Estimation of Capture Zones and Drawdown at the Northwest and West Wellfields in Miami-Dade County, Florida, Using Monte-Carlo Simulations Based on the USGS 2013 Study

Prepared for

Miami-Dade County

Department of Regulatory and Economic Resources-Division of Environmental Resources Management
and Water and Sewer Department

Prepared by

Groundwater Tek, Inc.

Naples, Florida

(Under Subcontract Agreement with Black & Veatch)

May 12, 2025

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Executive Summary

The Northwest Wellfield (NWWF) and the West Wellfield (WWF) are two of the wellfields used for drinking water supply in Miami-Dade County, Florida. To protect the safety of the water sources for the wellfields, efforts have been continuously made to establish the wellhead protection zones for these two wellfields. As part of wellhead protection zone delineation, travel-time capture zones and drawdown introduced from these two wellfields were delineated and assessed by the U.S. Geological Survey (USGS). The unique location of these two wellfields within the Lake Belt poses a challenge for wellhead protection zone delineation due to the presence of a large number of rock-mining quarry lakes.

To address the uncertainties associated with the wellhead protection zone delineation, the USGS applied a stochastic approach by performing reverse particle tracking analyses with unconstrained Monte Carlo simulations under steady-state average, wet and dry conditions (Brakefield et al., 2013). In the USGS 2013 study, five scenarios (three hydrological conditions with existing lake mining lake configuration (2004) and two special scenarios for lake expansion and seepage control under steady-state dry conditions) of unconstrained Monte Carlo simulations were conducted. Times of Travel (TOT) capture zones at 10-, 30-, 100- and 210-days were delineated based on the procedures proposed by Varljen and Shafer (1991).

Concerns were expressed by stakeholders regarding limitations of the model, so a technical work group (TWG) comprised of experts on groundwater modeling was convened to determine if the model could be improved. The TWG (2017) reviewed and responded to most of the stakeholders' major concerns but recommended further investigation of three issues. The key issue was whether the use of residence time for particles was appropriate and how to improve the work of the USGS. Groundwater Tek Inc. (GTI) was retained by Miami-Dade Department of Water and Sewer (WASD) and Department of Natural Resources (DNR) in 2019 to review the TWG's recommendations.

An alternative approach proposed by GTI, using a critical residence time, was used with concurrence from the Division of Environmental Resources Management (DERM) of Miami-Dade County to better address the travel time issue for particles moving through quarry lakes so the wellhead protection areas (WPAs) can be more accurately delineated (GTI 2019). Extra particles were added to the inflow lake cells of selected lakes to ensure a complete coverage of capture zones within the TOTs.

The main objectives of this work were to implement the recommendations of the TWG (2017) and suggestions from GTI and revise the stochastic delineation of the wellhead protection zones for the WWF and NWWF from previous USGS work (Brakefield et al. 2013). In this study, only the scenario with lake expansion and consideration of the slurry wall under steady-state dry conditions was modeled. Two sensitivity analyses were also performed to evaluate the TOT capture zones and drawdowns under different L-31N canal river cell conductance adjustments.

The Scope of work for this study is as follows:

(1) Review of previous USGS Modeling Work
- MODFLOW models developed and calibrated by the USGS.
- Particle tracking analysis.
- Unconstrained Monte Carlo simulations.
- Post-processing procedures and computer codes.
- Stochastic TOT capture zones delineation and drawdown assessments.

(2) Revision of Particle Tracking Codes

MODPATH code (version 5) and a number of post-processing codes were used in previous USGS study for the particle tracking analysis. Revisions to this and other related data-processing computer codes were modified to allow:

- Adjustment of critical residence time for each quarry lake.
- Placement of additional particles along the inflow side of lakes.
- Adjustment of release time for additional particles based on particle arrival time.
- Selection of the critical residence time.
- Time series analysis of initial and added particles for the capture zone delineation.

(3) Lake Data Preparation

- Collaboration with DERM/WASD staff to determine the critical residence time for affected quarry lakes.
- Preparation of the input data files including the inflow-cells for particle tracking for WWF and the NWWF for future lake expansion.

(4) Consideration of the Impacts of a Slurry Wall

- Development of an approach for consideration of partially penetrating slurry wall in a single layer MODFLOW model.
- Performance of sensitivity analyses using different seepage reduction values.

(5) Unconstrained Monte Carlo Simulations

Rerun the unconstrained Monte-Carlo simulations based on 10,000 randomly selected datasets for hydraulic conductivity and effective porosity under steady-state dry conditions, when future lake expansion is considered. The conductance of selected river cells was modified to represent the slurry wall constructed along the western levee of the L-31N canal.

(6) Post-processing Particle Tracking Results

- Review and make necessary changes to the post-processing tools developed by the USGS.
- Validation of the distribution of particle endpoints at various times of travel.
- Post-processing of the particle tracking results following the procedures proposed by Varljen and Shafer (1991).
- Review and make necessary changes to the JAVA scripts developed by the USGS for TOT capture zone statistical assessments.

(7) Generation of TOT Capture Zones and Drawdown Maps

Development of TOT capture zones for 10-, 30, 100- and 210-days and (0.1-foot) drawdown maps under steady-state dry conditions for the built-out future lake expansion conditions using the stochastic approach applied by the USGS with necessary revisions.

(8) Report Preparation

Preparation of a report describing the modeling procedures used including code revisions and results of the Monte Carlo simulations.

The following conclusions are based on the results of the work performed by GTI:

(1) As expected, the upper bound of 95% confidence interval (CI) of 210-day capture zones for steady-state dry conditions are the most extensive simulated capture zones for the NWWF and the WWF.

(2) The combined upper bound of the 95% CI capture zone for the NWWF encompasses the 210-day WPA published by MDC. However, the combined upper bound of the 95% CI capture zone for the WWF is considerable smaller than the 210-day WPA published by MDC.

(3) Canals surrounding the wellfields constrain the capture zones. Canals to the north, east and south of the NWWF and to the west of the WWF largely constrain particle movement and therefore affect the simulated TOT capture zones.

(4) Although studies performed by others indicate that the partially penetrating slurry wall reduces groundwater seepage from the ENP to the L-31N canal in the immediate vicinity of the slurry wall, the reductions have little if any effects on the simulated TOT capture zones and drawdowns of the NWWF and WWF.

Section 1: Introduction

The Northwest Well Field (NWWF) and West Wellfield (WWF) are two of the wellfields used for drinking water supply in Miami-Dade County (MDC), Florida. The locations of these two wellfields are shown in **Figure 1-1**. These two wellfields, designed to supply approximately 250 million gallons of water per day (MGD), pump from the highly transmissive Biscayne aquifer in the urban corridor between the Everglades and Biscayne Bay (Brakefield et al., 2013). These wellfields are located in an area known as the Lake-Belt Region where there are numerous limestone mines.

As part of the recent re-evaluation of the Wellfield Protection Areas (WPAs), the time of travel (TOT) capture zones and drawdowns associated these two wellfields were delineated by the U.S. Geological Survey (USGS). The USGS developed a countywide integrated surface water/groundwater model in 2007. This model was used with modifications by the USGS in 2013 to evaluate capture zones around NWWF and WWF. Reverse particle tracking analyses were performed with unconstrained Monte Carlo simulations under steady-state average, wet and dry conditions. Pollutants are represented by imaginary particles in the model. Wellhead protection zones were delineated following the stochastic approach developed by Varljen and Shafer (1991). The USGS study was documented in the report entitled in "Estimation of Capture Zones and Drawdown at the Northwest and West Wellfields, Miami-Dade County, Florida, Using an Unconstrained Monte Carlo Analysis: Recent (2004) and Proposed Conditions" (Brakefield, et al., 2013).

Concerns were expressed by stakeholders regarding the limitations of the USGS model. In response, a technical work group (TWG) was convened by Miami-Dade Division of Environmental Resources Management (DERM) to determine if the model could be improved. Of particular concern was whether travel times for potential pollutants within the lakes were adequately addressed in the USGS study.

The TWG in 2017 recommended that the USGS modeling be reviewed and revised in order to more accurately estimate potential pollutant travel times and define WPAs at the Northwest and West wellfields. Recommendations of the TWG for procedures to revise the modeling by changing to a hydrodynamics model were reviewed and generally found to be infeasible due to a lack of required data or the extreme computational requirements required to implement the procedures. Review and possible revision of the residence times for the lakes was considered feasible.

Groundwater Tek Inc. (GTI) was retained by MDC DERM/WASD to review the TWG's recommendation and Dr. David Chin's recommendation as a former member of the TWG. Based on the review, GTI in 2019 proposed an alternative approach to address the travel time for particles moving through quarry lakes so the WPAs may be better delineated. The approach proposed by GTI involved use of much shorter “critical” residence time than the residence time used by the USGS to represent the more conservative probability for a particle (representing a pollutant) to travel across a lake and pose a potential risk to a wellfield. Following the recommendation by Dr. Chin, GTI also proposed incorporating the critical residence time with releasing additional particles from upgradient lake inflow sides as appropriate based on particle travel times. As part of the review of the USGS model and TWG recommendations, GTI developed a hypothetical model to demonstrate the effects on the simulated delineations of capture zones when critical residence times are applied, and additional particles are released at a lake’s inflow margin cells. Results of the hypothetical model indicated that the particle capture areas for the prescribed times of travel (TOTs) were more conservative than those resulting from the methods used by the USGS.

GTI was subsequently retained by MDC DERM/WASD to address the TWG’s and Chin’s recommendations by implementing GTI’s proposed approach for using critical residence times and wellhead protection zone delineation with additional particles released from upgradient inflow sides at different release times. In addition, GTI was retained to develop and implement an alternative approach for addressing the slurry wall on the west side of the L-31N canal. The major tasks included:

- Determinations of critical residence times.
- Identification and addition of particles to the inflow margin cells at selected lakes.
- Update of the lake information for the lake expansion configuration.
- Adjustment of the river cell conductance of L-31N Canal to reflect seepage reduction due to construction of the slurry wall along the western side of the canal.
- Revision of particle tracking, and post-processing codes developed by the USGS.
- Performance of unconstrained Monte Carlo simulations under steady-state dry conditions and using critical residence times concurred for proposed lake expansion scenario.
- Performance of sensitivity analysis simulations under different river cell conductance values; and
- Preparation of TOT capture zone and drawdown maps.

Methods and results are described in the following sections. The revised maps of capture zones at specified TOTs of 10, 30, 100 and 210 days are presented. In addition, 0.1-foot drawdown contours under steady-state, dry conditions are also shown in several maps.

Section 2: Previous Investigation–USGS Delineation of Capture Zones of The Northwest Wellfield and West Wellfield

The following is a brief summary of the stochastic delineations of capture zones of the NWWF and WWF performed by the USGS in 2013, and evaluation of the USGS work performed by GTI. Capture zone delineations by the USGS are described in the report entitled "Estimation of Capture Zones and Drawdown at the Northwest and West Wellfields, Miami-Dade County, Florida, Using an Unconstrained Monte Carlo Analysis: Recent (2004) and Proposed Conditions" (Brakefield, et al., 2013).

2.1 USGS Model Overview

A numerical groundwater flow model used for the stochastic simulations was developed and calibrated by the USGS for a 9-year simulation period from 1996 to 2004. The groundwater flow model that the USGS developed for the study has 1,730 rows and 730 columns, and 1 layer. A uniformed grid of 50 m (or approximately 160 ft) was applied to both row and column directions. The model was calibrated for the time period of field data to acceptably match simulated and observed values for aquifer heads and net exchange of water between the aquifer and canals.

Steady-state simulations with existing lake configuration (2004) under dry, wet and average conditions were performed by the USGS with the unconstrained Monte Carlo analysis to estimate the median and the 95% CIs for both TOT capture zones and drawdowns. Two additional scenarios were also evaluated by the USGS: lake expansion and seepage control with a slurry wall (Brakefield et al., 2013). These two additional scenarios were evaluated under steady-state dry conditions.

2.2 USGS Representation of Lakes

Interaction between interconnected surface water management systems, including canals and control structures, and groundwater was recognized by the USGS as a unique aspect of the study area. The proximity of the NWWF and WWF to the quarries may also be considered unique. According to the USGS, the presence of a large of number of lakes had not previously been considered in the estimation of capture zones. No guidelines or site applications for wellhead protection area delineation in the presence of large number of lakes at other locations have been reported in literature (Chin et al., 2010).

The presence of lakes poses a technical challenge to the traditional capture-zone delineation technique which has been developed and applied for groundwater (USEPA 1987; 1994). Particle tracking codes, such as MODPATH (Pollock 1994) and PATH3D (Zheng, 1992), were developed for groundwater. The dynamics of water movement in a lake are quite different from that in the aquifer. It has been a widely accepted approach to simulate a lake using a high transmissivity (T) and high storativity (S) zone as a part of an aquifer (Anderson et al., 2002). The travel time through the lake is computed based on Darcy's law as groundwater in an aquifer. When fewer and smaller lakes are present, this approach is generally acceptable. However, when a large number of lakes and/or large lakes are involved, as in this study, the traditional approach based on groundwater movement through an aquifer with high transmissivity (T) and storativity (S) may not be appropriate.

To represent the lakes in the one-layer model of the Biscayne Aquifer used by the USGS, a bulk hydraulic conductivity value was calculated for lake cells. The USGS estimated lake cell transmissivity based on lake depth, an assumed 328,084-feet/day (100,000-meters/day) lake hydraulic conductivity, the underlying aquifer thickness, and the Biscayne aquifer hydraulic conductivity obtained from the corresponding model cells in the base-case deterministic simulations.

2.3 USGS Representation of The Slurry Wall

One of the special scenarios performed by the USGS was consideration of a slurry wall along the L-31N canal as then proposed measure of seepage control from the Everglades National Park (ENP). The USGS study was completed before the partially penetrating slurry wall was completely constructed. The groundwater model used by the USGS in the wellhead protection area delineation (Brakefield et al., 2013) consists of one layer representing the Biscayne aquifer. The ENP and the L-31N Canal were combined and modeled as the western model boundary in the study area using MODFLOW RIVER package. Therefore, the USGS model neither allowed addition of a partially penetrated slurry wall nor had the room to add the slurry wall between the ENP and the L-31N Canal. Therefore, the USGS applied a hydraulic flow barrier immediately east of the L-31N Canal to represent a slurry wall for their simulations that included the slurry wall.

2.4 USGS Unconstrained Monte Carlo Analysis and Particle Tracking

Groundwater models that provide estimates of capture zones and drawdown typically use a deterministic approach in which a single result is produced based on a single set of random model input parameters. Uncertainty in simulated results cannot be quantified with this approach. With the Monte Carlo analysis, capture zones and drawdown contours are determined for many different random parameter sets that are statistically equally plausible. Each parameter set and associated model result is called one realization. The approach is considered unconstrained because no attempt was made to calibrate the model after each realization. For the Monte Carlo analysis, 10,000 stochastic realizations using random horizontal hydraulic conductivity, conductance of canals, and effective porosity values were simulated for steady-state conditions representative of dry, average and wet hydrologic conditions to determine TOT capture zones.

To determine TOT capture zones, backwards particle tracking was performed. After each set of 10,000 realizations was simulated, the locations of 6 million particles surrounding the NWWF and 1.2 million particles surrounding the WWF were collected and processed for 10-, 30-, 100-, and 210-day TOT capture zones. Residence time for each lake was calculated for each realization as the volume of the lake divided by the steady-state outflow of the lake into the aquifer, which varies from one realization to another.

A post-processing adjustment, based on calculated residence times, was utilized to adjust daily particle endpoints to account for an estimate of residence-time of lakes. The USGS adjusted the particle travel time through a lake by applying the residence time of a lake to all the particles entering that lake within the prescribed TOTs.

After completion of the 10,000 realizations and post-processing adjustment of particle endpoints for each of scenarios, the median and 95% CIs were determined following the approach and steps suggested by Varljen and Shafer (1991). The median and 95% CIs were used to delineate the median and 95% CIs simulated capture zones for each scenario and TOTs by connecting the median particle endpoints points and the upper bound and lower bound 95% CIs of particle endpoints.

Drawdown for each scenario was computed as the head difference between two similar flow simulations for each realization, but the production wells in the WWF and NWWF were turned off in one of two flow simulations. Drawdown contours of 0.1 and 0.25 foot were assessed for each scenario under the steady-state hydrologic conditions. As with the particle tracking described above, after completion of the 10,000 realizations for each scenario, the median and 95% CI of capture zones of 10, 30, 100 and 210 days were determined by the USGS for each wellfield following the approach and steps suggested by Varljen and Shafer (1991).

2.5 Technical Working Group and Chin's Review of USGS Work

Following the USGS publication of the results of their study, some stakeholders expressed concerns with the USGS model, as well as with the draft revised boundaries for the Northwest Wellfield and West Wellfield Interim Protection Areas that were developed by Miami-Dade County based on the USGS modeling results.

To address the stakeholder concerns, MDC DERM/WASD established a technical working group (TWG), consisting of experts in water resources, representatives of the stakeholders, the academic community, regulatory agencies, and other government entities.

The TWG reviewed 14 individual stakeholder comments received by the County in response to the USGS report and the proposed Wellhead Ordinance (TWG 2017). In addition, Dr. David Chin from University of Miami and a former member of the TWG, raised his concerns regarding the USGS work.

The TWG's responses, including Dr. Chin's comments, are presented in the TWG report entitled Report of Miami-Dade County Wellfield Technical Workgroup (TWG, 2017: TECHNICAL REPORTS.pdf (miamidade.gov)). The TWG responded and recommended further investigations to address the following 3 of the 14 stakeholder comments:

Issue #1: Conduct further field tracer tests for improved representation of aquifer properties in the model;

TWG Recommendations: The TWG unanimously agreed that additional tracer tests are not necessary. The TWG recommended remodeling using a constrained Monte Carlo approach for key model parameters such as hydraulic conductivity and effective porosity and comparing the results of the remodeling effort to the existing USGS unconstrained Monte Carlo approach in order to determine the best approach for defining the wellfield boundaries.

Issue #2: Account for the dispersive transport mechanism;

TWG Recommendations: The members of the TWG agreed that the current modeling approach does not explicitly account for dispersion. However, all the members, except one, were of the opinion that advective transport modeling with or without the Monte Carlo simulations is an acceptable practice for WPA delineation and is adequate for this modeling effort.

Issue #3: Quantify the uncertainty of the residence time in the quarry lakes.

TWG Recommendation: The TWG recognizes that the USGS model does not adequately address particle movement through lakes, and therefore recommends the County investigate further refinements to the approach.

The TWG recognized that the USGS model did not adequately address particle movement through lakes, and therefore unanimously recommended that the County investigate further refinement to the approach. Use of a residence time of each lake by the USGS, corresponding to each realization, as the travel time for all of the particles that travel through the lake, was a major technical concern for the TWG. Use of residence time was considered by the TWG to be an issue because a significant number of particles may travel through a lake faster than the residence time. If the residence time is exponentially distributed, a particle may have a 63% chance to travel through the lake using less than the residence time (Chin, 2014; 2016a; 2016b; 2017; GTI, 2019). Particles that spend time less than the residence time are of importance because they could have greater probabilities of arriving and adversely impacting water supplying wells before the time that would be predicted based on the residence time. Therefore, residence times in quarry lakes is the main issue to be addressed in this study.

In addition to the TWG's recommendation to reevaluate the residence times, Dr. Chin also recommended consideration of inflow lake margin cells from up gradient directions (Chin et al., 2010). Chin made a comment that the wellhead protection areas should include areas adjacent to the contributory canals that could be sources of wellhead contamination (Chin, 2016b). GTI considers these recommendations to be reasonable and important because contaminants may move into the capture zones via surface water from areas that are not covered by the capture zones.

2.6 GTI Evaluation of USGS Work and TWG and Chin's Recommendations

GTI evaluated the USGSD work with respect to the TWG comments regarding particle tracking and residence time and suggested to the County potential ways to improve the USGS work. Detailed reviews of these TWG recommendations and suggestions made by GTI can be found in draft report prepared by GTI entitled "Review of Recommendations of The Technical Work Group for the Wellhead Protection Area Delineations of The West and Northwest Wellfields, Miami-Dade County, Florida" (GTI 2019).

2.6.1 Evaluation of Particle Tracking in Lakes in the USGS Model and GTI Recommendation

In the USGS model, the quarry lakes were represented implicitly as model's lake cells assigned with a high hydraulic conductivity value (100,000 m/day) and effective porosity of 1.0. This approach has been widely accepted (Anderson et al., 2002; Guha, 2008). To represent these quarry lakes in a one-layer model, a bulk hydraulic conductivity value was calculated for each lake cell as described in Section 2.2. The actual or estimated depth of these lakes were used as a weighting factor in the calculation of the bulk hydraulic conductivity of lake cells.

The USGS also compared the use of MODFLOW Lake Package which allows the lakes to be modeled explicitly to the use of cells assigned with high hydraulic conductivity values. Because they found that the difference was not significant, the approach using high hydraulic conductivity cells for lakes, which is easier and introduces fewer parameters, was adopted by the USGS (Brakefield et al., 2013).

The USGS used a backward particle tracking method combined with an unconstrained Monte-Carlo analysis to delineate the capture zones for specific travel times within the wellhead protection zones. The USGS applied 40 particles around each production well as their starting locations. These particles may sufficiently delineate the capture zones near the wellfields. However, if only the particles that are introduced at the well are tracked, then dispersion and mixing in a lake are not accounted for. The approach that the USGS used is commonly accepted in practice (Wheater et al., 2000; Anderson et al., 2015; Frind et al., 2002; Frind and Molson, 2018). As Chin et al. (2010) indicated, the application of conventional particle tracking codes is limited to cases where the tracked particles remain entirely within the aquifer. Therefore, the existence of quarry lakes in the vicinity of the wellfields poses a challenge to WPA delineation. In cases where particles will enter lakes that are in the cone of depression/capture zone, an alternate approach must be considered. No guidelines or site applications for delineating WPAs in areas where lakes present have been reported (Chin et al., 2010).

In a standard particle tracking analysis, as was used by the USGS, the number of particles applied is predefined and the particle tracking code will track each particle either forward or backward from their starting time to the ending time when the particles are either captured or specified travel time has been reached. In a backward particle tracking scheme, the particle pathlines tend to diverge or spread out with distance from the production wells. Large gaps may exist between two adjacent pathlines, especially at a distance far away from the production wells.

Figure 2-1 shows a generalized capture zone, surrounding some production wells that resemble the WWF, as the result of backward particle tracking. Most lakes shown are covered by the capture zone, but one large lake is only partially covered by the capture zone. The parts of the lake, not considered as a part of capture zone based on this simulation, are also potential contributory areas for pollutants. If there is a pollution source present in that area, the contaminants may then enter the lake and migrate to the capture zone after mixing with the lake's water. Figure 27 of the USGS 2013 report shows that some lakes within the vicinities of the NWWF and WWF are only partially within the capture zones resulting from the USGS simulations.

GTI recommended the placement of additional particles along the upgradient inflow lake margins to address the concerns regarding particle tracking. When lakes are present, additional particles may be introduced along the upgradient inflow bank of a lake to represent a pollutant from a groundwater discharge that moves into the lake. For computer simulations, the upgradient inflow margin is the lake margin on the upgradient side of the lake with respect to the regional direction of groundwater movement. As shown in **Figure 2-2**, any spill that may result in contribution of contaminants to a lake within a well's cone of depression may potentially be drawn to the production well. If the lake is well mixed, then a pollutant may migrate to any part of the entire lake. For backward tracking, if the travel time allows the particles to move out of the lake and continue to travel in the upgradient direction, then new particles may leave the lake from any location along the upgradient inflow-side and continue to travel beyond the lake to the production well (Chin et al., 2010). The upgradient inflow lake margin is identified after completion of each realization performed as part of the Monte Carlo analyses and may be unique for each particular realization.

Figure 2-3 illustrates the concept of combined capture zones when the upgradient inflow lake margins are considered. In the figure, Lake 1 is completely covered by the capture zone while Lake 2 is only partially covered by the capture zone. If the travel time allows, then an additional capture zone adjacent to the upgradient side of Lake 2 should be added to the capture zone.

Figure 2-4 demonstrates the concept of backward particle tracking through a lake as was performed in this study. An imaginary particle is reversely tracked in an aquifer-lake system where: (a) as the particle moves through the aquifer, (b) as the particle enters a lake, (c) as the particle diffuses and is hydrodynamically mixed throughout the entire lake. Additional imaginary particles are added in (c) to mimic the process of the hydrodynamic mixing and diffusion of the particle throughout the lake. Finally, as shown in (d), the new particles are added to each upgradient inflow location and will continue to move away from the lake during the backwards particle tracking process if the travel time still permits.

When a pollutant enters a lake, its concentration will be reduced due to diffusion and hydrodynamic mixing. However, the traditional approach for capture zone analysis and wellhead protection zone delineation assumes solutes traveling by advection, so the mixing process and associated reduction in pollutant concentration are not considered (USEPA 1994). Therefore, if additional particles are not added to represent the effects of diffusion and hydraulic mixing, results of the traditional approach may result in smaller capture zones.

2.6.2 Evaluation of Residence Time in the USGS Model and GTI Recommendation

The residence time for a lake provides an approximation of time that is required for the concentration of a solute to reach equilibrium or a well-mixed condition. The shorter the residence time, the quicker the lake water is mixed. Instead of using the residence time, the concept of critical residence time was introduced and recommended by GTI in 2019. The critical residence time is related to but is less than the residence time. This results in a more conservative time for particle migration through a lake. Consistent with Chin's postulations, the critical residence time approach recognizes that some particles may traverse a lake before thorough mixing has occurred and, therefore, assumes that mixing is thorough when a number or percentage of particles, determined based on a given CI, completes migration across a lake.

