92.5	
Outflow		
Evaporation	43.7	0.0
Seepage to GW*	48.8	35.0
TOTAL	92.5	

* Seepage flow to groundwater is different from Table 1b of Tetra Tech 2014b to conserve flow balance

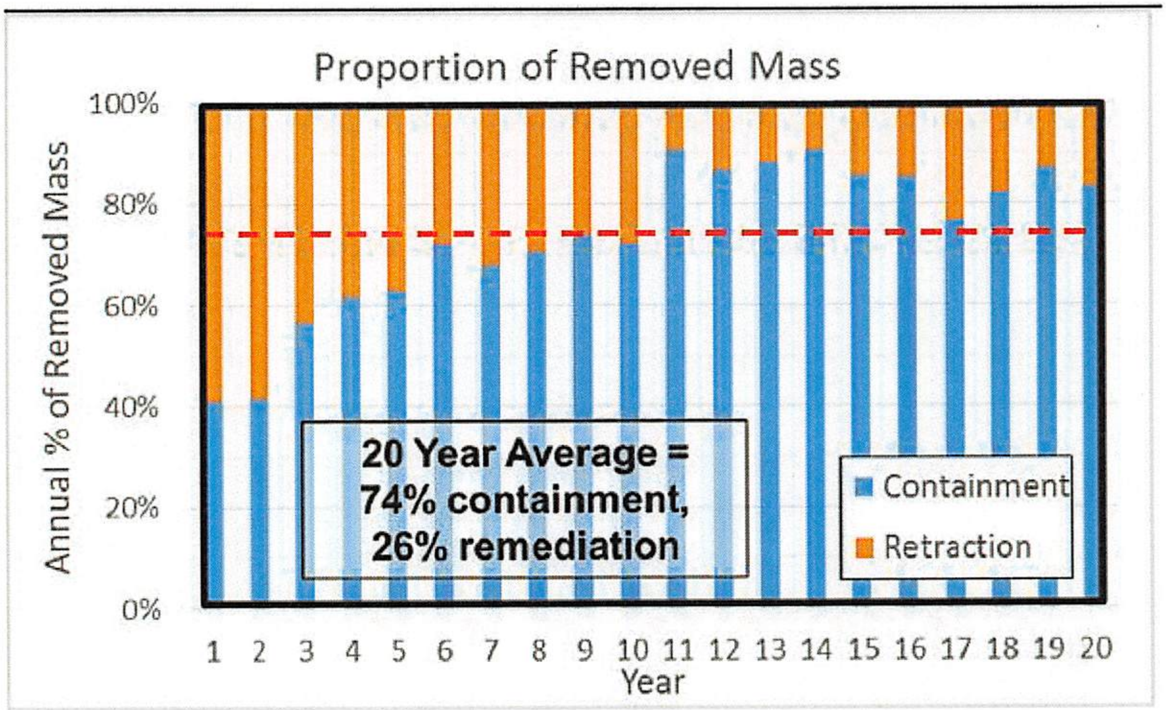
Demonstrative 26. Steady-state Water and Salt Balance Model for the CCS with added Floridan Water for a Groundwater Salinity beneath the CCS of 55 g/L

Demonstrative 27



Demonstrative 27. Tetra Tech, 2016m, Figure 6: Containment and retraction mass reductions in the Biscayne Aquifer in each year of the model simulation (layers 1 through 11 evaluated).

Demonstrative 28



Demonstrative 28. Tetra Tech, 2016m, Figure 7: Proportions of containment and retraction mass reductions in Biscayne Aquifer in each year of the model simulation (layers 1 through 11 evaluated).