When the critical residence time is set to zero, an instantaneous well-mixed condition is assumed, essentially ignoring the presence of the lake. The capture zones delineated under an instantaneous well-mixed assumption would be the most conservative but not realistic. An instantaneous well-mixed condition could only be applied for very small surface water bodies with high dynamics.

To demonstrate the concept of critical residence time in a lake and the release of new particles from the inflow margin as discussed above, a hypothetical MODFLOW model was developed by GTI. A detailed description and discussion are provided in the 2019 draft report prepared by GTI (GTI 2019).

The hypothetical single layer model used by GTI has 20 rows and 10 columns. A uniform grid spacing of 100 m was used in both the row and column directions (**Figure 2-5**). Two constant head boundaries were specified along the northern (water level = 8 m) and southern (water level = 2 m) borders, respectively. The rest of the model borders were specified as no-flow boundary conditions. One groundwater withdrawal well is located at the southern part of the model. The pumping rate for this well was assumed to 100 m^3/day. An L-shape lake is located 100 m north of the well. The bottom elevation of the lake is 2 m above an arbitrary datum.

A uniform hydraulic conductivity of 20 m/day was specified for all the model cells except for the lake cells which were assigned a value of 100,000 m/day. The layer bottom was set at an arbitrary datum for all of the cells except for the lake cells which had a value of 2 m above the datum. A backward particle tracking calculation was performed. Ten particles were put in a circular distribution at the well. A uniform effective porosity of 0.25 was assigned for the cells except for the lake cells which had a value of 1.0. The particles were reversely tracked against the groundwater flow gradient for 2,000 days.

Ten new particles were added to the northern margin (upgradient inflow side) of the lake. Their release time was determined based on the arrival time of the first particle that enters the lake and either the residence time or the critical residence time based on 5% probability of residence time distribution.

Figure 2-6 shows combined capture zones delineated under three different scenarios, (a), (b), and (c), using the residence time and critical residence time in the testing model. The results and scenarios are discussed briefly below:

(a) Capture zone generated using the USGS MODPATH code without any modification. The hydrodynamic effect of the lake on travelling particles was considered implicitly by the high values of hydraulic conductivity and effective porosity specified at the lake. In this scenario, 7 particles traveled through the lake. The average time these 7 particles spent in the lake was 653 days.

(b) The capture zone is delineated using an approach that was applied by the USGS in their study. The time for particles traveling through the lake was the hydraulic residence time (486 days). No new particles were added along the upgradient inflow-side of the lake.

(c) The capture zone delineated using the approach proposed by GTI for this study. This scenario contains two major changes from the approach used by the USGS: (1) the use of critical residence time (25 days) as the time for particles crossing the lake and release of 10 new particles along the upgradient inflow-side of the lake.

The reduced residence time results in a greater capture zone, assuming the time to capture is sufficiently long for particles to completely traverse the lake. In this example, the capture zone in scenario (a) is smallest because the average time the particles remain inside the lake is 653 days. The capture zone in scenario (c) is the largest because the critical residence time is 25 days based on 5% probability which allows the particles more time to continue travelling upgradient through the aquifer from the lake. The addition of new particles on the upgradient inflow side of the lake may have also contributed to an increase in the capture zone shown in the result for scenario (c).

Section 3: Revisions to the USGS Work

3.1 Introduction

In the USGS study of 2013, five scenarios (three hydrological conditions of dry, average, and wet, and two special scenarios) of unconstrained Monte Carlo simulations were conducted. All these five cases of stochastic simulations were run under steady-state conditions.

GTI revised the scenario under average dry conditions based on the lake expansion configuration for future wellhead protection delineation simulation. In addition, since the 5-mile-long slurry wall was constructed between 2012 and 2016, the hydraulic impact of this slurry wall was also included in this simulation. The following major revisions were made by GTI to the USGS simulations in this study:

- Replacement of residence time with critical residence time as recommended by GTI in 2019.
- Introduction of additional particles to upgradient inflow lake margin cells (including determination of particle release time) as recommended by GTI in 2019.
- Updating of the configurations of built-out mining lakes for lake expansion conditions as requested by the County.
- Representation of slurry wall by modification of river conductance of the L-31N canal between Tamiami Trail and SW 88th Street to mimic the eastward seepage reduction from the ENP to the canal and the County due to the construction of the slurry wall.

After 10,000 realization simulations were complete, the results were post-processed to assess the drawdowns and generate the capture zone maps for both wellfields using modified post-processing codes for pathlines and time series data from MODPATH.

3.2 Critical Residence Time

3.2.1 Overview of USGS Use of Residence Time and Concerns

As discussed in Section 2, a major concern regarding the USGS work was the travel time for particles in lakes and adjacent canals which were not explicitly simulated in the USGS model. The USGS used the residence time as the travel time through the various lakes in their particle tracking analyses. As stated in their comments, the TWG (2017) indicated that "the USGS model does not adequately address particle movement through lakes, and therefore recommends that the County investigate further refinements to the approach."

The residence time of a lake, calculated by the USGS as the volume divided by the flow, provides an average amount of time a particle would spend in a lake. In terms of a solute or a pollutant, the lake residence time defines the average time that dissolved substances would spend in the lake. The average residence time does not indicate how fast a specific contaminant may traverse a lake.

The USGS adjusted the particle travel time by applying the residence time of a lake to all the particles crossing that lake. For example, if a particle reaches a lake after 10 days, and the lake has a residence time of 90 days, the particle will need to be tracked backwards for an additional 110 days from the inflow side of the lake to obtain the 210-day capture zone location (Brakefield et al., 2013: p 22). This approach could lead to overestimates of the travel time for particles travelling through the lake because some significant amounts of particles may travel through the lake more quickly. Consequently, the extent of capture zones could likely be underestimated.

As Chin (2014) pointed out, if the residence time for a well-mixed lake is 150 days, there is a 63% probability that the travel time is less than 150 days. If it is desired to select a travel time that is exceeded 5% of the time only, then a travel time of 8 days should be used in particle tracking through the lake, not 150 days.

Because of the unique site locations, no cases that are similar to this study for WPA delineation have been reported other than the previous USGS study (Chin et al. 2010; Brakefield et al., 2013). MODFLOW/MODPATH is the most commonly applied approach for performing reverse or backward particle tracking for wellhead protection area delineation (USEPA 1994). When lakes are present, one of shortcoming of this approach is that it does not consider the lake's volume or the mixing process within the lake.

In the MODFLOW/MODPATH approach, some imaginary particles are placed as tracers around the pumping well and are moved against the hydraulic gradient until a specific TOT is reached. When lakes are present in the cone of depression/capture zone of a wellfield, the particle may travel entirely in the aquifer or may spend part its travel time in the lakes.

As a conceptual example for this study, a pumping well is located near a lake, as shown in **Figure 3-1**. One particle starting from a pumping well (Point A), will move to the lake edge (Point B). The travel time from A to B is assumed to be T_{a1}. Then it will get into the lake and move through the lake after some travel time T_{Lake}) to Point C. The particle will move back to the aquifer at Point C and continue to travel in the aquifer until the predefined TOT is reached (Point D). The travel time from Point C to Point D is assumed to be T_{a2}.

Therefore, the total travel time for this imaginary particle will be:

$$T_{total}=T_{a1}+T_{Lake}+T_{a2} \tag{3-1}$$

where T_{a1} is the travel time in the aquifer before reaching the lake; T_{a2} the trave time in aquifer after leaving the lake; T_{lake} is the trave time crossing the lake and T_{Total} is the total travel time from A to D.

The travel times within the aquifer, T_{a1} and T_{a2}, are readily determined in MODFLOW/MODPATH, based on Darcy's law. The time for the particle traveling through the lake, however, is more difficult to estimate. The hydrodynamics of a lake are much more complex compared to groundwater flow. The travel times and particle tracks within a lake are highly variable and depend on the mixing characteristics within the lake (Chin et al., 2017). The water movement in a lake is controlled by a number of factors including winds, geometry, depth, temperature, etc. However, it is not practical to develop hydrodynamics models for these lakes due to a lack of field data.

In the particle tracking part of the USGS study (Brakefield et al. 2013), the travel times through these lakes were adjusted based on the residence times, which were computed in each realization run based on the cell-by-cell flow out of each lake and lake's volume. Residence time is a measure of the average time a molecule of water spends in a lake or the mean time that water (or some dissolved substance) spends in a particular lake. The residence time defined for steady-state systems is equal to the lake volume divided by the inflow or outflow rate (Chow et al., 1988):

$$T_r = V/Q \tag{3-2}$$

where T_r is the residence time (T); V the lake volume (L^3); and Q the flow through the lake (L^3/T).

The residence time of a lake is a measurement of the time it takes to reach a well-mixed condition when the solute concentrations reach uniform in the lake. The larger the lake, the longer the residence time and the time for the lake to reach the well-mixed condition.

In the examples shown in **Figure 3-2**, one particle moving reversely from a pumping well to its source is shown (Brakefield et al. 2013). Case A shows a travel time prediction using conventional MODFLOW/MODPATH approach. In Case A, a particle reaches Lake 1 after traveling within the aquifer for 24 days. Then it spends 100 days traveling through Lake 1, 20 days in the aquifer to reach Lake 2, and 20 days moving through Lake 2. After exiting Lake 2, the particle then travels 10 more days in the aquifer to reach Point X. Total travel time for the particle to backward travel from the well to Point X is 174 days.

Case B shows the same pathline but a different travel time considering lake's residence time, as used by the USGS in their study. In Case B, the travel time of this particle within Lake 1 is replaced by the residence time (60 days) so it will leave Lake 1 after a total of 84 days. Then it spends 20 days traveling through the aquifer, and 10 days moving through Lake 2. After exiting Lake 2, the particle then travels 10 more days in the aquifer to reach Point X. Total travel time for the particle to travel backward from the well to Point X is thus 124 days. The total travel time in Case B is 50 days shorter than in Case A, as a result of using residence times in the lakes instead of the conventional MODFLOW/MODPATH approach.

Although more conservative than the conventional MODFLOW/MODPATH approach, use of the residence time in the WPA delineation may not be sufficiently conservative. The residence time represents the time for the lake to reach a well-mixed condition after the introduction of pollutants. Pollutants resulting from a spill on the upgradient margin of the lake may exit the lake before a well-mixed condition is achieved, thus reducing the actual residence time and overall travel time. As pointed out by Dr. Chin (2014), there is a 63.2% probability that travel time through the lake is less than the residence time assuming the travel times through a lake is described by an exponential probability density function (Chin, 2016a; 2016b; 2017). Therefore, the use of residence time to represent the travel time for particles moving through a lake is not conservative from the viewpoint of wellhead protection.

3.2.2 GTI Development of Critical Residence Time

The critical residence time, which is technically the minimum time for a particle to travel through the lake, may be significant in the WPA delineation. However, determining or measuring minimum travel time is challenging if possible. As described below, there are several possible ways to define the critical residence time:

- Determining critical residence time based on the probability of hydraulic residence time distribution and a risk management CI using the equation (Chow et al. 1988):

  $$P(t \leq t_c) = \int_{-\infty}^{t_c} f(x)\,dx = \mathrm{CI} \qquad (3\text{-}3)$$

  where $f(x)$ is a probability density function.

- Randomly selecting critical residence time from the residence time probability distribution for each Monte Carlo realization run.
- Approximating travel times by an exponential distribution as indicated by Chin (2014). Chin (2016a; 2016b) also demonstrated that normalized residence time is exponentially distributed except for one case when the transverse wind is dominant. If the travel time for a lake is assumed to be exponentially distributed and the residence time is n, then the probability for the travel time less than or equal to t_c would meet the predefined CI:

  $$P(t \leq t_c) = \frac{1}{n}\int_{0}^{t_c} e^{-t/n}\,dt = 1-\exp(-t/n) = CI \qquad (3\text{-}4)$$

- Selecting the shortest travel time among the particles that travel through the same lake without any time adjustment (i.e. based on the results of the standard MODPATH code). The advantage of this approach of taking the shortest travel time as the critical residence time is that the geometry of the lake can be factored into consideration.
- Ignoring the residence time by setting the residence time as 0. This approach essentially assumes that lakes are either instantaneously well-mixed or absent. Under this assumption, the travel times for particles crossing lakes are not considered. Elimination of the travel time for particles traveling through lakes will be the most conservative (i.e., a larger capture zone) but maybe unrealistic or over-conservative for large lakes.

The following alternative method for calculating critical residence times through the lakes was suggested by Chin in 2014 and provided for consideration by GTI in 2019. This alternative method yields more conservative residence times. In cases where the lake is well-mixed, the residence time in the lake can be described by an exponential probability density function given by (Chin 2014; 2016a; 2016b; 2017; GTI 2019):

$$f(T_{lake}) = \frac{1}{T_r}\exp\left(-\frac{T_{lake}}{T_r}\right) \qquad (3\text{-}5)$$

where $f(T_{Lake})$ is the probability density function (pdf), T_r is the residence time of the lake, and T_{Lake} is the travel time through the lake. If we define the ratio of T_{Lake}/T_r as the dimensionless residence time:

$$t^*=T_{Lake}/T_r \qquad (3\text{-}6)$$

The cumulative density function (*cdf*) can be obtained:

$$F(t^*)=P(T\leq t^*)=1-\exp(-t^*) \qquad (3\text{-}7)$$

Figure 3-3 shows the probability of travel time less than the dimensionless residence time (t*). From Figure 3-3, it is clear that the probability of a particle traveling through the lake less than or equal to the residence time (i.e., $t^*\leq 1$) is 63.2%, which agrees with Dr. Chin (2014), who indicated that there is a 63.2% probability that travel time through the lake is less than the residence time assuming the travel times through a lake is described by an exponential probability density function (2016a; 2016b; 2017). **Table 3-1** shows the probability of travel time less than or equal to the values of some dimensionless residence time.

As Chin suggested (2014), if it is desired to select a travel time that is only exceeded 5% of the time (which would normally be desirable), then a travel time of approximately 5% of the travel time should be used as the T_{Lake} (i.e., $t^*=0.05$). For a lake with residence time of 100 days, the probability of travel time through the lake less than $t^*=0.05$ or 5 days in this case is about 5%, corresponding to the 95% CI.

Figure 3-4 illustrates an example of travel time adjustments using the critical residence time, of the lakes. Two previously discussed cases, Case A and Case B, are also included in the figure for comparison. In Case C, where the critical residence time (as 5% of the residence time) is applied, the particle travels backwardly from the well to Point X in 58 days.

In accordance with the recommendation from Chin (2014), the critical residence time of 5% of the residence time was chosen for this study. The critical residence times for the lakes were converted for model input in Fortran using the following:

$$C_{tr} = NINT(0.05 \times T_r) \qquad (3\text{-}8)$$

where C_{tr} is the critical residence time (in days) and T_r is the residence time of the lake at current realization; *NINT( )* is the nearest integer function, defined in Fortran, which converts a real number to its nearest integer.

As shown in Equation 3-2, the residence time is computed as the ratio of lake volume to the flux out of the lake. Because the flux varies with realizations, actual residence time and critical residence time also vary with realizations during the Monte Carlo simulations.

3.3 Additional Particles from Inflow Lake Margins

Particles assigned to the production wells are released at time = 0 of a simulation. Release times for particles introduced on the upgradient inflow side of a lake are unknown prior to the execution of MODPATH. The release times for particles that are introduced to upgradient inflow sides are dependent upon the arrival times when the first particle enters the lakes and the critical residence times for the lakes. When multiple lakes are present, as in this study, it is more difficult to determine the release times for these added particles because particles may come from wells or from other lakes.

The time for the first particle to enter the lake must first be determined. After the entrance time for the first particle is known, the release time is calculated as the sum of the entrance time of the first particle and the critical residence time of the lake. An example of particle tracking with multiple lakes is shown in **Figure 3-5.** Once the earliest arrival time (t_a) is determined, then we can define the release time (t_o) for added particles added to the upgradient inflow margin as:

$$t_o = t_a + t_c \tag{3-9}$$

where t_a is the arrival time when the first particle reaches the lake from either the production well or from another lake and t_c is the critical residence time for a particle to cross the lake.

Additional particles are only activated if their release time is less than the TOT specified for the simulation. For example, if the release time for the additional particles is 150 days, these particles would be introduced for 210-day capture zone, but not for the capture zones for 10-, 30- or 100-day TOTs.

The following process was followed for adding additional particles to upgradient inflow side cells:

(1) Identification of lakes – Capture zones of the base-case for steady-state dry conditions for both wellfields were used to identify the lakes where addition of particles to the lake cells at inflow margin was necessary.

(2) Determination of inflow cells – Particles were placed in each model cell along a lake's edge. Then backward particle tracking analyses were performed under deterministic base-cases for steady-state dry conditions. Added particles moved different directions with some of them remaining in the lake and some of them moving out the lake, depending on the flow direction of each particular realization. Only the particles that moved out of the lake were selected and used for backward tracking and capture zone delineation analysis.

(3) Determination of release times - Time-series data from each realization were used to identify the earliest arrival time of a particle entering the lake. The release time for additional particles to the upgradient inflow margin of a lake is determined as the sum of the earliest arrival time plus the critical residence time for the lake.

The activation time for additional particles depends on the arrival time of the first particle entering the lake where the additional particles are added. Therefore, the number of activated particles varies with realizations, and it also depends on if their release time is less than the specified TOTs.

3.4 Lake Expansion

Rock mined from the Lake Belt supplies one-half of the limestone used annually in Florida. According to the South Florida Water Management District (SFWMD) website regarding the Lake Belt Mitigation Committee, the Lake Belt Area encompasses 77.5 square miles of environmentally sensitive land at the western edge of the Miami-Dade County urban area. The wetlands and lakes of the Lake Belt offer the potential to buffer the Everglades from the potentially adverse impacts of urban development. The Northwest Wellfield – located at the eastern edge of the Lake Belt is the largest drinking water wellfield in the State and supplies approximately 40 percent of the potable water for Miami-Dade County.

Future expansion of rock-mining activities in the Lake Belt area has been proposed. Stochastic capture-zone delineation analysis was performed by the USGS to assess the potential effect of mine expansion under the 2004 dry conditions. The USGS scenario assumed a 150%, or 25-square mile, increase in the surface area of the lakes from the 2004 surface area.

The configuration of lake expansion was provided by the MDC DERM/WASD. Additional mining and associated lake expansion is evident mainly to the west of the NWWF and WWF. Some of the existing mining lake configurations used in the USGS modeling study (not including the USGS lake expansion scenario) were enlarged according to the proposed mining plan. The combined existing and expanded lake configurations of the lake expansion scenario are shown in **Figure 3-6**. The lake numbers are arbitrarily assigned only for the purpose of lake identification in this study.

Lake depth data is required to compute the lake/aquifer thickness ratio and thus the composite aquifer transmissivity. The depth data for most of the expanded mining lakes was provided by the MDC DERM/WASD. For the future lakes without proposed depth information, the depths were estimated based on either depths of existing adjacent lakes or a generalized depth map provided by the County staff. **Table 3-2** shows the name of the lakes, areas, and depths used in this study.

As part of this study, GTI delineated capture zones for the future lake expansion configuration using the revisions to the USGS codes as described previously. Similar to the procedures of adding particles to the inflow margins of lakes, as discussed in previous section, additional particles were placed along the lake cells of inflow margin of several lakes. Initially, 919 additional particles were placed along the lakes where the inflow margin cells were located. After a test run using the data for the base-case deterministic simulation, 57 and 54 additional particles were selected for the NWWF and WWF respectively. Their approximate locations are shown in **Figure 3-7**. These 111 additional particles are combined with other 720 particles used by the USGS in each Monte Carlo simulation for the lake expansion scenario.

3.5 GTI Representation of the Slurry Wall

A 5-mile-long slurry wall was constructed between 2012 and 2016 along the levee west of the L-31N Canal between Tamiami Trail and SW 88th street to reduce the groundwater seepage from the Everglades National Park (ENP) to the canal (AMEC 2012; 2016). The slurry wall was constructed to a depth approximately 35 ft below the land surface, so it is partially penetrating the Biscayne aquifer.

The groundwater model used by the USGS in the wellhead protection area delineation (Brakefield et al., 2013) consists of one layer representing the Biscayne aquifer. The ENP and the L-31N Canal were combined and modeled as the western model boundary in the study area using the MODFLOW RIVER package. Therefore, the USGS model does not allow addition of a partially penetrated slurry wall, nor does it have the room to add the slurry wall between the ENP and the L-31N Canal as where the slurry wall was constructed.

The ENP was not explicitly included in the USGS model but its impacts to the Biscayne aquifer were combined with the L-31N Canal as a hydrogeological boundary (modeled with River package) in the model. Determination of the groundwater seepage from the ENP to the L-31N Canal and the wellfields is challenging. The hydraulic impacts of the slurry wall to the groundwater seepage have not been well studied after the slurry wall was constructed.

GTI proposed that the flow from the river cells along L-31N Canal defined in the USGS model, after calibration or adjustment, should hydraulically represent the seepage from both the ENP and L-31N Canal to the WWF area reasonably well prior to the slurry wall construction. GTI, with concurrence from DERM/WASD staff, developed an alternative approach that represents the slurry wall by adjusting river conductance for the L-31N Canal to reflect the potential groundwater seepage reduction.

The seepage flow into or out a river cell in MODFLOW can be estimated as:

$$Q=f_w*C*\Delta H \qquad (3\text{-}10)$$

where Q is the flow (L^3/T), C is the river conductance (L^2/T) and ΔH is the head difference between the river stage and head in the hosting aquifer (L). f_w is an adjustment factor associated with the slurry wall. Before the wall was constructed, f_w=1.0.

As shown in the equation above, the flow to/out of a river cell is proportional both to the river conductance and the head difference between the canal stage and groundwater head in the aquifer. Note that the flow term Q, in this particular application of the USGS model after model calibration (Brakefield et al., 2013), includes not only the flow in/out of the L-31N canal, but also the deep seepage beneath the canal from the ENP. Thus, the change of the seepage beneath the canal towards the WWF area can be modeled by applying an adjustment factor (f_w)

to the river conductance in a steady-state model to reflect the change of groundwater seepage out of the river cells due to the construction of the slurry wall while everything else can be kept unchanged, as in the USGS model.

Developing the alternative approach for representing the ENP and slurry wall used by GTI in this study included building a one-dimensional multiple layer cross-sectional groundwater flow model based on the three-dimensional groundwater model developed by the USGS for the Miami-Dade County (Hughes and White, 2014) (referred as the USGS county-wide model). Simulated reductions in seepage provided adjustment factors that were subsequently applied to river conductance values of selected river cells along the L-31N Canal for simulations performed by GTI.

The USGS county-wide model uses three model layers to represent the Biscayne aquifer (Hughes and White 2014). The GTI cross-sectional model was built based on this county-wide MODFLOW model to evaluate the hydraulic impacts of the slurry wall. The aquifer properties and layer structure were extracted from the county-wide model for the cross-sectional model. The cross-sectional model has 1 row, 11 columns and 3 layers representing the Biscayne Aquifer. The bottom layer is the most transmissible layer while the middle layer is least transmissible so layer 2 behaves as a semi-confining unit. Detailed information about the cross-section model and the assessment of seepage reduction can be found in **Appendix A**.

Both ends of the cross-section model were set as constant head boundary conditions, representing the ENP and the WWF area. WWF Well #29 which has a maximum permitted pumping rate of 5 mgd (CDM 2008), was selected for this modeling exercise.

The slurry wall was added to the western side of L-31N in layers 1 and 2 (elevations from 4 to -30.4 ft (NAVD88) fully penetrating the first two layers. An approximate value of hydraulic conductivity of 5×10^{-6} cm/sec (or 0.014 ft/day) was used for the slurry wall in this study based on the actual testing data (AMEC 2012). The slurry wall was simulated using MODFLOW's Horizontal Flow Barrier Package (HFB) (Hsieh and Freckleton, 1993; Harbaugh et al., 2000).

The hydraulic impact of the slurry wall to the groundwater seepage from the ENP was assessed by the differences of the seepage fluxes under the base condition and the condition with slurry wall. The only difference between the two simulations is that the base run represents the conditions prior to the construction of the slurry wall while the other run represents the conditions after the slurry wall construction.

To better visualize the groundwater seepage flow paths, particle tracking analyses were also performed. A number of particles were added to Column 1 at different depths and at some of cells in layer 1 representing the ENP.

Figure 3-8(a) shows modeled head contours and pathlines from the base run simulation when Kv=Kh for all layers. **Figure 3-8(b)** shows modeled head contours and pathlines from the simulation with a slurry wall penetrating layers 1 and 2 when Kv=Kh for all layers. As shown in

Figure 4-8(b), the flow from the ENP is essentially along the model layers. Some deep groundwater seepage moves up from layer 3 to the canal.

Table 3-3 summarizes the seepage flowing into (Q_{in}) Column 5 (containing the canal) and leaving (Q_{out}) Column 5 under the base run conditions and the slurry wall. Q_{in} represents the groundwater seepage from the ENP to Column 5 and Q_{out} represents the seepage from Column 5 flowing east towards the WWF area. Table 3-3 also contains the changes of seepage fluxes due to the construction of the slurry wall.

The seepage per unit width beneath L-31N prior to the construction of the slurry wall is about 536 cfd/ft of levee, which is comparable to the estimate from Nemeth et al. (2000), who modeled seepage rates between -200 and 500 cfd /ft of levee. Based on the total fluxes shown in Table 3-3, the total simulated seepage from the ENP (Q_{in}) is reduced by about 6.14% due to the construction of the slurry wall. The total reduction of flow to the L-31N Canal is 16% but the total seepage to the WWF area is only 0.3%.

MFL (2011) conducted a modeling study evaluating the performance of the slurry wall between the ENP and the L-31N canal. MFL (2011) found that the slurry wall would reduce the horizontal flow to the L-31N canal in shallow flow zones (Zones 1 and 2) but would increase the seepage flux in the deep flow zones. MFL evaluated the reduced seepage flows under various configurations of the slurry wall with different lengths and depths. MFL estimated the total flow from the ENP would be reduced approximately 33.5%, from 164 cubic feet per second (cfs) to 109 cfs due to the construction of a proposed 7-mile long 30 ft deep slurry wall along the west side of the L31-N canal.

The total flow reduction (as percentages) from the ENP due to the slurry wall, estimated by MFL (2011), is about 5 times higher than the estimate from the GTI study (about 6%). The MODFLOW models used by MFL and GTI are quite different in many aspects. One of the key factors might be vertical anisotropy. In this USGS county-wide model, the horizontal and vertical hydraulic conductivities were set equal as isotropic, and in the MFL (2011) model, the vertical hydraulic conductivity was set as 1/10 of the horizontal hydraulic conductivity.

A sensitivity analysis simulation was performed to investigate the vertical anisotropy values with respect to the modeling results. In this run, a 1/10 vertical anisotropy (K_v=0.1*K_h) was applied to all the layers while everything else remained unchanged. Based on the results of this sensitivity simulation, the simulated seepage reduction from the ENP (Q_{in}) is approximately 10.2% due to the construction of the slurry wall.

Based on results of the cross-section model and the MFL study (2011), the river conductance of the L-31N canal between Tamiami Trail and SW 88th Street was reduced by 0.3% in the base simulation. Two sensitivity simulations were also performed to assess the effects of changing river conductivities on the modeled hydraulic impacts of the slurry wall:

> Sensitivity simulation 1 (SA1): The river conductance was reduced by 10.2% based on the cross-sectional model assuming a 10:1 vertical anisotropy.

Sensitivity simulation 2 (SA2): The river conductance was reduced by 33.5% based on the MFL 2011 study based on a 10:1 vertical anisotropy for all the flow zones.

Section 4: GTI Monte Carlo Simulations and Capture Zone Analyses

4.1 Monte Carlo Simulations

The goal of wellhead protection area delineation is to establish an area where pollutants may potentially travel to the production wells within the time frames specified. There are a number of ways to delineate wellhead protection areas (USEPA 1994). Among them, drawdown and TOT are probably most commonly used. Therefore, the TOT capture zones are established based on the times of travel (TOTs). TOT capture zones are often delineated using groundwater flow models with particle tracking analyses, as was done by the USGS and GTI.

The numerical groundwater flow model used for the stochastic simulations was calibrated by the USGS for a 9-year simulation period (1996-2004). Detailed information regarding the model calibration can be found in the USGS report (Brakefield et al., 2013). The steady-state simulations for dry conditions were used with the Monte Carlo analysis to estimate the median and the 95% CIs for both capture zones and drawdowns.

To address the uncertainty in the groundwater flow model as well the TOT capture zone delineations, 10,000 realizations were used. In each realization, randomly generated hydraulic conductivity distributions and effective porosity values were used. The heads and cell-by-cell flows from each flow simulation were used for the backward particle tracking analysis to determine the stochastic TOT capture zones. The TOT capture zones are determined following the procedures described by Varljen and Shafer (1991).

A complete set of 10,000 Monte Carlo simulations from the original USGS study was conducted by GTI as a step of verification. The results obtained from this verification run were the same as the results presented in the USGS report. This verification process also validated the tools developed by the USGS and GTI, used in the pre- and post-processing procedures.

4.2 Drawdown Assessment

Drawdowns were computed from the head difference between a pumping condition and no pumping condition for both wellfields using the same realization. After completion of 10,000 realizations, 10,000 drawdown files were collected and processed, and the 95% CIs of 0.1-foot drawdown were computed. The 0.1-foot drawdown was also computed for the base-case deterministic simulations.

4.3 Delineation of TOT Capture Zones

The particle endpoints at TOTs of 10, 30, 100 and 210 days were computed and saved for each realization for each wellfield. After completion of all 10,000 realizations, the locations of these particle endpoints were collected and grouped. In the USGS study, the numbers of particles used in the Monte Carlo capture zone analysis were fixed at 120 for the WWF and 600 for the NWWF respectively. Each group in the USGS study contained 6 million particles for the NWWF and 1.2 million particles for the WWF for each TOT. All these particles were released at the beginning of the particle tracking simulation.

In the GTI study, additional particles were placed at inflow lake cells of selected lakes with their release times depending on the particle movement of all particles through aquifers and lakes included for the realization. Some added particles were activated if their release times were shorter than the specified capture TOTs (10, 30, 100 and 210 days). For example, if the release time is 50 days, then an added particle may be counted in the 100-day and 210-day TOTs. Therefore, the final number of activated particles varies with realizations. In the GTI study, some groups may have more endpoints due to added particles to the inflow lake cells.

All particle endpoint locations were converted to their polar coordinates (the distance from the wellfield center and radius angle from due east direction). The centers of the wellfields were determined by GTI using the same method as used by the USGS. Equations for determining locations of the wellfield centers were extracted from the USGS post-processing tools and are:

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} WX_i \qquad (4\text{-}1a)$$

$$\bar{Y} = \frac{1}{N}\sum_{i=1}^{N} WY_i \qquad (4\text{-}1b)$$

where $\bar{X}$ and $\bar{Y}$ are the wellfield geometric center coordinate (L) and WX and WY are the individual well's coordinates (L). N is the number of production wells for the wellfield: N=3 for the WWF and N=15 for the NWWF.

Next, the analysis of data using the method proposed by Varljen and Shafer (1991) was performed. Particles within each group were evenly (by number) distributed to 500 radius classes that cover the area completely (for 360 degrees) surrounding each wellfield (**Figure 4-1**). Each radius class includes approximately 1/500th of the total particles sorted and counted in counterclockwise direction starting from 0 degree (due east direction). If 1/500th of the total particles is not a whole number, then the number of particles per class was rounded up. In this way, some classes may have one particle endpoint less than others, but the error should be negligible considering the lowest total number of particles per class is at least 2,400 for the WWF and 12,000 for the NWWF. In this figure, each green point represents one of the 1,368,437 particle endpoints at the TOT of 210 days from the WWF.

The median and 95% CIs of all the particle endpoints within each of the 500 classes were then calculated based on the polar coordinates. As described in the USGS report, the calculation of the 95-percent CIs was based on the 2.5 and 97.5 percentiles of the cumulative distribution function of the particle endpoints in each class. The 50th percentile in a given particle class is equivalent to the median distance for that travel time from the center of the wellfield. The 95-percent CIs were approximated by discarding those endpoints whose distances were less than the 2.5 percentile or greater than the 97.5 percentile within each radial class. If the median positions and the confidence limits from each of the classes are connected orderly, e.g., counterclockwise as a polygon, a travel-time specific capture zone based on the median or the upper bound of the 95% CI was then developed.

Varljen and Shafer (1991) suggested the number of the endpoints (or particles) in each radius class can be defined in the model post-processing code as:

$$N=(NR \times NP)/m \tag{4-2}$$

where *N* is the number of particle endpoints per class; *NP* is the number of particles used in one realization and *NR* the number of realizations; and *m* is the number of radius classes (i.e., 500).

The equation above is no longer suitable in this study since NP is no longer a constant but varies with realizations. To ensure all the particle endpoints are accounted, the number of endpoints per class is calculated as:

$$N=INT(NT/m)+1 \quad \text{if } Quotient(NT/m)>0 \tag{4-3}$$

$$N=INT(NT/m) \quad \text{if } Quotient(NT/m)=0 \tag{4-4}$$

where *NT* is the total number of particles endpoints for a specified travel of time of travel. In this way, some classes may have one particle endpoint less than others, but the error should be negligible considering the total number of endpoints per class is at least 2,400 for the WWF and 12,000 for the NWWF. In Equations 4-3 and 4-4, *INT( )* is a function with return of the integer portion of a fraction.

4.4 Post-Processing for TOT Capture Zone Delineation

Two types of capture zone delineation analyses were required for this study:

- Time Series Analysis: The output from particle tracking analyses using MODPATH is the daily locations of each particle from its release time until it is captured or reached the end of specified travel time is reached. The results are used to define the capture zones for a specific TOT (Time of Travel): 10, 30, 100 and 210 days.

- Pathline Analysis: The output is the pathlines of each particle from the release time until it reaches the end of specified travel time is reached. The pathline analysis allows the viewing of the complete capture zones of each realization.

In addition to the post-processing code for counting particles described above, GTI made the modifications described below to enhance the efficiency of simulations and presentation of results.

After completion of MODPATH executions, the UGSS developed post-processing computer programs using TR_Analysis.f90 for both the WWF and the NWWF. These codes were used to read the time series data generated from MODPATH and adjust the travel time of each particle based on the residence time of the lake or lakes that the particle traveled through. At the end, the TOTs at 10, 30, 100, and 210 days were identified and saved for each realization.

The post-processing computer codes were revised to better use computer memories and to gain higher computational efficiency. Some minor errors in handling time adjustment in the original USGS codes were fixed. The revised codes were thoroughly tested and verified before they were used.

Section 5: Discussion of Results

5.1 Introduction

The primary scope of this study was to simulate the WWF and NWWF capture zones previously delineated by the USGS in 2013 based on a stochastic approach by implementing the 2019 GTI-proposed actions to address the recommendations from the TWG and Dr. Chin. As discussed in previous sections of this report, the major changes to the USGS work are the application of critical residence times, addition of particles at the upgradient inflow side lake cells at some selected lakes and consideration of the hydraulic impacts from the slurry wall. The lake expansion scenario was revised based on the latest information provided by the MDC staff. The conductance values of 167 river cells in the L-31N Canal corresponding to the length of the slurry wall between Tamimi Trail and SW 88th Street were modified to account for the hydraulic impacts due to the construction of the slurry wall.

5.2 Base-case Deterministic Simulations

A deterministic simulation based on one set of input parameters under steady-state dry conditions using lake expansion configuration was developed. Unlike the Monte Carlo simulations in which hydraulic conductivity and effective porosity are randomly selected in each of 10,000 realization, one representative set of hydraulic conductivity and effective porosity are used in the base-case deterministic run. Based on the determinations discussed in Section 3.3, additional particles were added to the inflow sides of selected lakes at locations shown on Figure 3-7. The conductance of the selected 167 river cells was reduced by 0.3%.

Figure 5-1 shows the simulated 0.1-foot drawdown contour and particle endpoints after 10, 30, 100 and 210 days for the base-case deterministic simulations under steady-state dry conditions.

Simulated backward-tracked particle positions for the base-case scenario demonstrate the effect of critical residence times for the lakes. Particle endpoint locations indicate that the simulated TOT capture zones for the NWWF extends radially and is controlled by the existence of lakes surrounding the wellfield. Most particles with travel times of 10 and 30 days remain within the aquifer, while the particles with travel times of 100 and 210 days move beyond the lake zones to the west direction onto the aquifer. To the east, north and south of NWWF, where numerous quarry lakes are present, the 100- and 210-day TOT particle endpoint locations mimic the configurations of the lakes and extend further from the wellfield than to the west. This is due to the critical residence-time adjustment effectively reducing particle travel time through the lakes and increasing the simulated areal extents of the capture-zones. The eastern margin of the 100- and 210-day TOT particle endpoints indicate that, although lakes are present, the simulated 100- and 210-day TOT capture zone east of the NWWF is constrained by the surrounding canals.

For the WWF, all the lakes are present to the west and northwest of the wellfield. Therefore, the simulated capture zones are radial to the north, east, and south of the WWF where particles are primarily moving through the aquifer. The irregular shapes of the simulated

100- and 200-day TOT simulated capture zones to the west and northwest of the WWF are due to the influence of the lakes.

The extent of the 0.1-foot drawdown, as shown in Figure 5-1, is also strongly impacted by the existence of lakes and canals. When a larger number of lakes are present, the extent of the 0.1-foot contour will be closer to the wellfield, otherwise the 0.1-foot drawdown contours will extend farther from the wellfields. The relationship between the drawdown contours and surrounding canals clearly indicates that these canals are the import sources of water for the wellfields.

5.3 Unconstrained Monte-Carlo Simulations

5.3.1 0.1-foot Drawdown Contours

Drawdowns of 0.1 ft for the NWWF and WWF were estimated using the Monte Carlo simulations. **Figure 5-2** shows the median and 95% CIs for 0.1-foot drawdown contours for these wellfields under steady-state dry conditions. The median and 95% CI of the drawdowns were computed from the collection of drawdowns from 10,000 individual simulations (realizations). The median and the upper and lower bounds of the 95% CIs were contoured for the 0.1-ft drawdowns as shown in Figure 5-2.

The effects of canals are also evident in the relationships between the cones of depression associated with the NWWF and WWF and other nearby wellfields. Drawdown contours around the WWF coalesce with drawdown contours around other well fields to the east. For purposes of this analysis, maximum design-capacity pumping rates used by the USGS were used for well fields outside of the NWWF and WWF. Deterministic base-case simulated drawdowns are very similar to the median drawdowns obtained from the Monte Carlo simulations. Canals, both within the model domain and at the model boundaries, constrain simulated capture zones.

5.3.2 Particle Tracking and TOT Capture Zones

Simulated 95% CI bands and median TOT capture zones for the base-case steady-state dry hydrologic conditions are shown in **Figures 5-3** through **5-6**, respectively. Particle endpoints for the 210-, 100-, 30-, and 10- day TOTs for the base-case deterministic simulation are also included in these maps.

As shown in these figures, the extents of the TOT capture zones are strongly affected by the presence of quarry lakes. In the absence of lakes, the width of the 95% CI band reflects ambient flow conditions and uncertainty in the distribution of hydraulic properties and fluxes. In the presence of lakes, the width of the 95% CI band also reflects the uncertainties associated with critical residence times for the lakes and adjustments of particle travel times through lakes.

The extents of the 95-percent CI contours differ due to the hydrologic conditions in areas surrounding the wellfield where there are no lakes. This difference becomes more obvious for longer travel times such as 100 days and 210 days because more random values are assigned to more model cells as part of the Monte Carlo simulations. For travel time of 10 days and 30 days, most particles still travel within the aquifer at the WWF, so the simulated capture zones are not significantly impacted by the lakes. The NWWF is surrounded by quarry lakes at close distances, so even the 30-day capture zone is affected by the lakes. For 10-day capture zone of the

NWWF, most particles from the base-case deterministic simulation are still within the aquifer but the upper bound of the 95% CI covers a number of surrounding lakes to its west.

The 210-day median of simulated capture zones are similar to but cover larger spatial extents than the simulated capture zone particle positions for the base-case deterministic simulations. The simulated TOT capture zones for the NWWF extend more toward the west (regionally downgradient direction) than toward the east due to the presence of canals to the north, east and south of the NWWF. The width of the 95% CI band is generally narrower to the north, east and southeast of the NWWF because the simulated capture zones are constrained by canals and critical residence time adjustments of the backward-tracked particles in the adjacent lakes.

Simulated median TOT zones and 95% CI bands associated with the WWF are generally narrower to the east and south of the WWF because of the regional groundwater gradient (east to west) and, for the longer TOTs, due to absence of lakes east of the WWF. The simulated median TOT zones and 95% CI are more extensive towards the west (regionally downgradient direction), northwest, and southwest directions due to the presence of lakes and added particles at selected lakes.

The 100- and 210-day TOT zones only cover Lake #32. Lake #31, just north of Lake #32, is not included in these TOT capture zones. There is a proposed berm separating these two lakes, as shown in Figure 3-6.

The median and upper bounds of the 95-percent CI are larger than the 0.1-foot drawdown contours in the west of WWF. These are caused by several factors: (1) the 0.1-foot drawdown contour line is not a limit for particles continuing to travel; (2) Particles may travel fast across a lake due to use of small critical residence time (e.g., the upper bound of 95% CI of 210-day TOT capture zone to the northwest of the WWF); and (3) Added particles may be activated from the inflow side of lakes (e.g., the upper bound of 95% CI of 210-day TOT capture zone west of NW 127th Ave.

Figure 5-7 shows the comparison of areal extents of the upper bound of 95% CIs of 210-day TOT capture zones and the current 210-day Wellhead Protection Areas (WPA) for the NWWF and WWF (wellfield-protection-areas.pdf (miamidade.gov)). Geometries of the combined upper bound of the 95% CI capture zones for both the NWWF and WWF are considerably different than the 210-day WPAs published by Miami-Dade County. The combined upper bound of the 95% CI capture zone for the NWWF encompasses the 210-day WPA published by Miami-Dade County. However, the combined upper bound of the 95% CI capture zone for the WWF is considerable smaller than the 210-day WPA published by Miami-Dade County.

Differences in the geometries and sizes between the combined upper bound of the 95% CI capture zones and the published Miami-Dade County WPAs are due to differences in the models used to generate capture zones and pumping rates for the wellfields. Differences in geometries are attributed to the model used by GTI to develop the upper bound of the 95% CI capture zones. Also, according to the USGS, the pumping rate for the WWF of 140 million gallons per day (MGD) used by the County to generate the current WPAs was reduced to 25 MGD (Brakefield et al., 2013).

5.4 Sensitivity Analysis of River Cell Conductance Adjustments

As discussed in the previous section, a 5-mile long partially penetrating slurry wall was constructed between 2012 and 2016 along the western levee of the L-31N canal to reduce the groundwater seepage from the ENP to the canal. Also as discussed in previous section, the hydraulic impacts of the slurry wall were considered in this study by adjusting the conductance of the selected river cells representing the L-31N canal and the ENP. The results presented were from the base-case simulation in which the river conductance was reduced by 0.3%, based on the results of a cross-sectional model developed in this study. Detailed discussion regarding the representation of the slurry wall can be found in Appendix A.

Two sensitivity simulations were performed to further assess the effects of changing river cell conductance on the modeled hydraulic impacts of the slurry wall:

SA1: The river conductance was reduced by 10.2% based on the cross-sectional model assuming a 10:1 vertical anisotropy.

SA2: The river conductance was reduced by 33.5% based on the MFL 2011 study that used 10:1 vertical anisotropy for all flow zones.

Simulated 95% CI bands and median TOT capture zones for the steady-state dry hydrologic conditions under seepage reduction of 0.3% (Base-case), 10.2% (SA1) and 33.5% (SA2) are shown in **Figures 5-8, 5-9** and **5-10**, respectively. The upper bounds of the 0.1-foot drawdown for these two sensitivity analysis runs are also included in these maps.

Figures 5-11 and **5-12** show the comparisons of the upper bounds and 95% CI of 210-day capture zones and 0.1-foot drawdowns under different river conductance adjustments. The results shown in these figures clearly indicate that simulated TOT capture zones and drawdowns are not sensitive to the river cell conductance adjustments associated with the construction of the partially penetrating slurry wall. This might be explained by the fact that the head-differences between the river stage and aquifer head remains small so the flow out of the canal is not sensitive to the river cell conductance. The seepage reductions estimated from the cross-sectional model and the multiple layer model (MFL 2011) were all based on the 10:1 vertical anisotropy, which likely had a greater canal stage-aquifer head gradient.

Based on these results, although studies by others indicate that the partially penetrating slurry wall reduces groundwater seepage from the ENP into the L-31N canal in the immediate vicinity of the slurry wall, the partially penetrating slurry wall has little if any effect on the simulated capture zones to the NWWF and WWF wellfields.

Section 6: Summary, Conclusions, and Limitations

6.1 Summary

The Northwest and West Wellfields are two of the wellfields used for drinking water supply in Miami-Dade County, Florida. To protect the water sources for the wellfields, efforts have been made to establish the wellhead protection zones for these two wellfields. In support of WPA delineation, simulated TOT capture zones and drawdowns associated with withdrawals from these two wellfields were determined by the U.S. Geological Survey (USGS) in 2013 based on a stochastic approach.

The unique location of these two wellfields within the Lake Belt area poses a challenge for wellhead protection zone delineation. To address the uncertainties associated with the wellhead protection zone delineation in the Lake Belt, the USGS applied the stochastic approach by performing reverse particle tracking analyses with unstrained Monte Carlo simulations under steady-state average, wet and dry conditions for the NWWF and WWF. Residence times for the lakes were calculated by the USGS to account for distances traveled by particles through lakes. Residence times for each lake used by the USGS essentially were representative of the average time a particle would spend traversing a given lake. Previous modeling efforts in support of the delineation of WPAs treated the lakes as areas with high transmissivity values and effective porosity of 1.0.

GTI was retained by MDC Department of Water and Sewer (WASD) and Department of Regulatory and Economic Resources (RER) to review the TWG's recommendations. After reviewing the recommendations of the TWG and Dr. Chin, GTI proposed an alternative approach based on suggestions by Dr. Chin in 2017 to address the travel time for particles moving through a lake so the WPAs may be more conservatively delineated. GTI was also requested to develop an approach to include the hydraulic impacts of the partially penetrating slurry wall along the L-31N canal in the process of TOT capture zone delineation and drawdown calculation.

The major tasks that GTI performed in this study included:

- Determination of critical residence times.
- Identification and addition of particles to the inflow cells at selected lakes.
- Update of the lake information for a revised buildout lake expansion scenario.
- Assessment of the hydraulic impacts of construction of the partially penetrating slurry wall along the L-31N canal to the groundwater seepage from the ENP.
- Development of a method to represent the partially penetrating slurry wall in the single layer model by adjusting the river cell conductance of affected L-31N canal.
- Unconstrained Monte Carlo simulations for steady-state dry conditions and post-processing using critical residence times for proposed lake expansion scenario.

- Revision of the post-processing codes for time series analysis; and,
- Preparation of TOT capture zones and drawdown maps.

After the revisions discussed in Section 3 of this report were made, unconstrained Monte Carlo simulations were performed with the lake expansion configuration under steady-state dry conditions. Two sensitivity simulations were also performed to assess the effects of changing river cell conductance on the modeled hydraulic impacts of the slurry wall. Each of these Monte Carlo simulations contains 10,000 realizations, and each realization contains a stochastically distributed set of hydraulic conductivity and randomly selected effective porosity. Revised computer codes were used in the post-processing of time-series data of each particle. The 95% CIs and median of the distribution of particle endpoints were computed for each requested TOTs (10, 30 100 and 210 days) of each wellfield following the approach of Varljen and Shafer (1991). The TOT capture zones for wellfield were generated based on the 95% CIs. The 0.1-foot drawdown contours from the base-case deterministic simulation and Monte Carlo simulations were computed for the NWWF and WWF.

6.2 Conclusions

The following conclusions are based on the results of the work performed by GTI as described in this report:

(1) As expected, the upper bound of 95% confidence interval (CI) of 210-day capture zones for steady-state dry conditions are the most extensive simulated capture zones for the NWWF and WWF.

(2) The combined upper bound of the 95% CI capture zone for the NWWF encompasses the 210-day WPA published by MDC. However, the combined upper bound of the 95% CI capture zone for the WWF is considerable smaller than the 210-day WPA published by MDC.

(3) Canals surrounding the wellfields constrain the capture zones. Canals to the north, east and south of the NWWF and to the west of the WWF largely constrain particle movement and therefore affect the simulated TOT capture zones.

(4) Although studies performed by others indicate that the partially penetrating slurry wall reduces groundwater seepage from the ENP to the L-31N canal in the immediate vicinity of the slurry wall, the reductions have little if any effects on the simulated TOT capture zones and drawdowns of the NWWF and WWF.

6.3 Limitations

Since the objective of this study was to revise the previous USGS work of 2013 following the recommendations from the TWG and Dr. Chin, the same groundwater flow model was used, except for the incorporation of critical residence times and the approach for consideration of the slurry wall. Therefore, nearly all the limitations stated in the USGS report of 2013 are valid and applicable to this study.

References

Amec Foster Wheeler Environment & Infrastructure, Inc. 2012. AS-BUILT REPORT PHASE 1 SEEPAGE BARRIER LEVEE L-31N, for Miami-Dade Limestone Products Association, Inc., Miami, Florida, 1029 p.

Amec Foster Wheeler Environment & Infrastructure, Inc. 2016. AS-BUILT REPORT – PHASE 2 SEEPAGE BARRIER LEVEE L-31N, for Miami-Dade Limestone Products Association, Inc. Miami, Florida, 1562 p.

Anderson, M.P., R.J. Hunt, J.T. Krohelski, and K. Chung, 2002. Using high hydraulic conductivity nodes to simulate seepage lakes, *Ground Water*, 40(2), pp117-122.

Anderson, M.P., W.W. Woessner, R.J. Hunt, 2015. Applied Groundwater Modeling, 2nd edition, Academic Press, 564 p.

Brakefield, L., J. D. Hughes, C. D. Langevin, and K. Chartier, 2013. Estimation of Capture Zones and Drawdown at the Northwest and West Well Fields, Miami-Dade County, Florida, Using an Unconstrained Monte Carlo Analysis: Recent (2004) and Proposed Conditions, USGS Open-File Report 2013–1086.

CDM, 2008. Miami Dade County Water Supply Facilities Work Plan, Support Data, March 2008.

Chin, D., J.J. Iudicello, K.C. Kajder, P.M. Kelly, D.V. Porzilli, and H. Guha, 2010. Lake Effect in Wellhead Protection, *Journal of Water Resources Planning and Management* 136(3):403-407.

Chin, D., 2014. USGS delineation of travel time contours in NWWF and WWF, letter-communication to Department of Regulatory and Environmental Resources, Miami-Dade County, August 11, 2014.

Chin, D. 2016a. Tracer transport through seepage lakes. *Journal of Hydrologic Engineering* 21(7): 06016004(6).

Chin, D. 2016b. Evaluation of the USGS Model for Estimating the Capture Zones and Drawdowns at the Northwest and West Wellfields Miami-Dade County, Florida (Draft 2.0, July 2016), Technical Working Group Draft Final Report Attachment B.

Chin, D. 2017. Delineation of wellhead protection areas containing seepage lakes, *J. Water resources management*, 144(3), 10 p.

Chow, V.T., D.R. Maidment and L.W. Mays, 1988. Applied Hydrology, McGraw-Hill Publishing Company, 572 p.

Frind, E.O., D.S. Muhammad, and J.W. Molson, 2002. Delineation of three –dimensional well capture zones for complex multi-aquifer systems, Ground Water, 40(6), p. 586-598.

Frind, E.O., and J.W. Molson, 2018. Issues and options in the delineation of well capture zones under uncertainty, Ground Water, 56 (3), p. 366-376.

Groundwater Tek Inc. (GTI) 2019. Review of Recommendations of The Technical Work Group for the Wellhead Protection Area Delineations of The West and Northwest Wellfields, Miami-Dade County, Florida (Draft), prepared for Miami-Dade County Department of Regulatory and Economic Resources' Division of Environmental Resources.

Guha, H., 2008. A stochastic modeling approach to address hydrogeologic uncertainties in modeling wellhead protection boundaries in karst aquifers: *J. of the American Water Resources Association*, 44 (3), pp 654-662.

Hsieh, P.A., and Freckleton, J.R., 1993. Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey modular three- dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 92-477, 32 p.

Hughes, J. D. and Jeremy T. White 2014. Hydrologic Conditions in Urban Miami-Dade County, Florida, and the Effect of Groundwater Pumpage and Increased Sea Level on Canal Leakage and Regional Groundwater Flow, Scientific Investigations Report 2014–5162 Version 1.2, July 2016.

MacVicar, Fedrico & Lamb, Inc. (MFL) 2011. Evaluating the performance of a partial penetrating seepage barrier between Everglades National Park and the L-31N Canal, Appendix A: Results and analysis of computer simulation of various seepage barrier configurations, August 29, 2011, prepared on behalf of the Miami-Dade Limestone Products Association.

Nemeth, M. S. Walter M. Wilcox, and Helena M. Solo-Gabriele, 2000. Evaluation of the Use of Reach Transmissivity to Quantify Leakage beneath Levee 31N, Miami-Dade County, Florida, USGS Water-Resources Investigations Report 00-4066.

Pollock, D.W., 1994. User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94–464, 6 ch.

Technical Work Group (TWG), 2017. Report of The Miami-Dade County wellfield technical workgroup, prepared for Miami-Dade County Department of Regulatory and Economic Resources' Division of Environmental Resources Management, July 31, 2017.

USEPA (U.S. Environmental Protection Agency), 1987. Guidelines for delineation of wellhead protection areas, EPA/440/6-87-010 (NTIS PB88-11430).

USEPA (U.S. Environmental Protection Agency), 1994. Handbook: Ground Water and Wellhead Protection, EPA/625/R-94/001, Office of Research and Development and Office of Water, Washington D.C. 269 p.

Wheater, H.S., J.A. Tompkins, M. van Leeuwen and A.P. Butler, 2000. Uncertainty in groundwater flow and transport modelling – a stochastic analysis of well-protection zones, *Hydrological Processes*, 14. pp. 2019-2029.

Varljen, M.D., and J.M. Shafer, 1991. Assessment of uncertainty in time-related capture zones using conditional simulation of hydraulic conductivity: Ground Water, v. 29, no. 5, p. 737–748.

Zheng, C., 1992, PATH3D, A ground-water path and travel-time simulator, version 3.2 user's manual, S.S. Papadopulos & Associates, Inc., Bethesda, MD.

TABLES

Table 3-1: Probability of Selected Dimensionless Residence Time (t*)

t*	**Probability (T≤t*)**
1.0	0.632
0.75	0.528
0.5	0.393
0.25	0.221
0.1	0.095
0.05	0.049

Table 3-2 Build-out Mining Lakes

PHASE	Owers	Area (ACRES)	Depth(ft)
1	FR25E	195.873	55e
1	TARG	300.806	65
1	WRQS23S	317.991	55
1	FR25W	318.626	55e
1	FEC7	318.996	65
1	FRI15	319.061	60e
1	SCL34	349.432	50
1	WRQS23N	357.709	60
1	WRQS13	394.519	55
1	TAR10	434.617	63e
1	FR22	438.533	60
1	SCL33	497.324	50
1	TAR1	553.764	65
1	TARF	573.987	65
1	TAR3	574.095	65
1	FR26	591.128	55
1	TARBC	609.763	65
1	FEC5	621.456	65
1	SHOMA	627.256	45e
1	KROME	930.900	45
1	FEC6	1523.220	65
2	APAC16	488.069	60e
2	SCL28	512.835	55e
2	TAR4	536.355	65
2	FRI9	579.915	63e
2	FEC21	779.767	65
3	FR23	44.262	60e
3	FR23	44.262	60e
3	FEC27	297.509	65e
3	FR21	386.796	60e
3	KROMEN	625.390	45
3	FEC16	625.639	65e
3	TAR33	751.487	65e

e= estimated

Table 3-3: Changes of Groundwater Seepages and L-31N Flow

(All values in cubic feet per day (cfd))

Base	**Q_{in}**	**Q_{out}**	**To Canal**
Layer 1	32,2545	167,713	549,776
Layer 2	2,320	1,283	
Layer 3	1,106,872	712,965	
Total	1,431,737	881,961	549,776

Wall	**Q_{in}**	**Q_{out}**	**To Canal**
Layer 1	55	162,347	464,219
Layer 2	126	1,266	
Layer 3	1,343,598	715,947	
Total	1,343,779	879,560	464,219

Changes	**Q_{in}**	**Q_{out}**	**To Canal**
Layer 1	-322,490	-5,366	-85,557
Layer 2	-2,194	-17	
Layer 3	236,726	2,982	
Total	-87,958	-2,401	-85,557

FIGURES

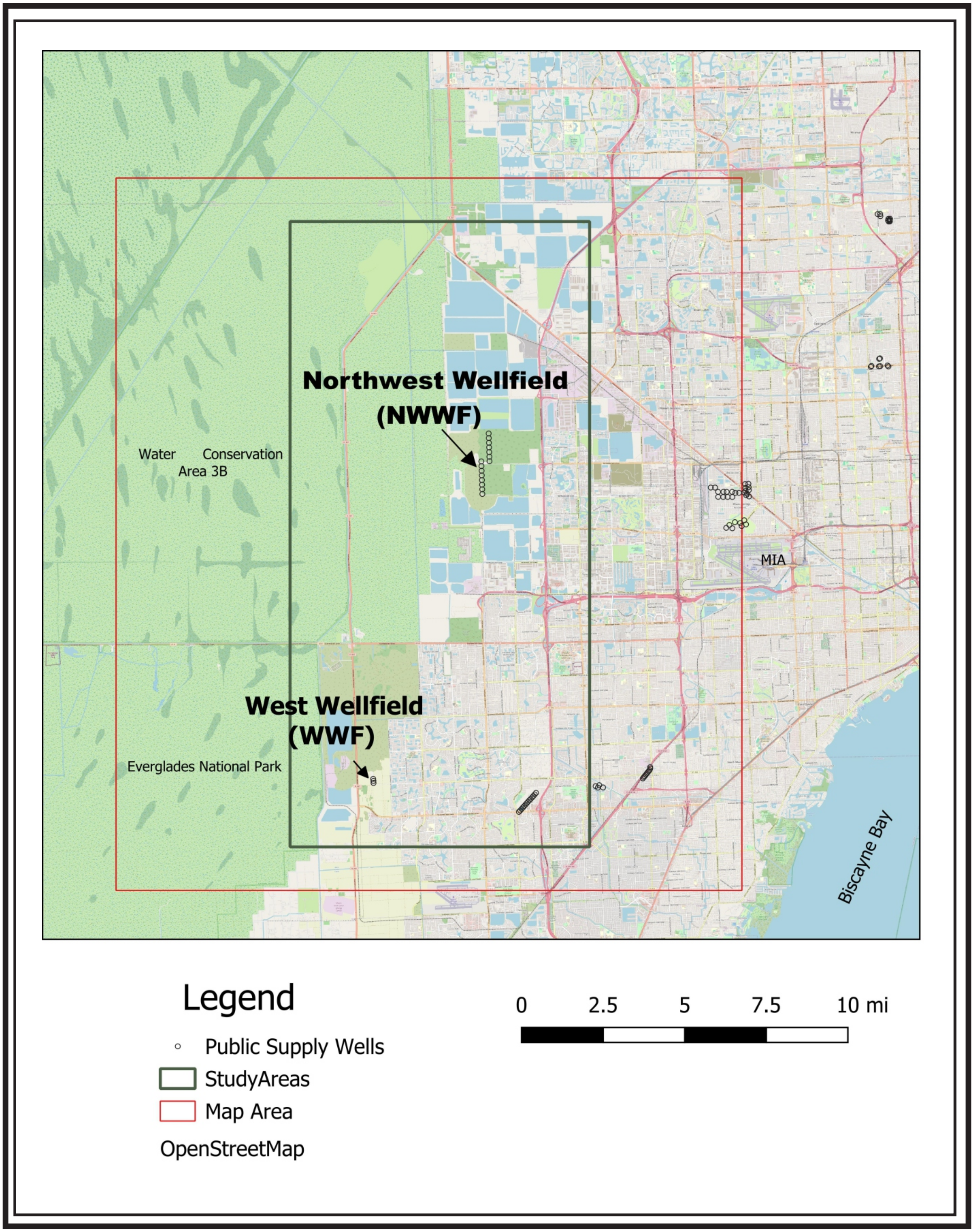

Figure 1-1
Locations of Northwest Wellfield (NWWF) and West Wellfield (WWF) of Miami-Dade County, Florida.

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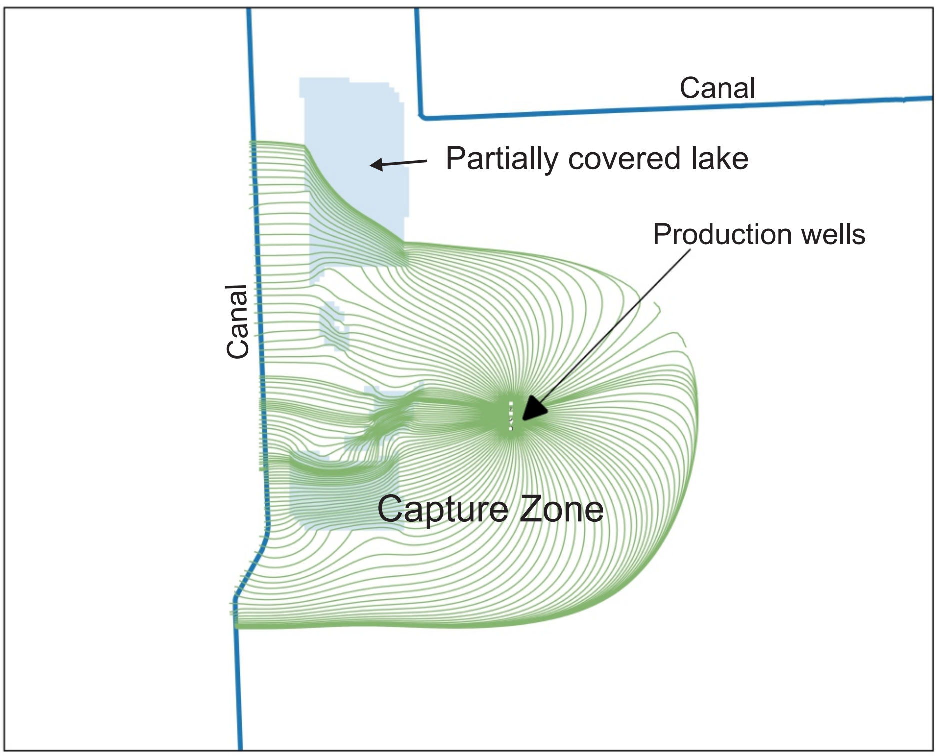

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Figure 2-1
Schematic showing a generalized capture zone and a partially covered lake.

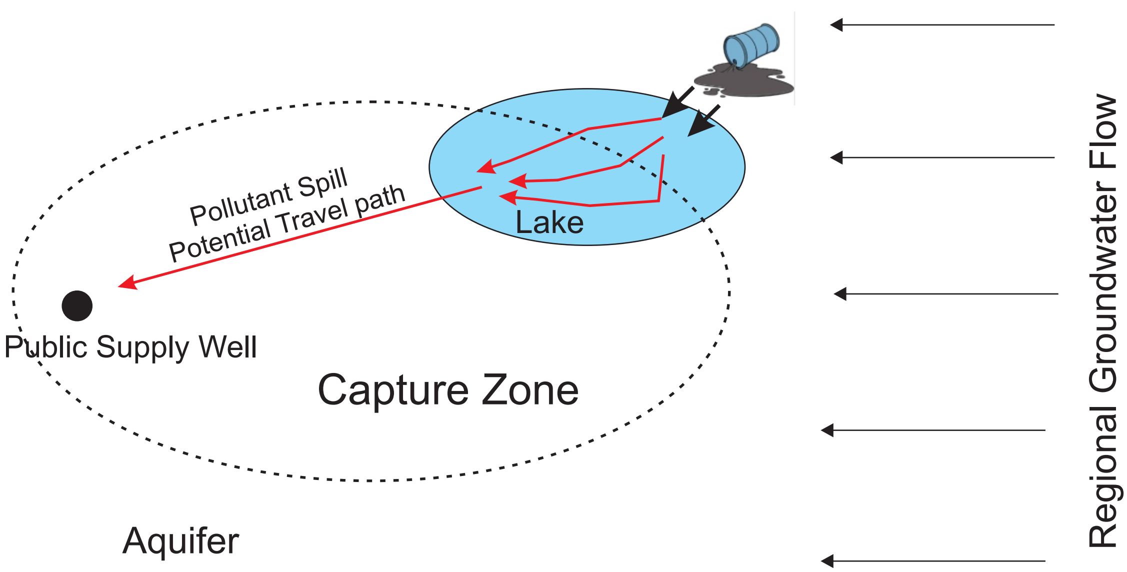

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Figure 2-2
Schematic showing a potential threat from
a contamination source outside the capture zone through a lake.

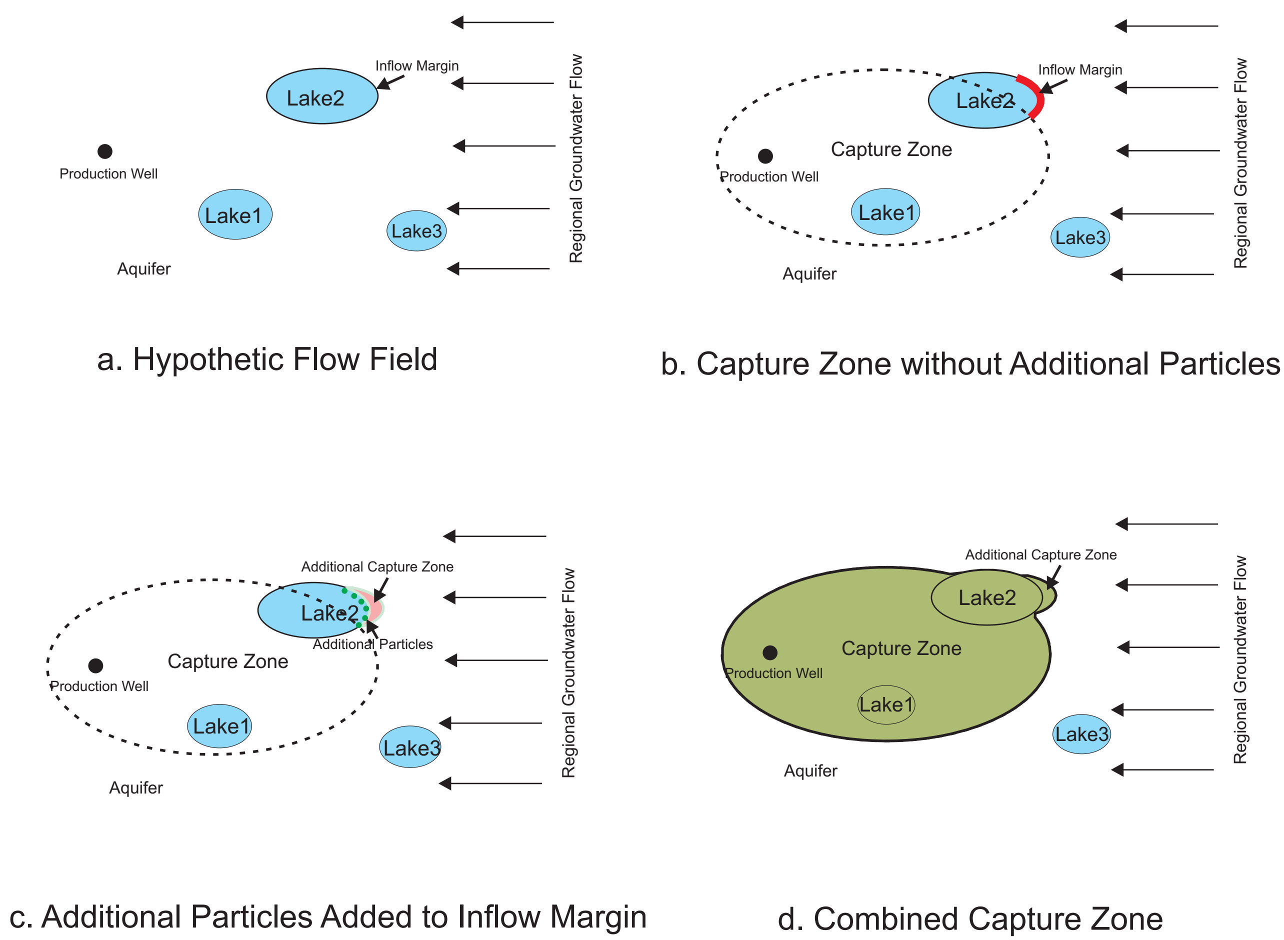

Figure 2-3
Schematic showing extra particles added to the inflow lake margin cells and combined capture zones.

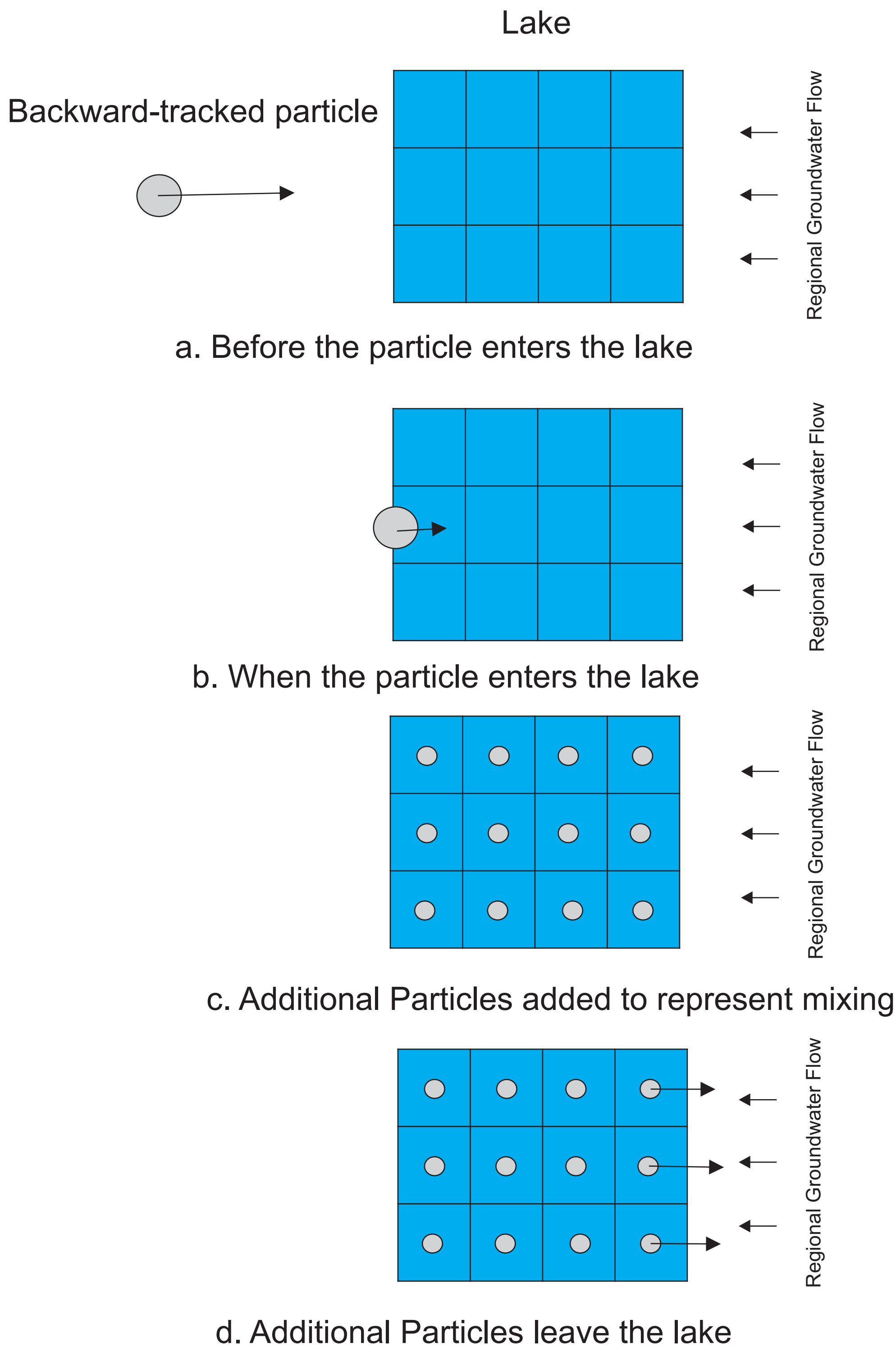

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Figure 2-4
Schematic showing a backward tracked particle moving through and spreading out in a lake.

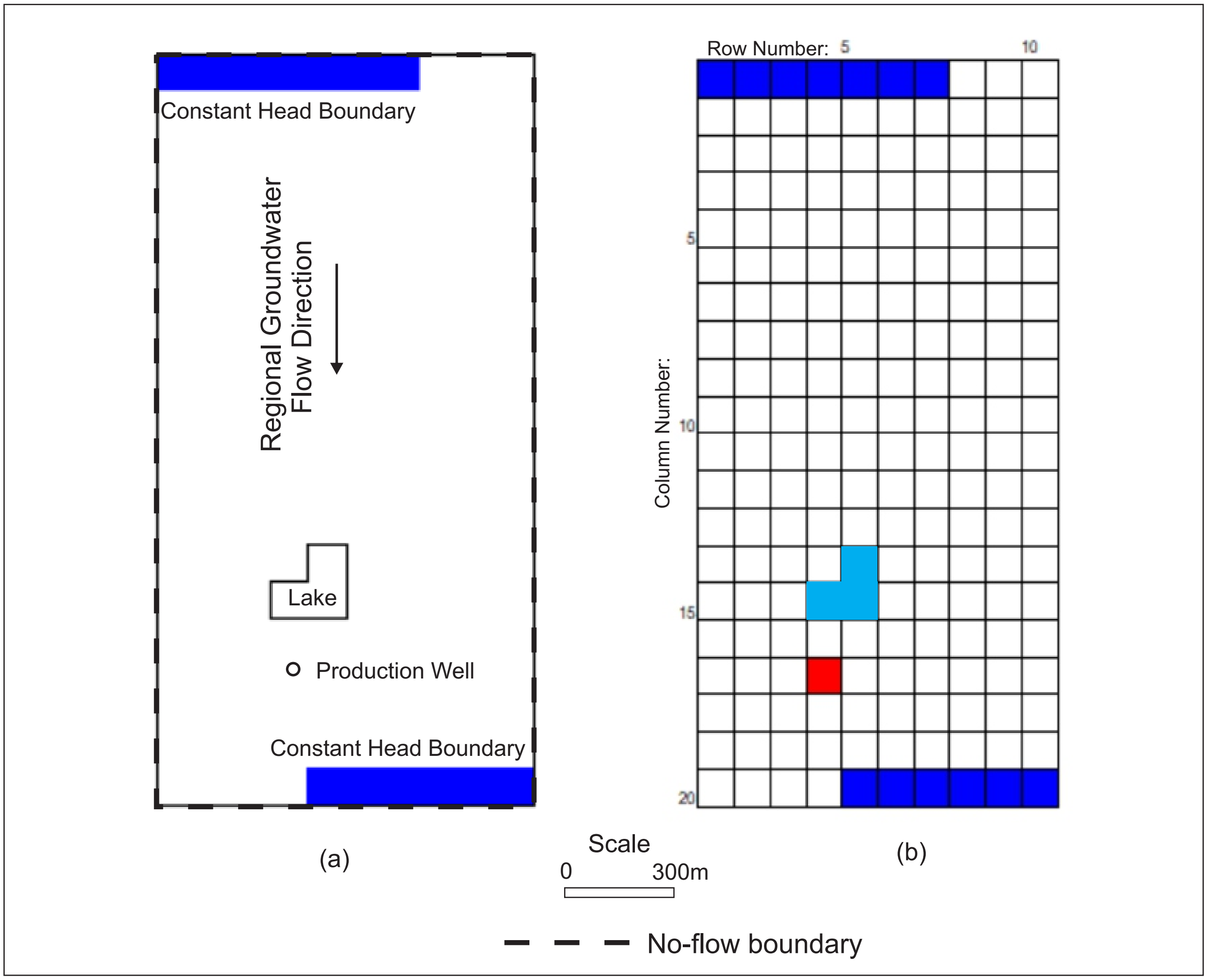

Figure 2-5
Design of the hypothetic testing model:
(a) boundary conditions (b) model grids.

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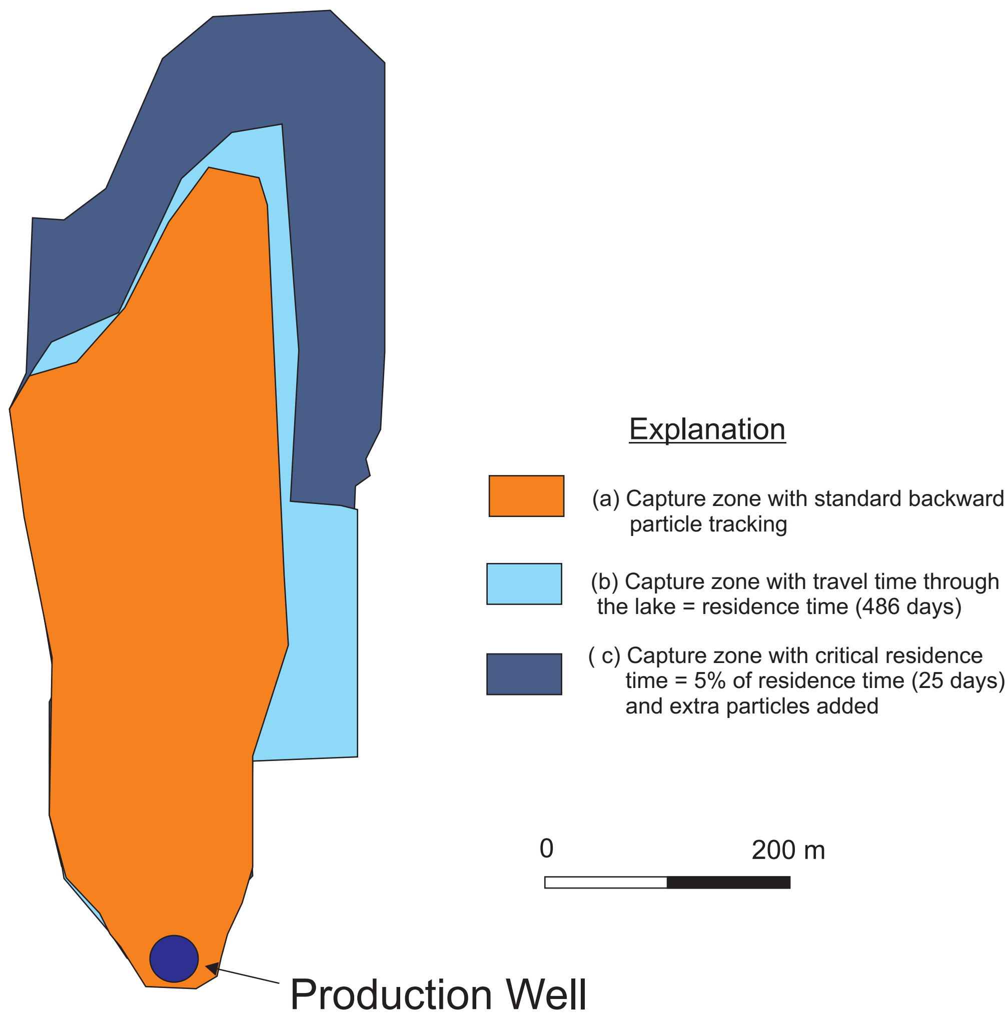

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Figure 2-6
Combined capture zones delineated based on a hypothetical model and different approaches and assumptions.

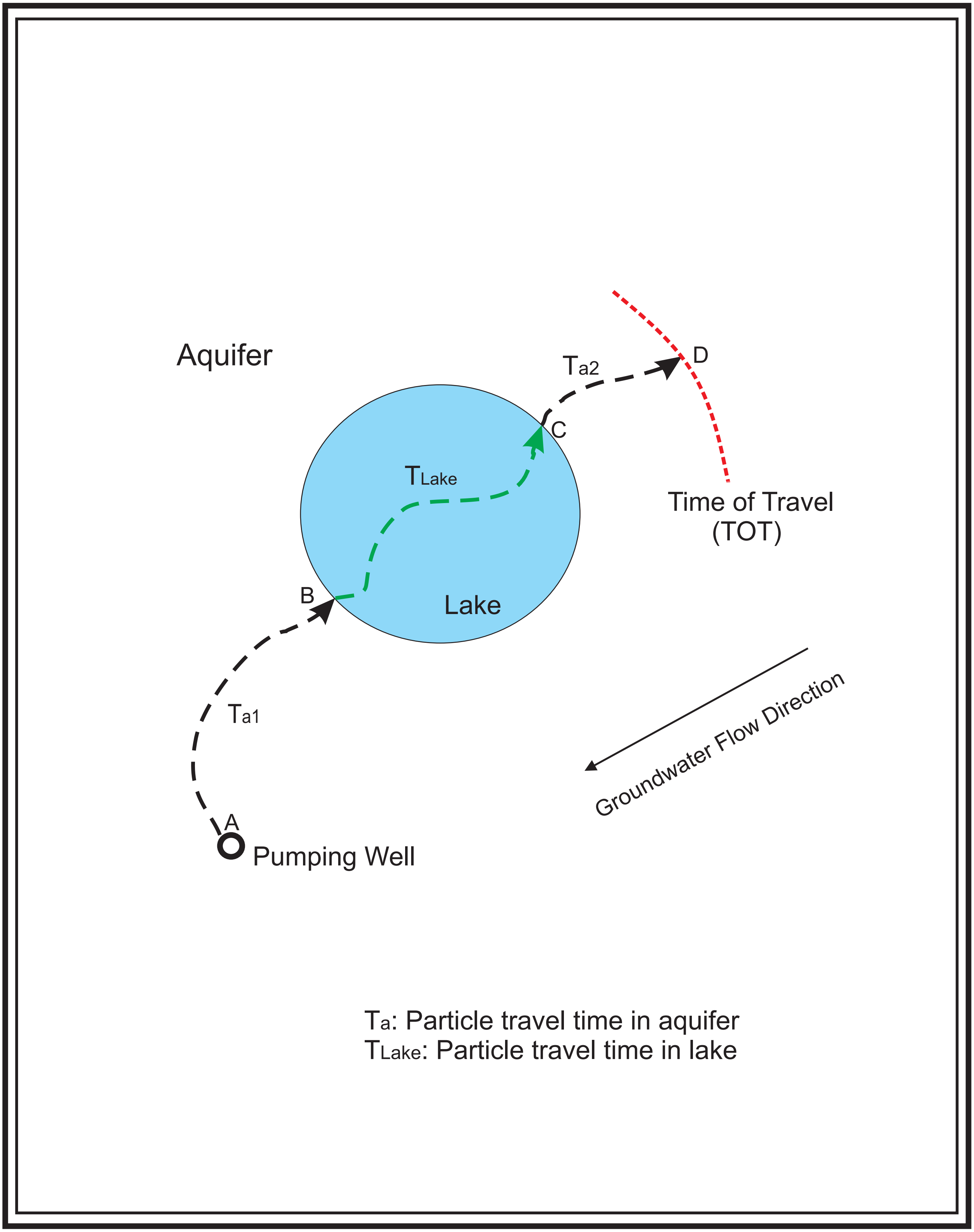

Figure 3-1
A generic schematic showing a backward-tracked particle traveling through a lake.

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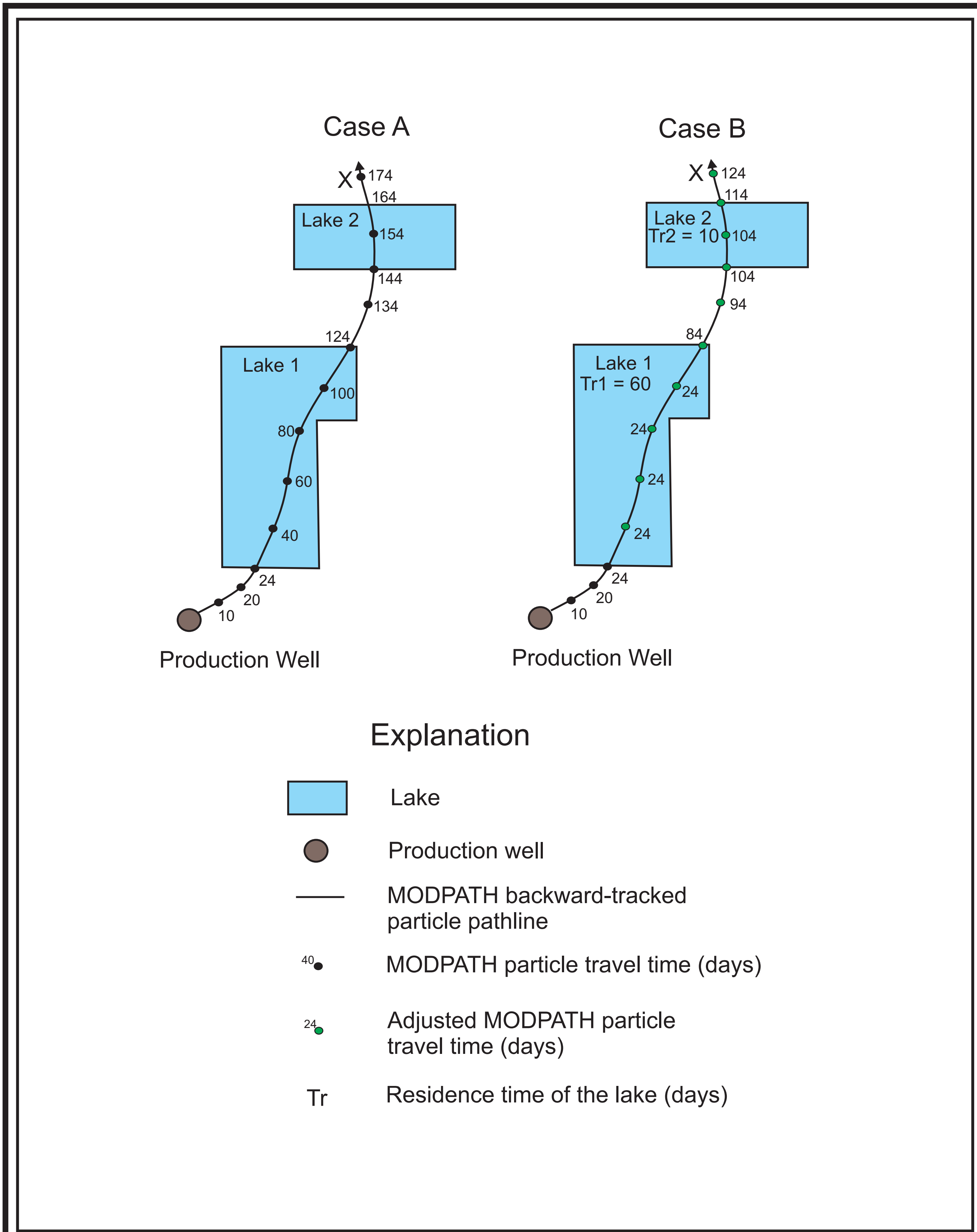

Figure 3-2
Travel time adjustment from (a) MODPATH travel time to (b) residence time (after Brakefield et al., 2013).

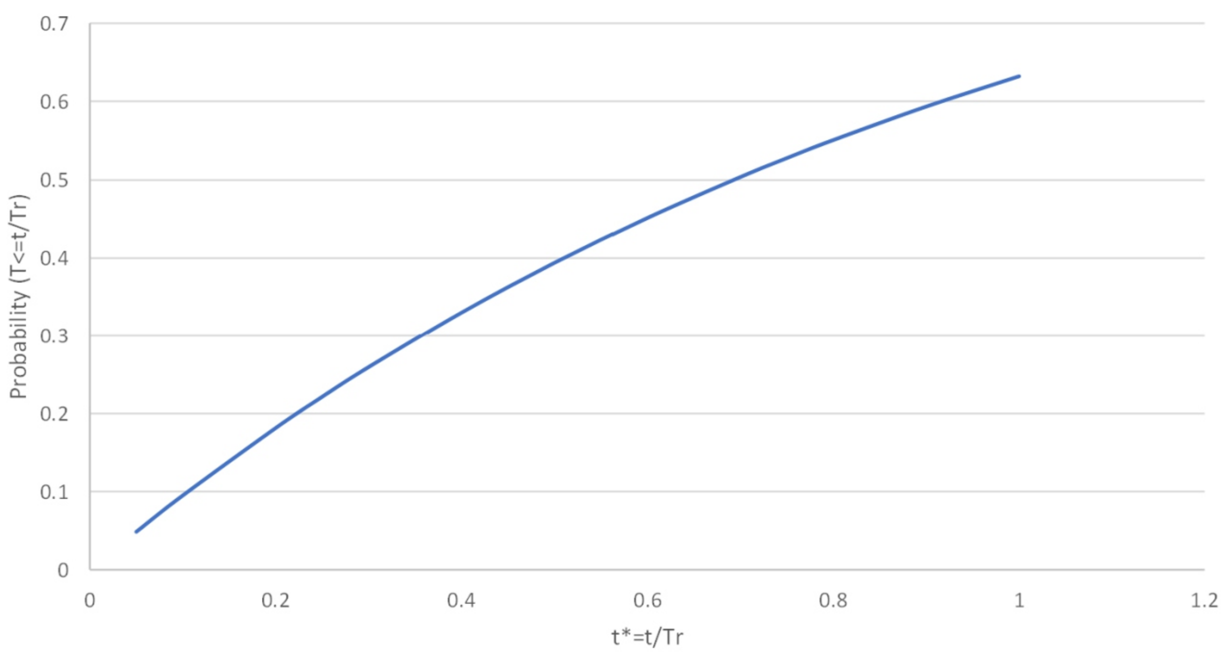

Figure 3-3
Probability of travel time less than or equal to dimensionless residence time.

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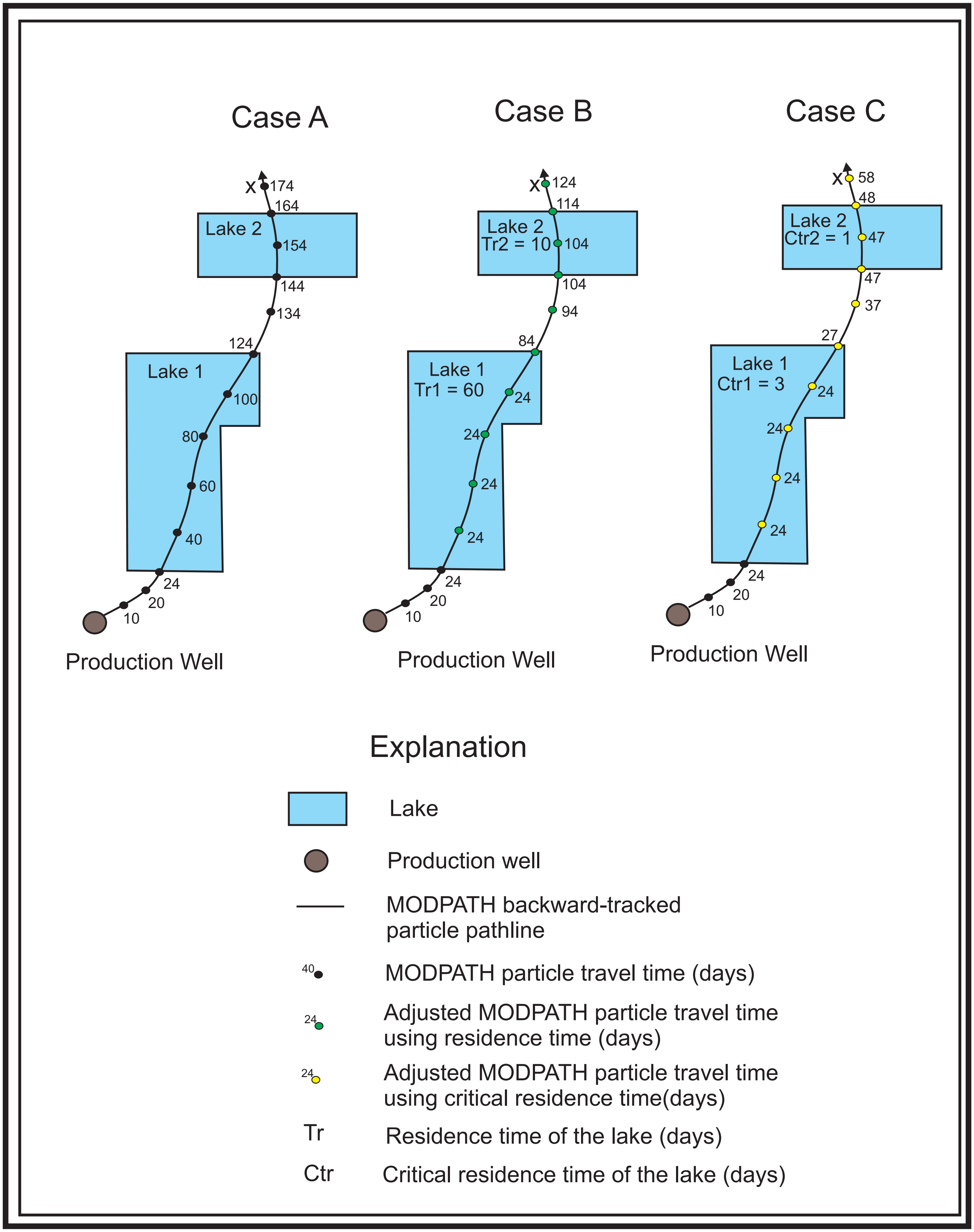

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Figure 3-4
Travel time adjustment from (a) MODPATH travel time to (b) residence time and (c) critical residence time for a reverse-tracked particle moving through lakes.

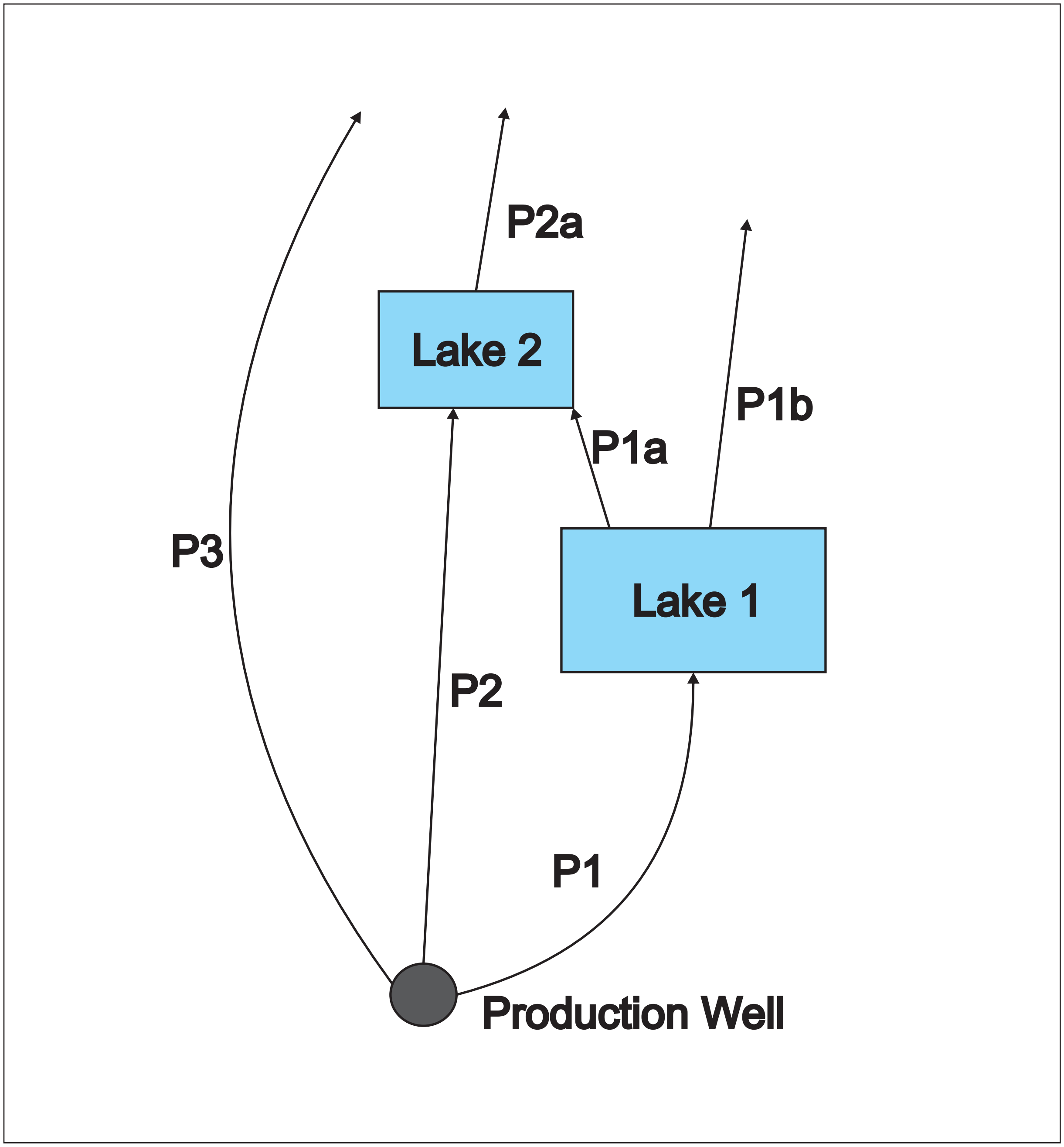

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Figure 3-5
Schematic showing backward-tracked particles from a production well moving into two lakes.

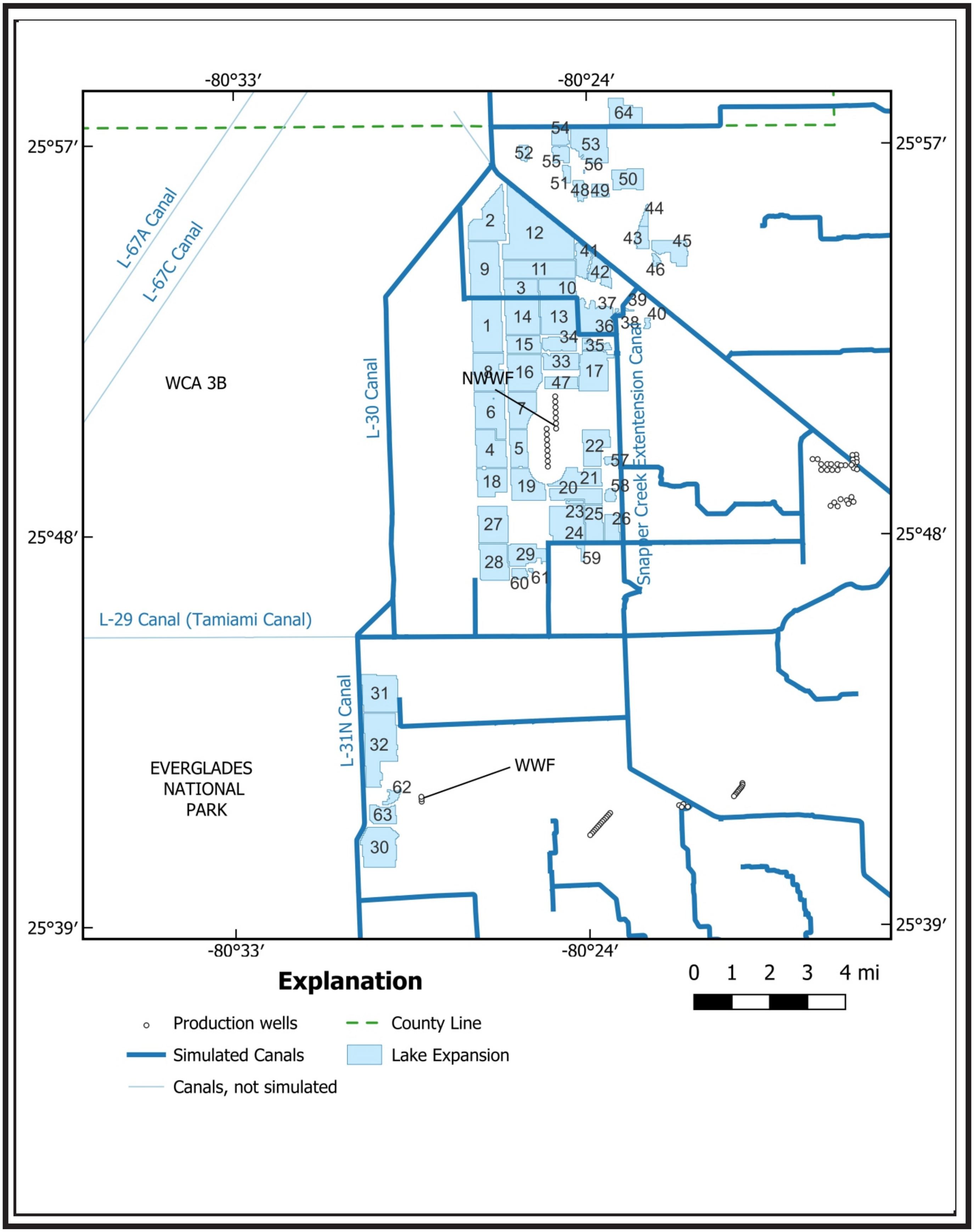

Figure 3-6
Location of lakes of the lake-expansion used in the model
(Numbers are arbitrarily assigned lake identification numbers).

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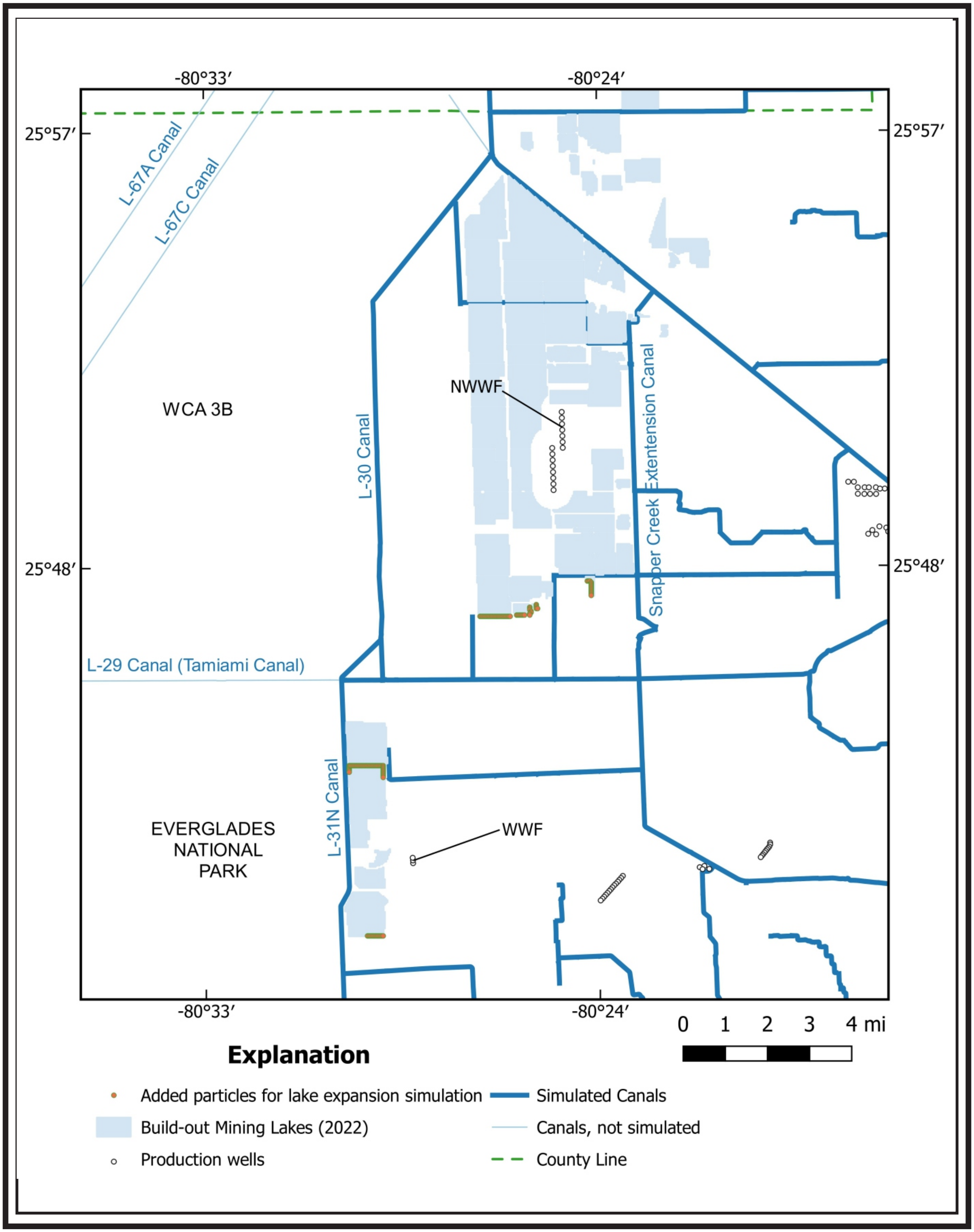

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Figure 3-7
Added particles at inflow lake cells for simulation of proposed lake-expansion scenario.

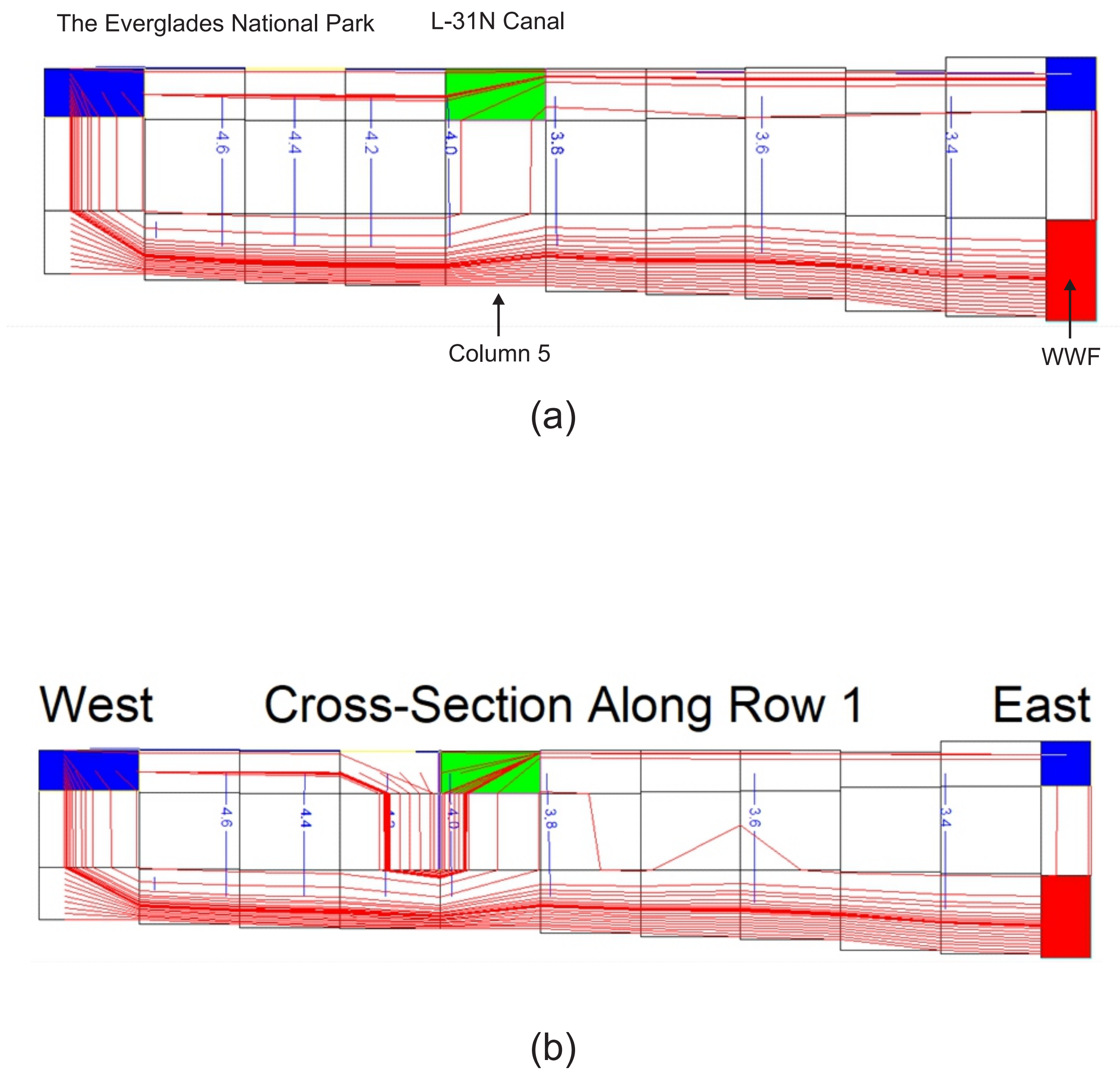

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Figure 3-8
Simulated head contours (blue lines) (ft, NAVD88) and pathlines (brown lines) of the base run simulation: (a) without slurry wall (b) with slurry wall.

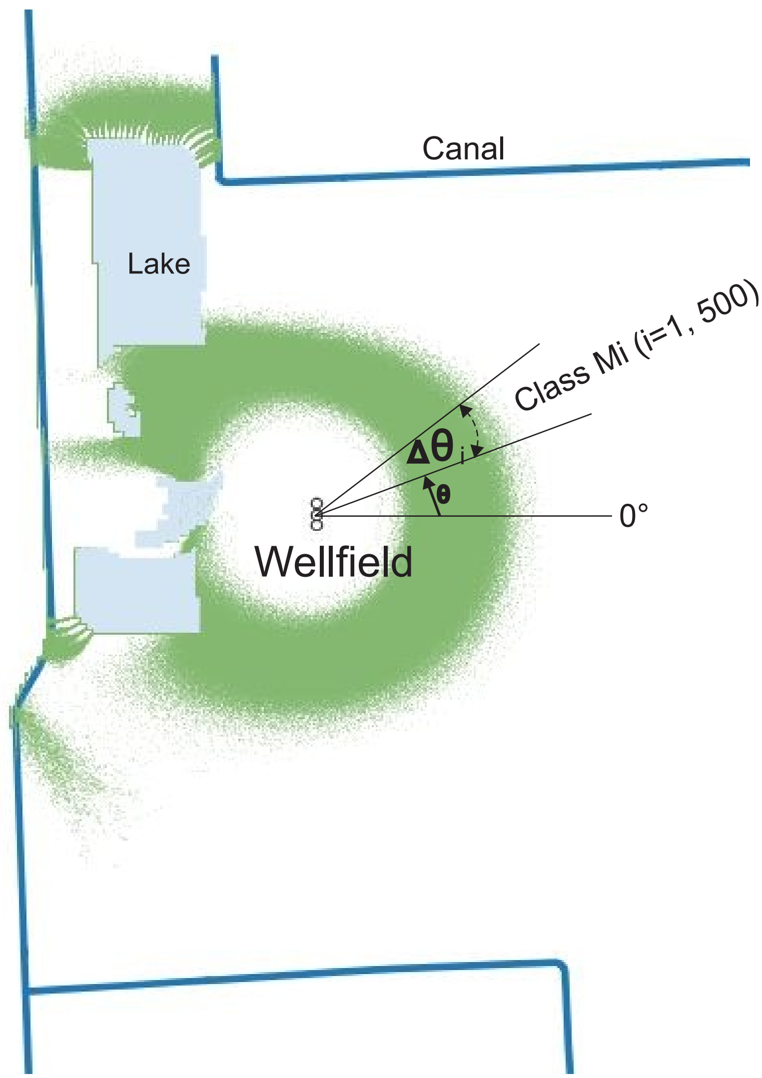

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Figure 4-1
An example of the radial class division described by Varljen and Shafer (1991).

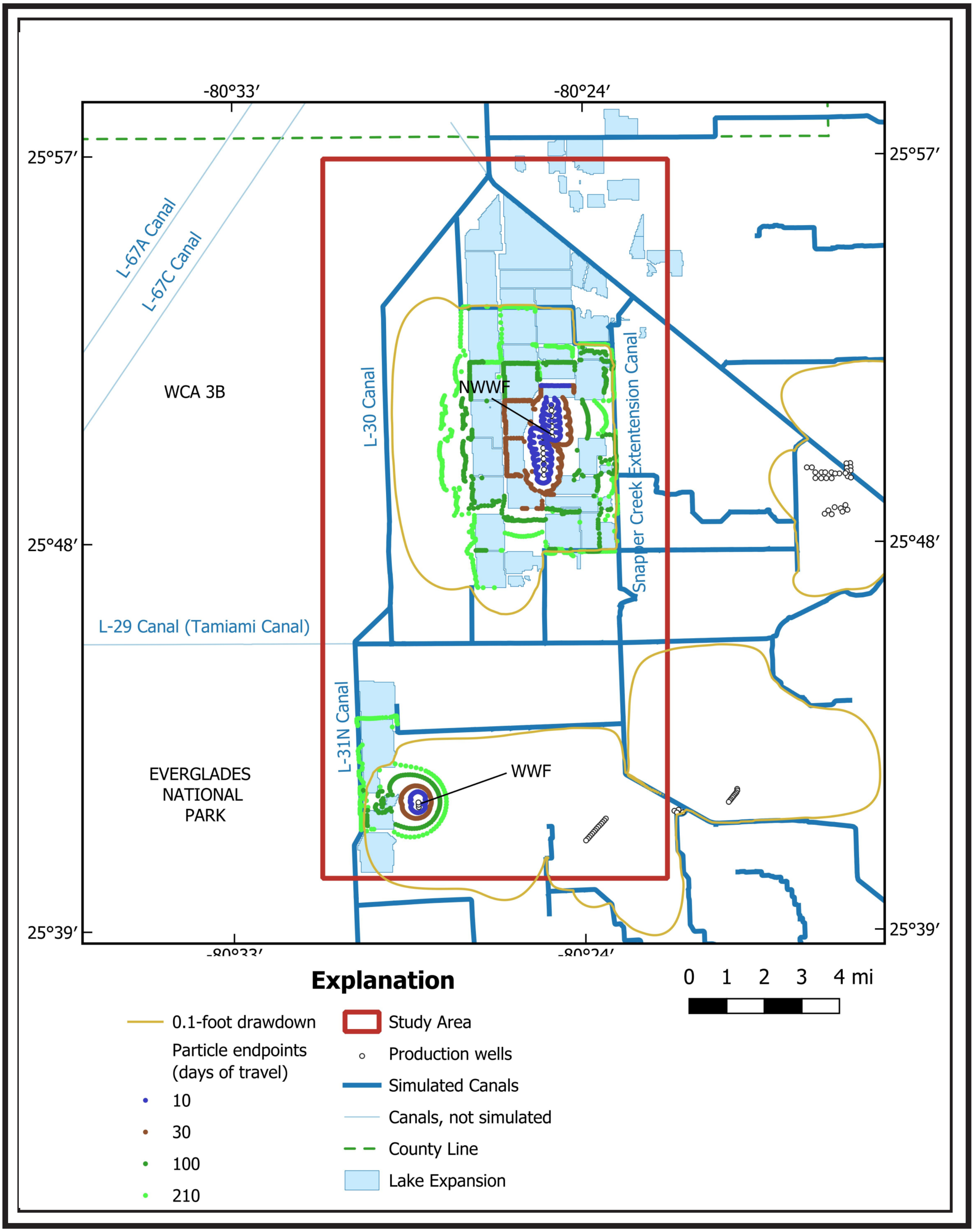

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Figure 5-1
Simulated 0.1-foot drawdown contours, and particle endpoints for travel times of 10, 30, 100, and 210 days for the base-case deterministic simulation for steady-state dry conditions.

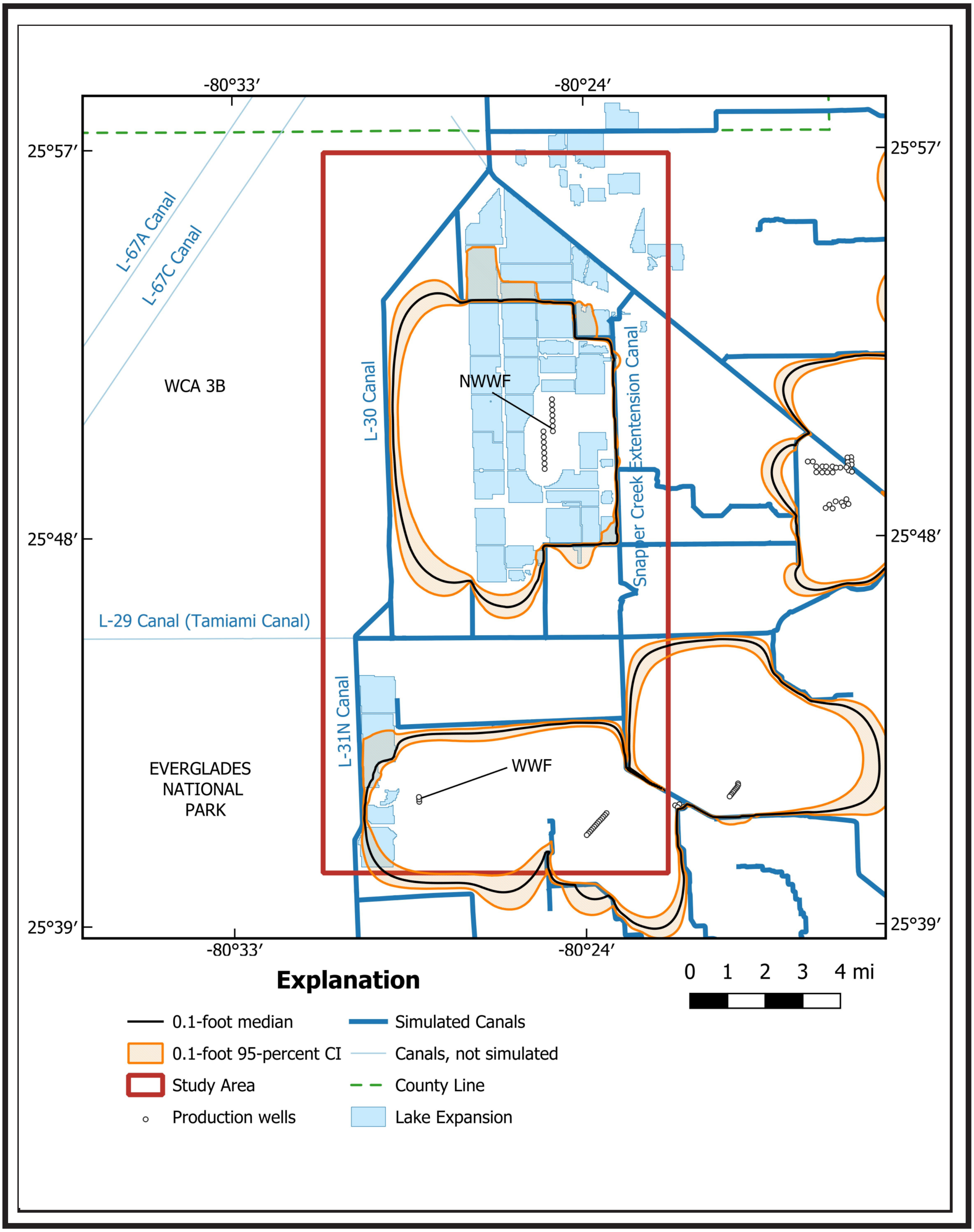

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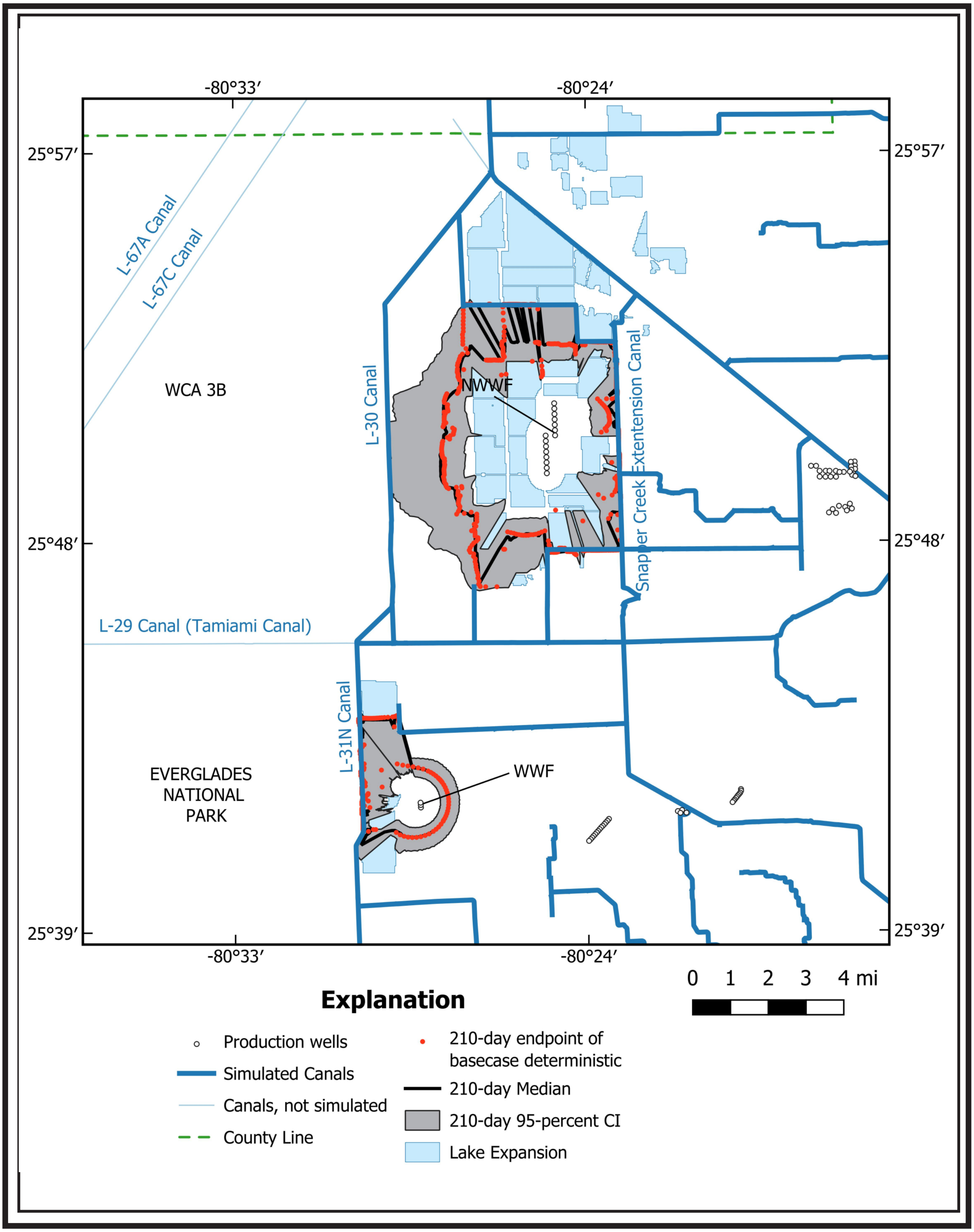
Figure 5-2
Median and 95-percent confidence intervals for 0.1-foot drawdown for the NWWF and WWF for steady-state dry conditions.



GTI
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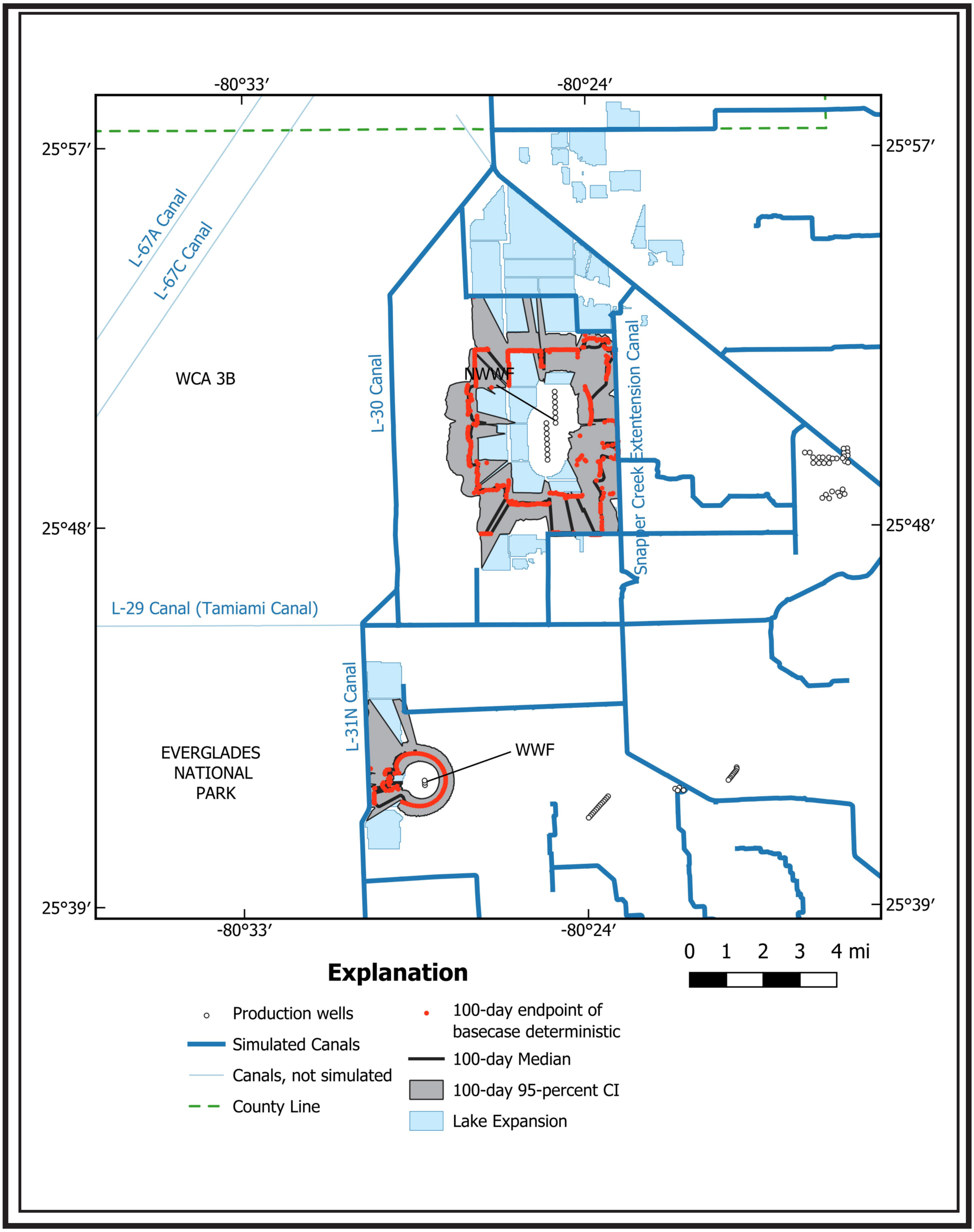
Figure 5-3
Median and 95-percent confidence intervals for the 210-day capture zones for the NWWF and WWF for steady-state dry conditions, and particle endpoints for 210 days of travel for the base-case deterministic simulation.



GTI
Groundwater Tek Inc.

Figure 5-4
Median and 95-percent confidence intervals for the 100-day capture zones for the NWWF and WWF for steady-state dry conditions, and particle endpoints for 100 days of travel for the base-case deterministic simulation.

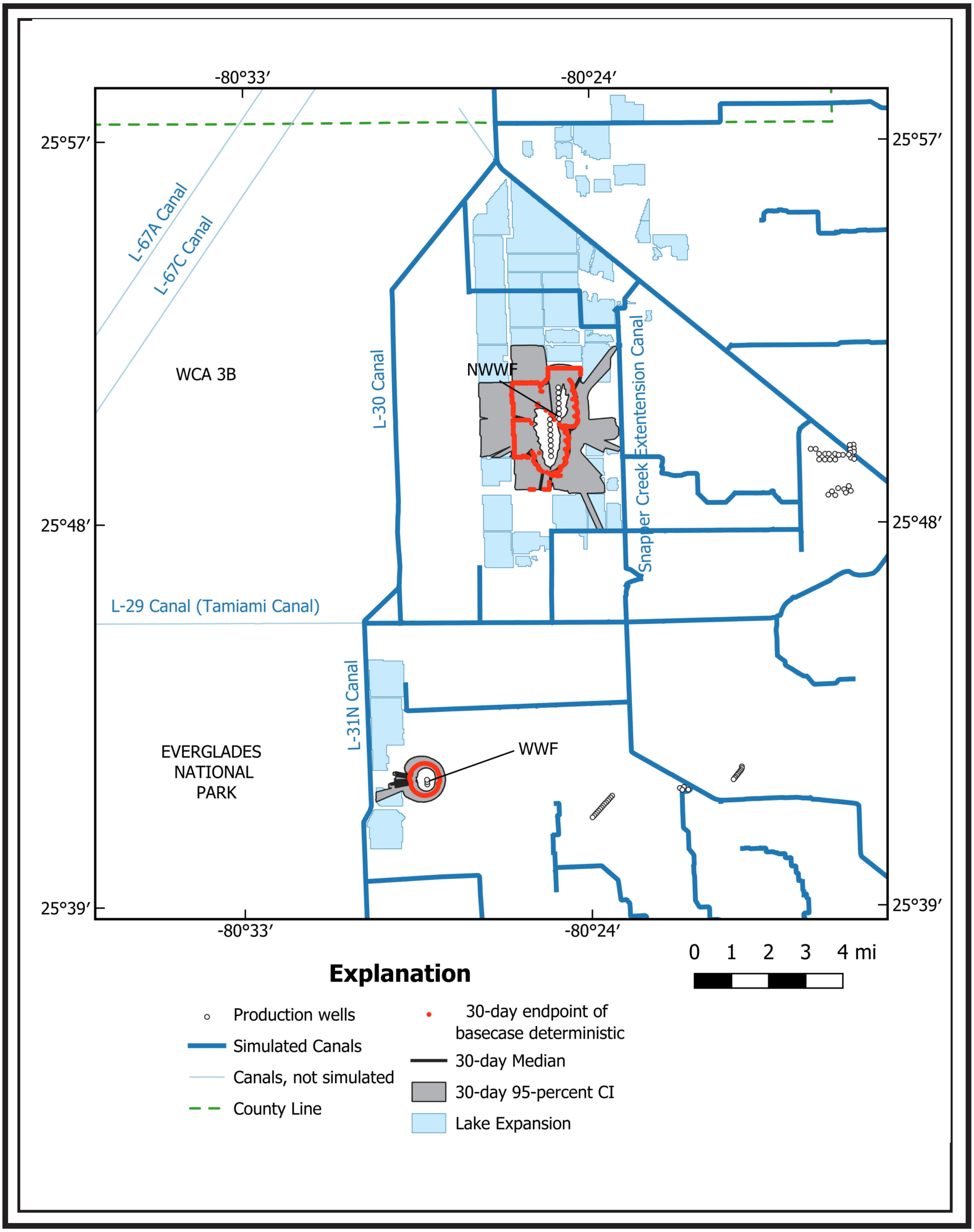


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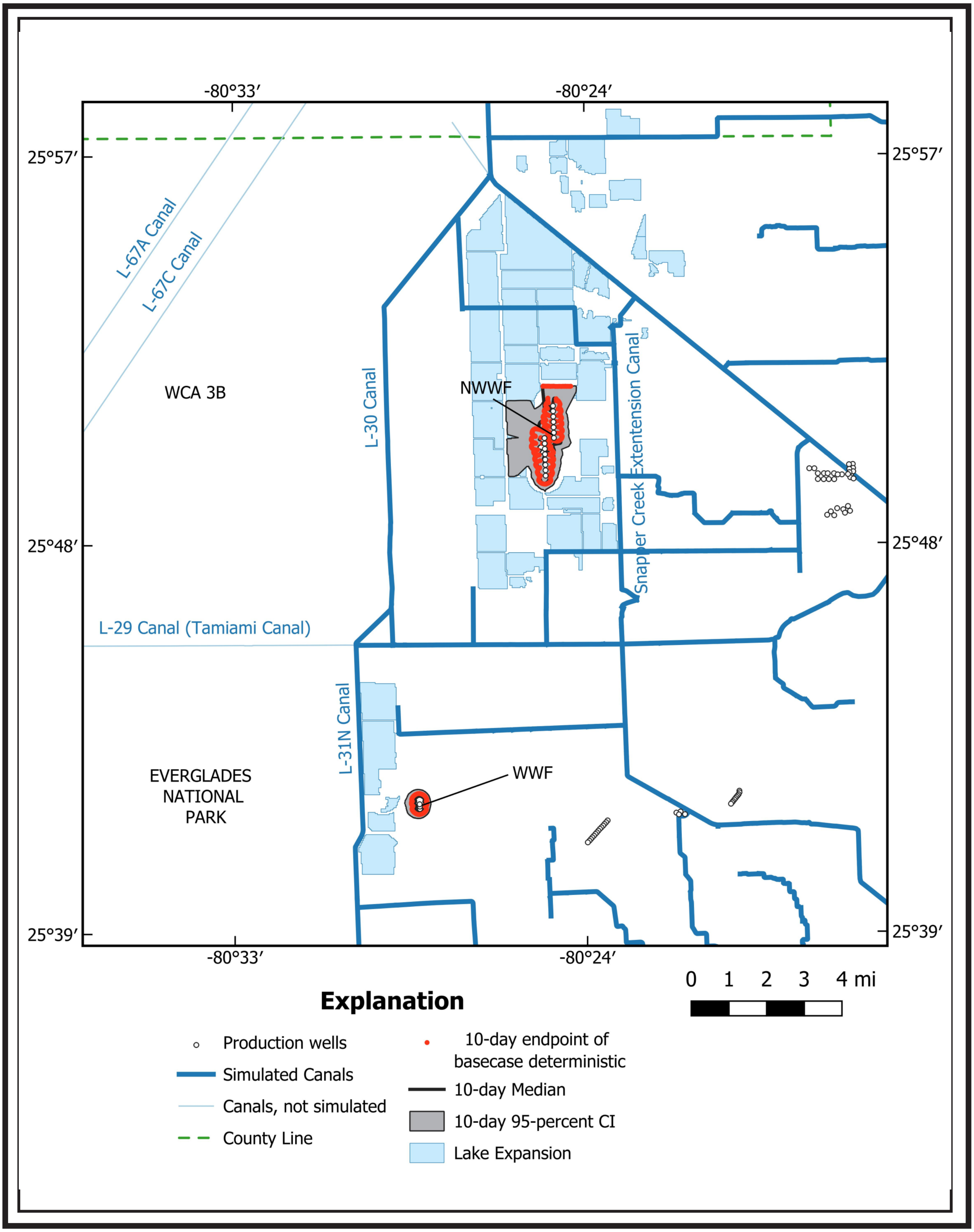
Figure 5-5
Median and 95-percent confidence intervals for the 30-day capture zones for the NWWF and WWF for steady-state dry conditions, and particle endpoints for 30 days of travel for the base-case deterministic simulation.



GTI
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Figure 5-6
Median and 95-percent confidence intervals for the 10-day capture zones for the NWWF and WWF for steady-state dry conditions, and particle endpoints for 10 days of travel for the base-case deterministic simulation.

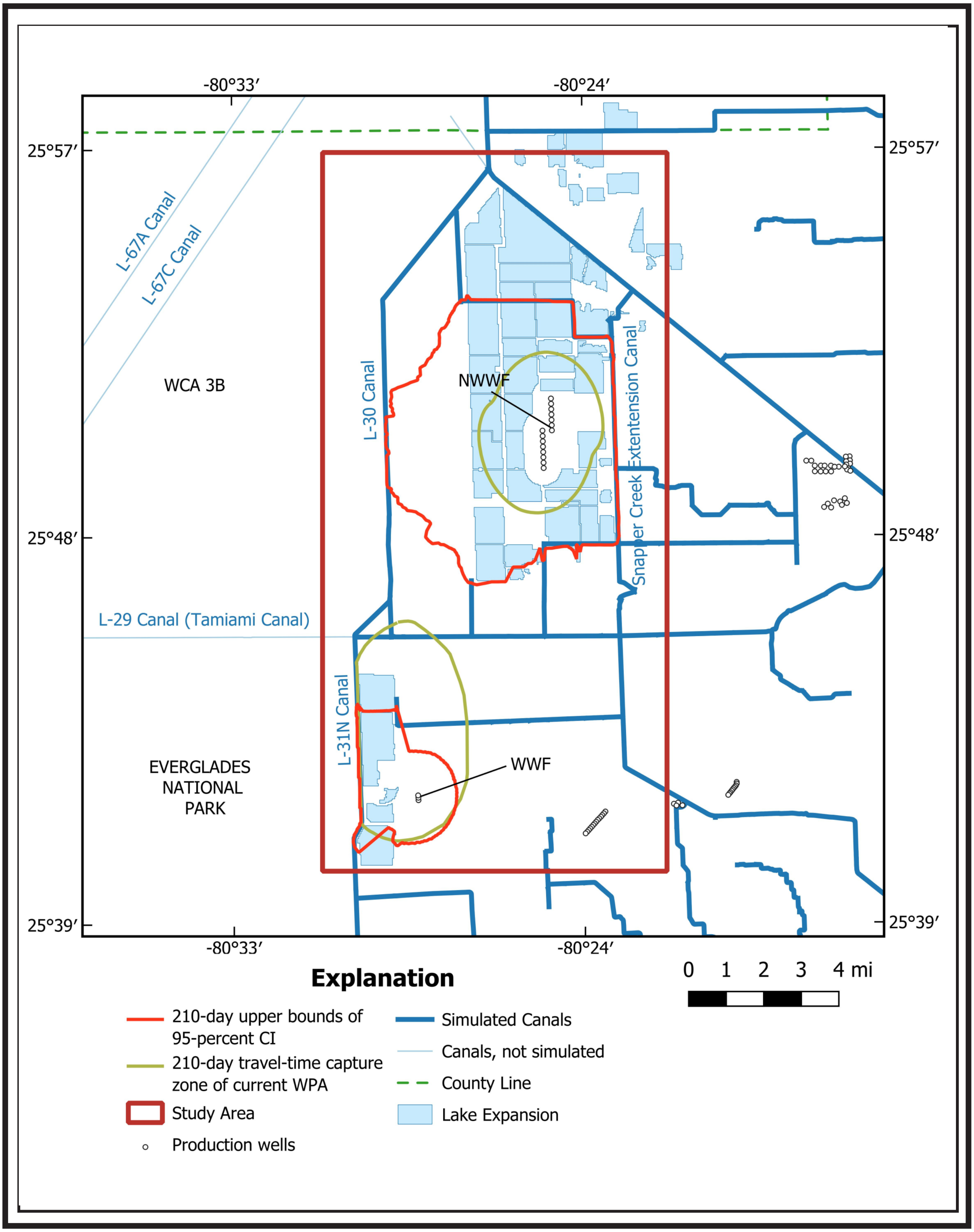

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Figure 5-7
Areal extents of the upper bounds of the 95-percent confidence intervals for the 210-day capture zones for the NWWF and WWF for steady-state dry conditions and the current 210-day Wellhead Protection Areas .

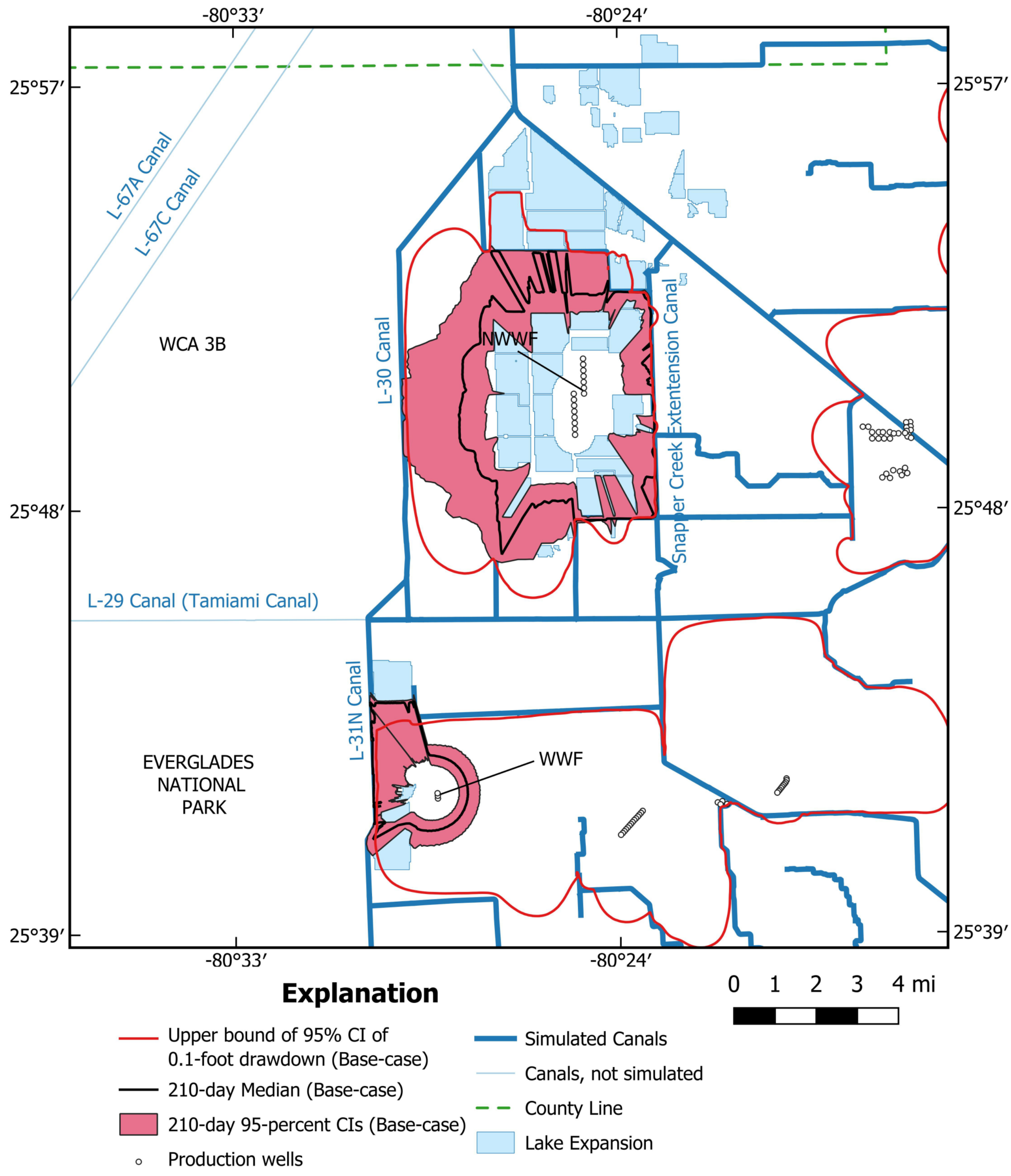

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Figure 5-8
Upper bounds and medians of the 95-percent confidence intervals for the 210-day capture zones and upper bound of 0.1-foot drawdown for both wellfields for steady-state dry conditions with seepage reduction of 0.3% (Base-case).

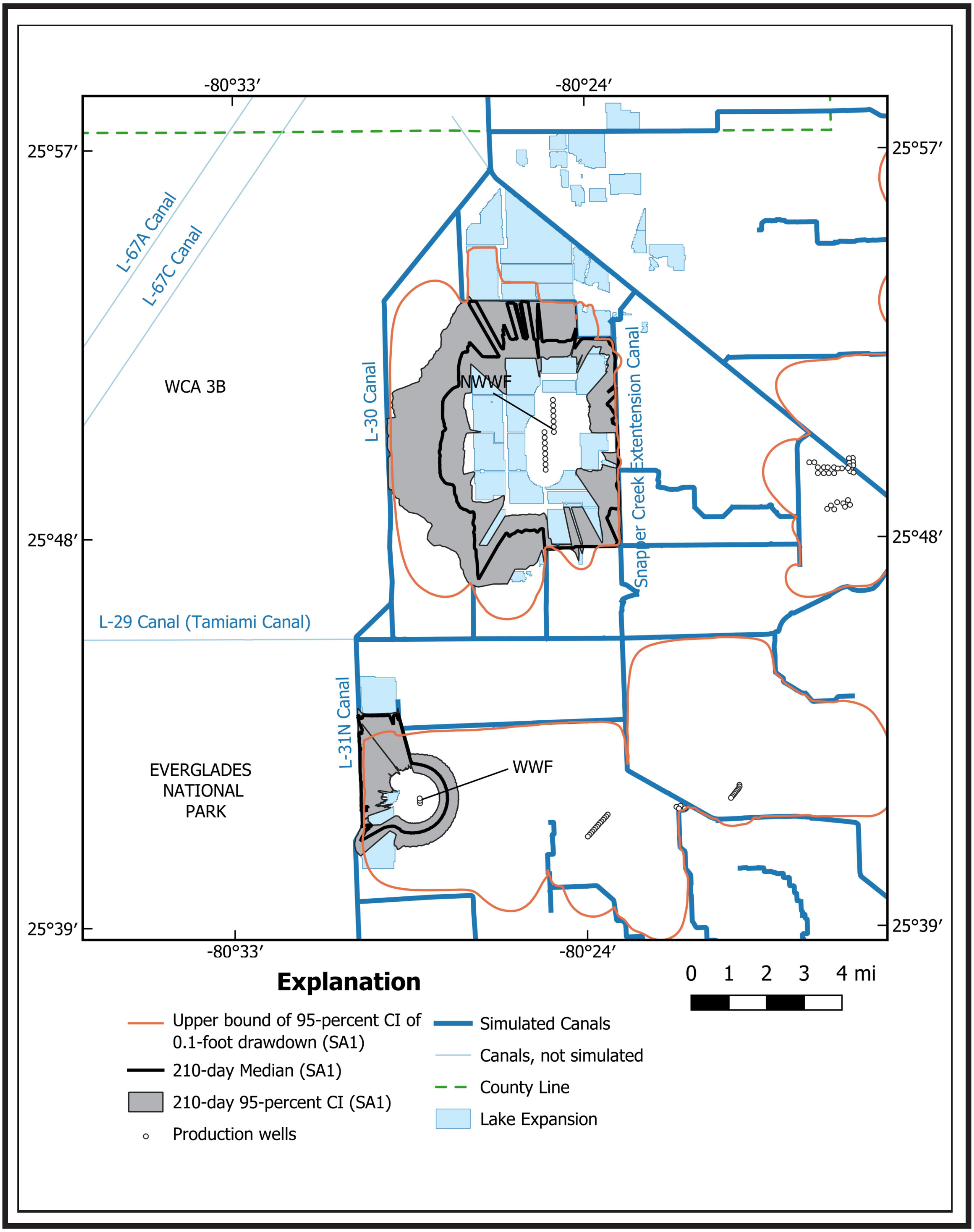

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Figure 5-9

Upper bounds and medians of the 95-percent confidence intervals for the 210-day capture zones and upper bound of 0.1-foot drawdown for both wellfields for steady-state dry conditions with seepage reduction of 10.2% (SA1).

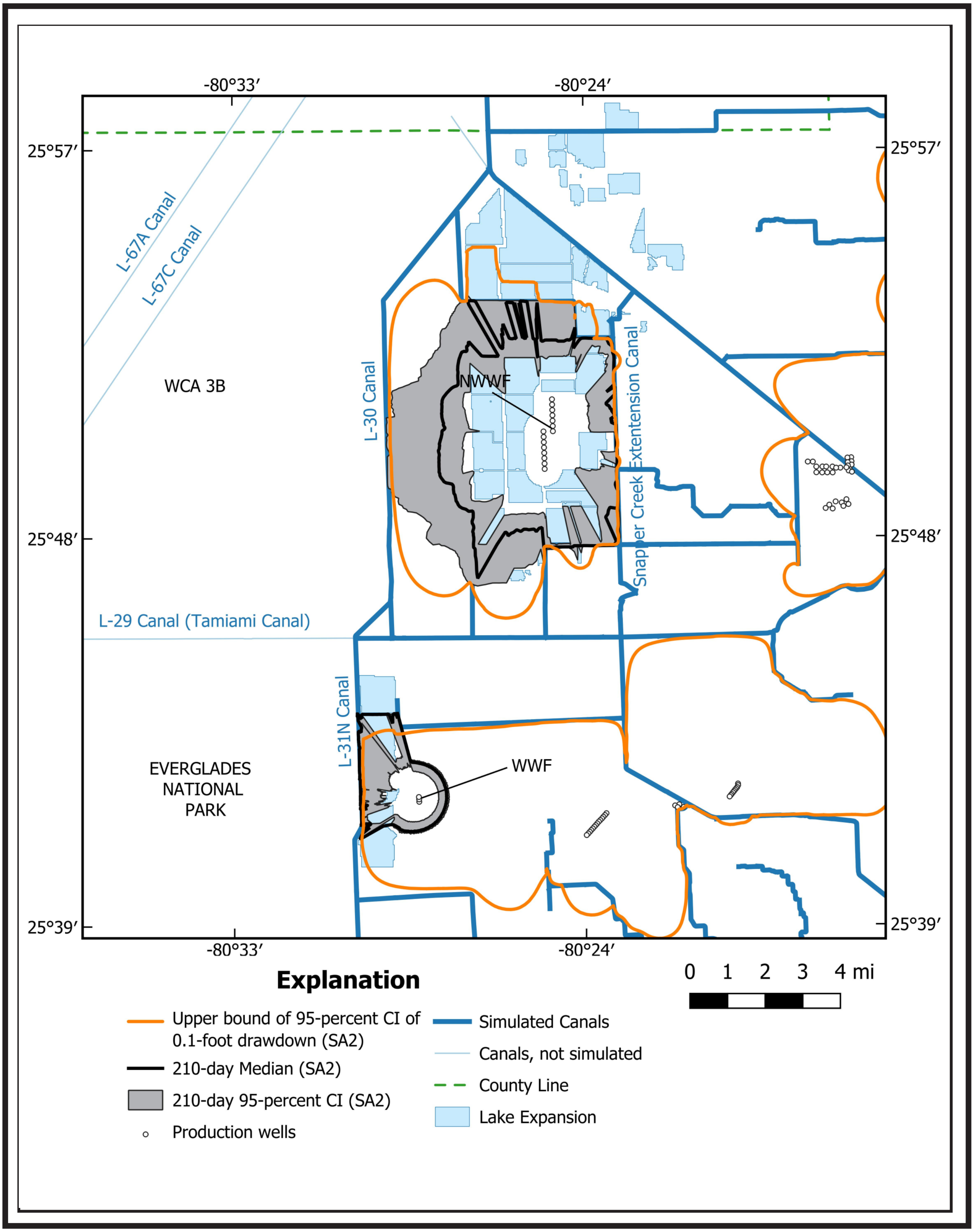

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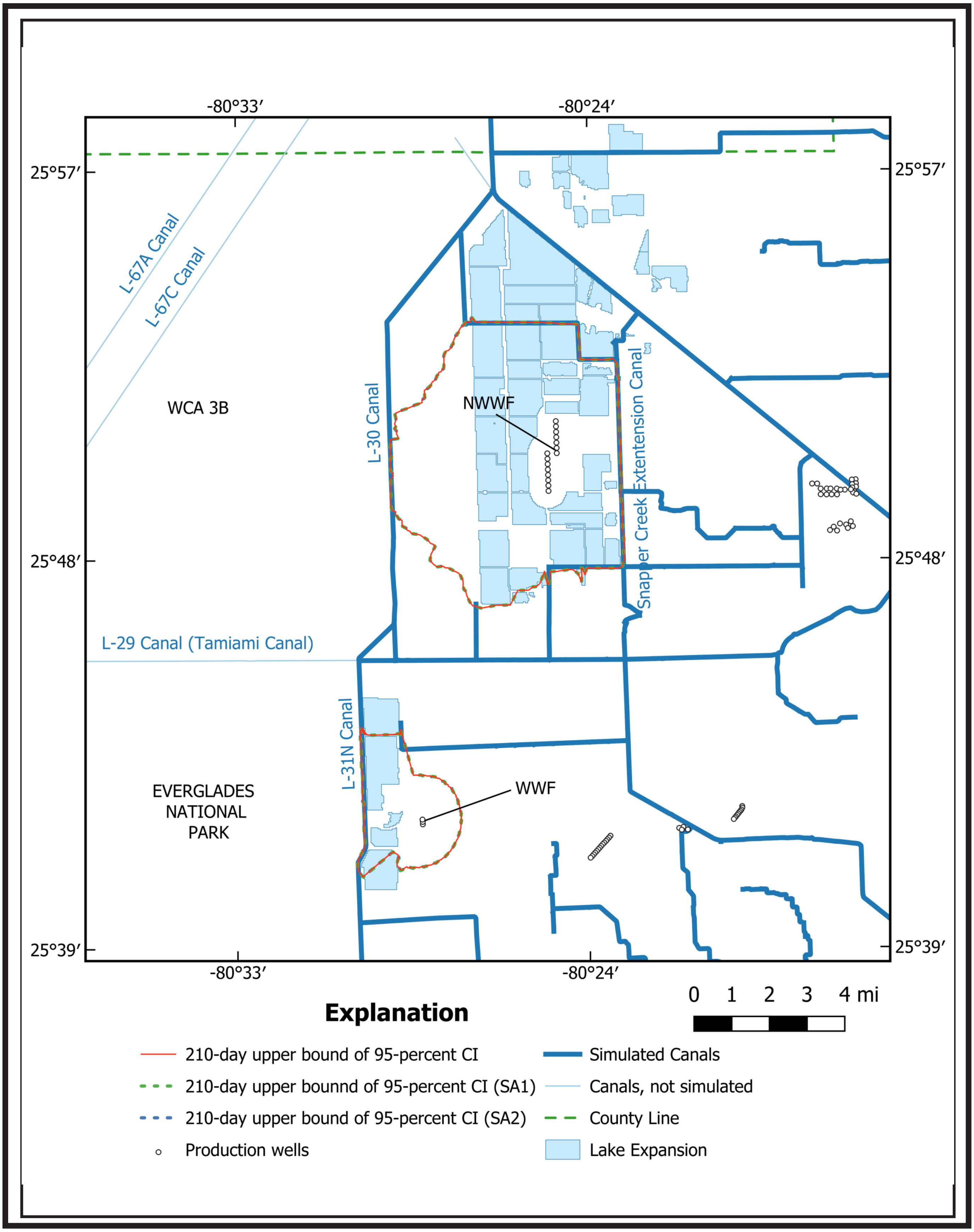
Figure 5-10
Upper bounds and medians of the 95-percent confidence intervals for the 210-day capture zones and upper bound of 0.1-foot drawdown for both wellfields for steady-state dry conditions with seepage reduction of 33.5% (SA2).



Groundwater Tek Inc.

Figure 5-11
Comparison of the upper bounds of the 95-percent CIs for the 210-day capture zones under different seepage reductions (Base-case, SA1 and SA2).

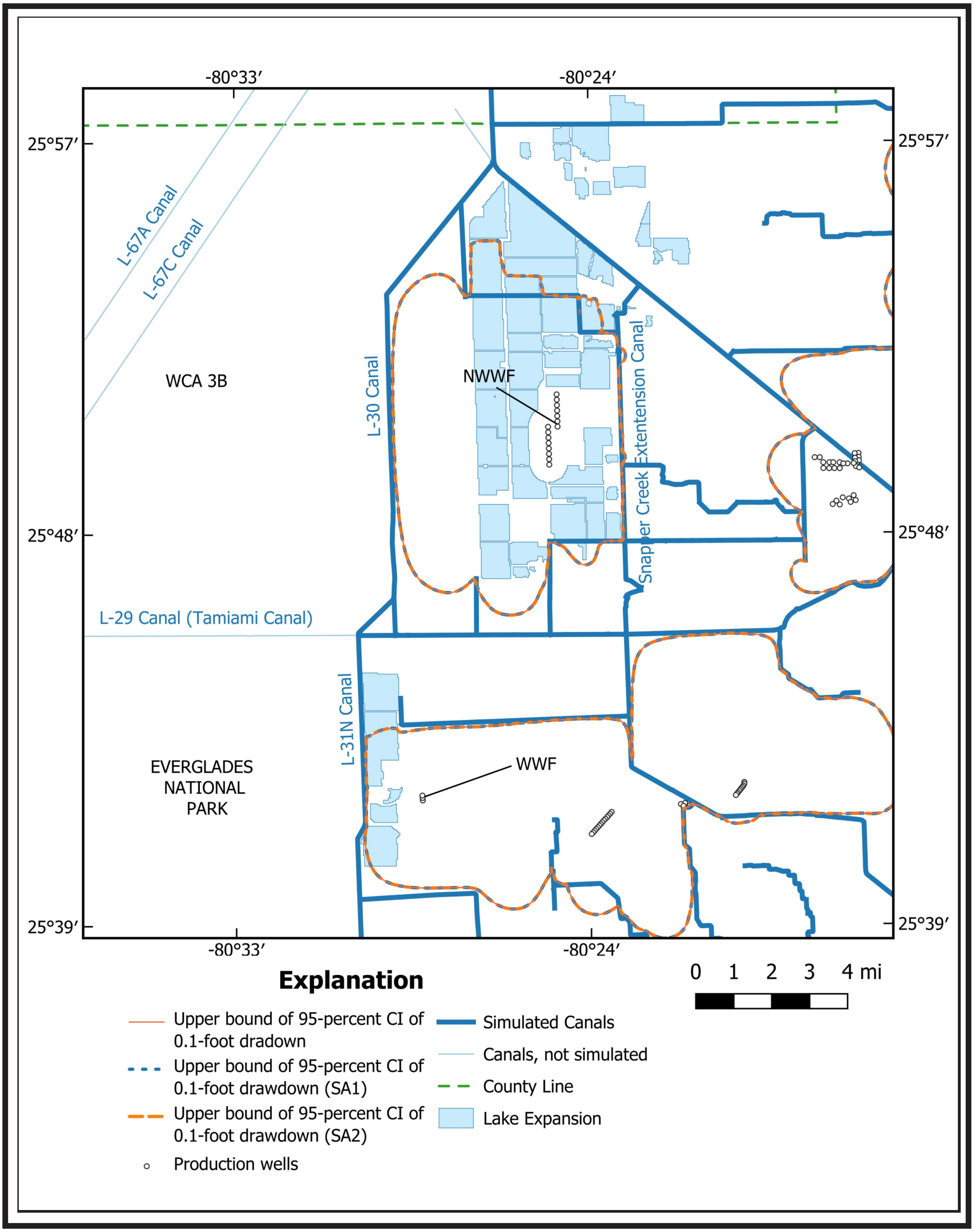


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Figure 5-12
Comparison of the upper bounds of 95-percent CIs 0.1-foot drawdown under different seepage reductions (Base-case, SA1 and SA2).

Appendix A: Impact Analysis of the Slurry Wall to Groundwater Seepage from The Everglades National Park

TECHNICAL MEMORANDUM

Subject: Impact Analysis of the Slurry Wall to Groundwater Seepage from The ENP (Draft)

From: Weixing Guo, P.D., P.G. Groundwater Tek Inc. (GTI)

To: Mr. Mayorga, Wilbur, Chief (Environmental Monitoring & Restoration Division. RER).

Date: October 20, 2023

The purpose of this memorandum is to provide DERM and WASD staff of Miami-Dade County the status of and preliminary results of the impact analysis of the slurry wall to the groundwater seepage from the Everglades National Park (ENP).

Background Information

To reduce the lateral groundwater seepage from the ENP to the L-31N canal, a 5-mile long slurry wall was constructed along the western levee of the L-31N canal, starting from US-41 (AMEC 2012 and 2016).

The slurry-wall was constructed in two phases:

Phase 1 (Feb. 2012 to July 2012): Starting from US41 due south, 2 miles long along the west side of L31N canal between the canal and the levee (AMEC 2012).

Phase 2 (Oct. 2015 to Apr. 2016): 3 miles extended from the southern end of Phase 1. To approximately SW 88th St. (AMEC 2016).

Information contained in the design drawings indicates that the constructed slurry wall is approximately five miles long. The constructed slurry wall is 32” wide and 35 feet deep. The location of the completed slurry wall is shown in **Figure 1**. **Figure 2** is a plan and profile drawing prepared by AMEC (2016).

Figure 1. Location of the slurry wall along L-31N Canal (AMEC 2016).

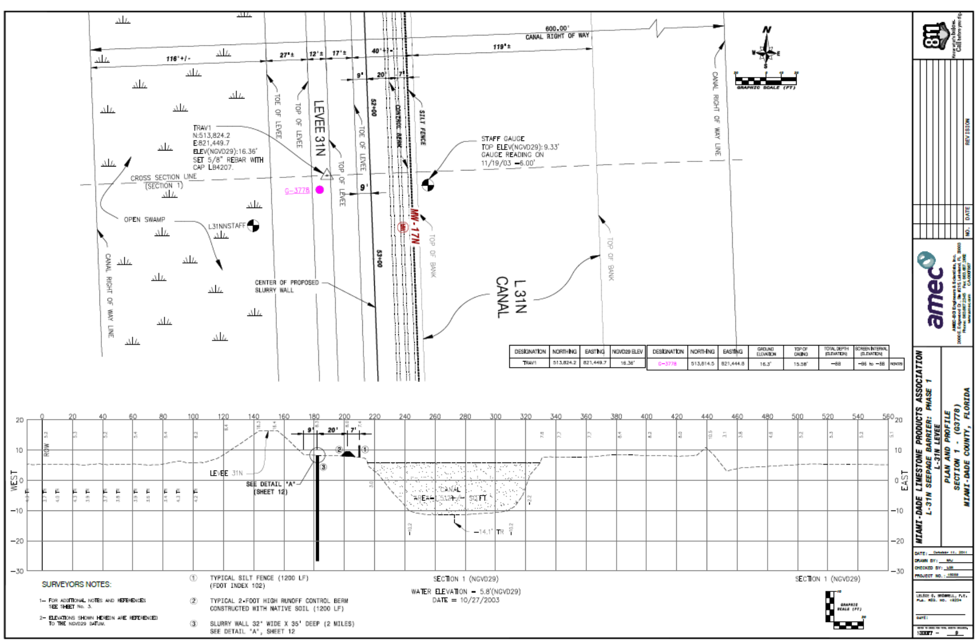


Figure 2. Plan and profile of the slurry wall (AMEC 2012).

Previous studies

Several previous studies regarding the relationship between groundwater in the ENP and the WWF have been conducted. However, it appears that there are no published reports that address the hydraulic impacts from the slurry wall after it was constructed.

In 2004, Wilcox et al. (2004) conducted a study using stable isotopes and showed that the water withdrawn by WWF may contain 60% of water derived from the seepage from the ENP.

Prior to the construction of the slurry wall, a multi-layer groundwater flow transient model was developed by MacVicar, Fedrico & Lamb, Inc. (2011), referred as MFL (2011) in this technical memorandum, to assess the hydraulic impacts of the slurry wall on the groundwater seepage from the ENP. Their modeling results suggested that the then-proposed 7-mile long, 30-foot deep slurry wall could force the seepage in the shallow flow zones to the deep flow zones and the total seepage from the ENP along the length of the slurry wall could be reduced by 33.5%.

Brown (2015) assessed the mean daily net seepage into 20,000 meters of the L-31N canal between structure S-335 (just north of Tamiami Trail) to structure S-331 (just north of SW 168th Street) from 1991 to 2010, using a water budget analysis approach. Brown found there was net seepage into the canal for all the years studied. Brown determined that 94% of the seepage into the canal occurred along the northern segment of the canal between S-335 and immediately south of the C-1W canal. The mean daily net seepage into the canal decreased by 32% between the period of 1991 – 1999 and the period of 2000 to 2010 along the northern segment of the canal. The study concluded that the decrease in net daily seepage was explained by the doubling of the percentage of time that the northern segment of the L-31N canal was providing recharge to the aquifer. The study also acknowledged that the results for the southern segment were not as certain due to a lack of observation wells to the east of the L-31N canal.

Approach and Objective

The groundwater model used by the USGS in the wellhead protection area delineation (referred to as the USGS wellfield model in this report) (Brakefield et al., 2013) consists of one layer representing the Biscayne aquifer. The ENP was not explicitly included in the USGS wellfield model, but its impacts to the Biscayne aquifer were combined with the L-31N canal as a hydrogeological boundary (modeled with River package). Therefore, the USGS wellfield model did not allow addition of a partially penetrated slurry wall or had the room to add the slurry wall between the ENP and the L-31N canal.

In order to model the partially penetrating slurry wall on the western side of the L-31N canal as it was constructed, addition of wellfield model layers and increasing the size of the active model area to include a portion of the ENP in the model along the L-31N canal would be necessary so a partially penetrating slurry wall could be accurately incorporated into the model.

However, it would be difficult to split the model layer because that would require redistribution of the aquifer properties based on revised model layer thicknesses and groundwater pumping rates according to the well screen depth intervals. Eventually, the new model would have to be recalibrated or verified before use for wellhead protection area delineation.

An alternative approach to evaluate the effects of the slurry wall on the capture zone of the WWF using the USGS wellfield model, as modified by GTI, includes representing the reduction in seepage resulting from the slurry wall by adjusting the river cell conductance for the L-31N canal in the River package. To estimate the reduction of seepage from the ENP due to the slurry wall, GTI built a one-dimensional multiple layer cross-sectional groundwater flow model based on the groundwater model developed by the USGS for the Miami-Dade County (Hughes and White, 2014) (referred as the USGS county-wide model in this report). This county-wide model uses three model layers to represent the Biscayne aquifer. The aquifer properties and layer structure were extracted for the cross-sectional model. The estimated reduction in simulated seepage available to the WWF determined using the cross-sectional model can be used to adjust the conductance in the River package in the USGS/GTI wellfield model to correlatively reduce the contribution of seepage from the L-31N canal to the WWF.

As previously stated, the ENP was not explicitly included in the USGS wellfield model, but its impacts to the Biscayne aquifer were combined with the L-31N canal as a hydrogeological boundary. The river conductance along L-31N defined in the USGS wellfield model, after calibration or adjustment, hydraulically represents the seepage from both the ENP and L-31N to the WWF area reasonably well prior to the slurry wall construction.

The seepage flow into or out a river cell in MODFLOW can be estimated as:

$$Q=f_w*C*\Delta H$$

where Q is the flow (T^3/L), C is the river conductance (L^2/T) and ΔH is the head difference between the river stage and head in the hosting aquifer (L). f_w is a dimensionless adjustment factor associated with the slurry wall. Before the wall was constructed, f_w=1.0.

As shown in the equation above, the flow is proportional both to the river conductance and the head difference between the canal stage and heads in the aquifer. Note that the flow term Q, in this particular application of the USGS wellfield model after model calibration (Brakefield et al., 2013), includes not only the flow in/out of the L-31N canal, but also the deep seepage beneath the canal from the ENP. Thus, the change of the seepage beneath the canal towards the WWF area can be modeled by applying an adjustment factor (f_w) to the river cell conductance in a steady-state model to reflect the change of groundwater seepage out of the river cell due to the construction of the slurry wall while everything else can be kept unchanged as in the USGS wellfield model.

Therefore, as a simplified approach, the cross-sectional model was used to estimate the hydraulic impact of the slurry wall to the seepage from the ENP. By comparing the seepage change between a base run without the slurry wall and a run with the slurry wall using the cross-sectional model, the change of seepage flow from the ENP before and after slurry wall construction was estimated. Estimated change in seepage from this cross-sectional model can be used to adjust the river conductance of the L-31N canal in the USGS wellfield model used by GTI (with modifications) to approximate the hydraulic impacts of the slurry wall instead of explicitly modeling the slurry wall. With this simplified approach, the WWF wellfield capture zone that considers the existence of the slurry wall can be estimated.

The Cross-sectional Model Development

The cross-sectional model was built upon the USGS county-wide model (Hughes and White 2014). The cross-sectional model has 1 row, 11 columns and 3 layers representing the Biscayne Aquifer. The bottom layer is the most transmissible layer while the middle layer is least transmissible so layer 2 behaves as a semi-confining unit. The location of the cross-sectional model is shown in **Figure 3**. Most model cells are 1,640 ft wide in the column direction as their original size in the USGS county-wide model. In the column direction, a width of 2,670 ft was used based on the width of the main capture zone of WWF Well #2. The last cell is the half size of the others to better locate the WWF. A plan view of the model grid system is shown in **Figure 4**. These cells match the model cells from row 75, columns 17 to 27 in the USGS county-wide model (Hughes and White 2014).

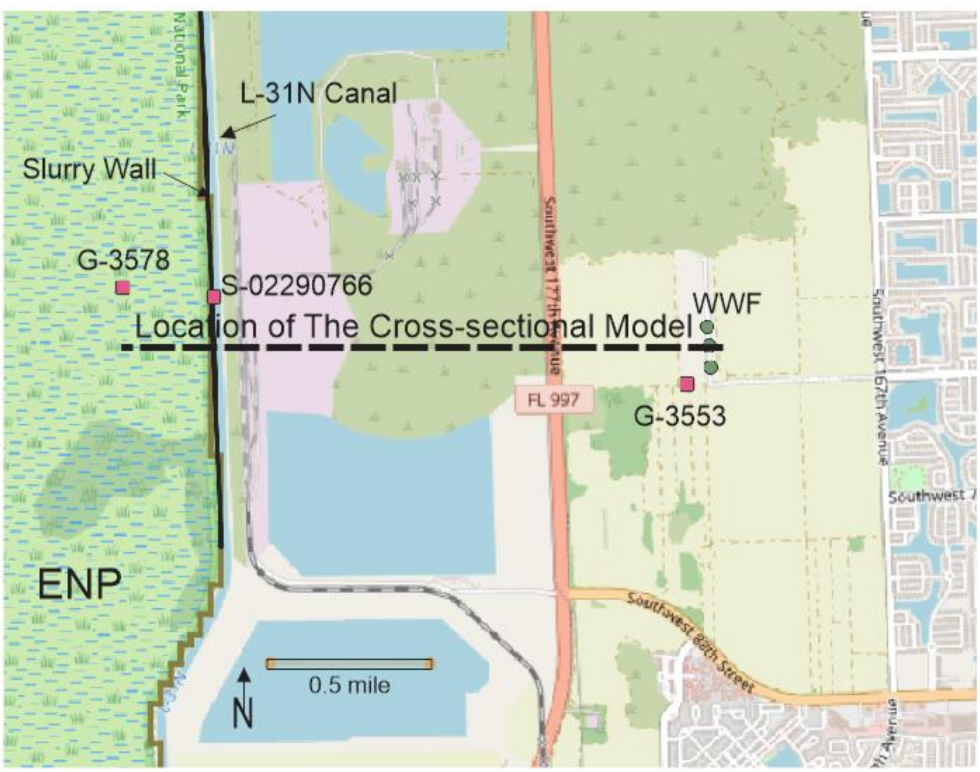


Figure 3. Approximate location of the cross-sectional model.

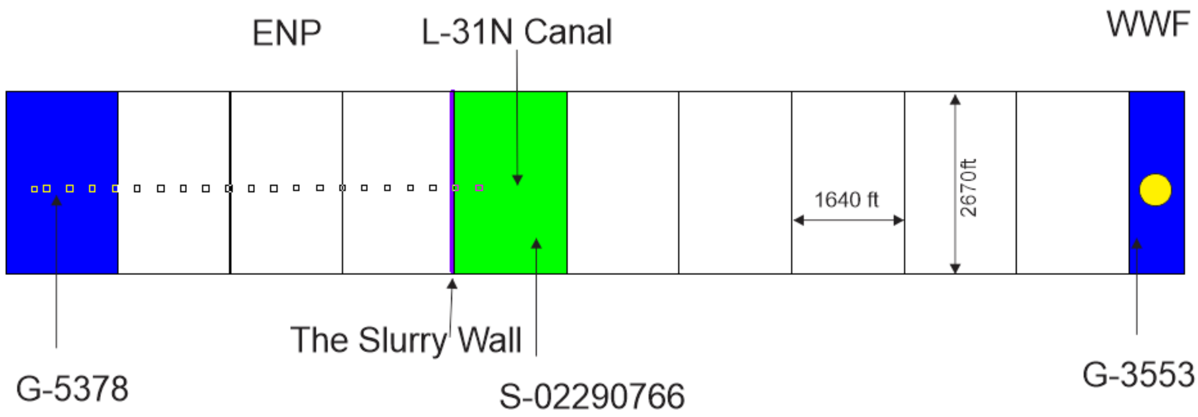


Figure 4. Plan view of the cross-sectional model grids and features.

As stated previously, the model has 3 layers representing the Biscayne aquifer as shown in **Figure 5**. The layer top and bottom information, as well the hydraulic properties (horizontal and vertical hydraulic conductivities) were obtained from the USGS county-wide model (Hughes and White 2014).

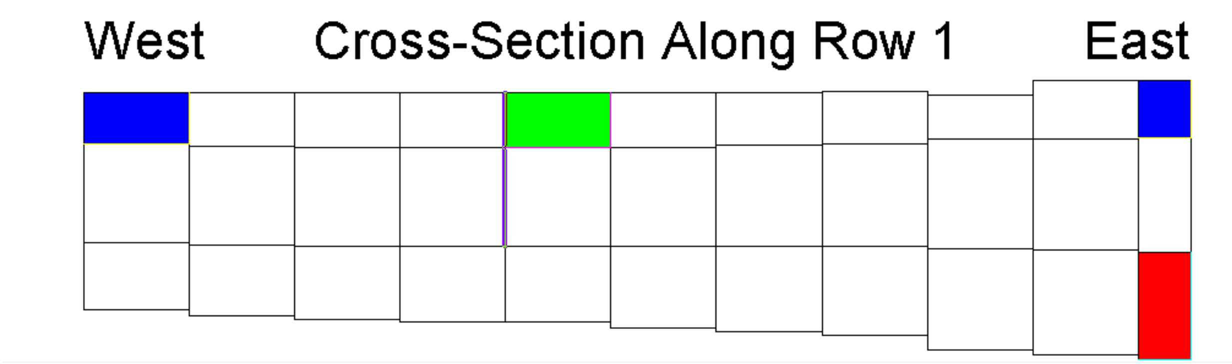


Figure 5. Cross-sectional view of the cross-sectional model.

Both ends of the model are set as constant head boundary conditions. The left side (the west) boundary represents the water level at the ENP, and the right side (the east) boundary represents the water level at the WWF area. The east side boundary also serves as the source of water for the WWF since the WWF likely extracts some water from the east side of the wellfield.

The water level data for the ENP (from USGS well G-3578), L-31N canal (USGS gage station S-02290766) and the area in proximity of WWF (USGS well G-3898) were used to define the water levels at these locations. All water levels were converted from NGVD 29 to NAVD 88 by a constant shift (-1.55 ft), based on a computer code (VERCON) developed by NOAA. The mean water levels at G-3578, G-3553, and S-02290766 are shown in **Table 1**:

Table 1. Mean water levels and stages of selected wells and gage station.

Well or Structure	**Periods of Data Records**	**Water Levels (ft, NAVD 88)**
G-3578	10-Mar-95 - 6-Sep-23	5.02
G-3553	17-Feb-94 - 29-Aug-23	3.22
S-02290766	11-Jun-1994 – 9-Sept-2023	3.84

The WWF consists of three extraction wells tapping the lower portion of the Biscayne aquifer (layer 3 of the cross-sectional model). The total permitted maximum pumping rate for WWF is 25 million gallons per day (mgd), as modeled in the wellhead protection area delineation. The well located in the middle of the WWF (i.e., Well #2), with maximum permitted pumping rate of 5 mgd, is selected for this modeling exercise, based on the capture zone of this well under average dry conditions, as shown in **Figure 6.** This well has three separate capture zones: one extends to the western direction, and the other two capture zones extend originally eastwards then wrap around the individual capture zones for Well #1 and Well #3. The capture zone extending to the west is the main capture zone and is shown in Figure 6. The width of its main capture zone at the L-31N canal is approximately 2,670 ft. This value was used to define the size of the model cell in the row or south-north direction.

Figure 6. The main capture zone of the WWF #2 well.

The model was run under steady-state conditions. MODFLOW 2005 (Harbaugh et al., 2005) was used to execute the model. All layers are set as “unconfined” in the MODFLOW LPF package.

The model with the slurry wall is similar to the base condition model described above. The slurry wall is simulated using MODFLOW's Horizontal Flow Barrier Package (HFB) (Harbaugh et al., 2000; Hsieh and Freckleton, 1993). A slurry wall is added to the western side of L-31N between Columns 4 and 5 only in layers 1 and 2 (elevations from 4 to -30.4 ft (NAVD88) and it fully penetrates the upper two layers of the model as shown on Figures 4 and 5. The slurry wall, according to the testing data (AMEC 2012), has a hydraulic conductivity value between 1.7 to 8.2 x 10^{-6} cm/sec. An approximate value of value of 5 x 10^{-6} cm/sec (or 0.014 ft/day) was used in this study. The thickness of the slurry wall was set as 32" (2.67 ft) as it was actually constructed.

Preliminary Results and Discussion

The hydraulic impact of the slurry wall to the groundwater seepage from the ENP is assessed by the differences of the seepage fluxes under the base condition without the slurry wall and the condition with slurry wall. The only difference between the two simulations is the base run represents the conditions prior to the construction of the slurry wall while the other run represents the conditions after the wall construction.

To better visualize the groundwater seepage flow paths, particle tracking analyses were also performed. A number of imaginary particles were added to Column 1 at different depths. Particles were also added to Layer 1 from the ENP (Column 1) to the L-31N canal (Column 5) to demonstrate the pathlines originating from the surface of the ENP.

Figure 7 shows modeled head contours and pathlines from the base simulation when Kv=Kh for all layers. **Figure 8** shows modeled head contours and pathlines from the simulation with a slurry wall penetrating layers 1 and 2 when Kv=Kh for all layers.

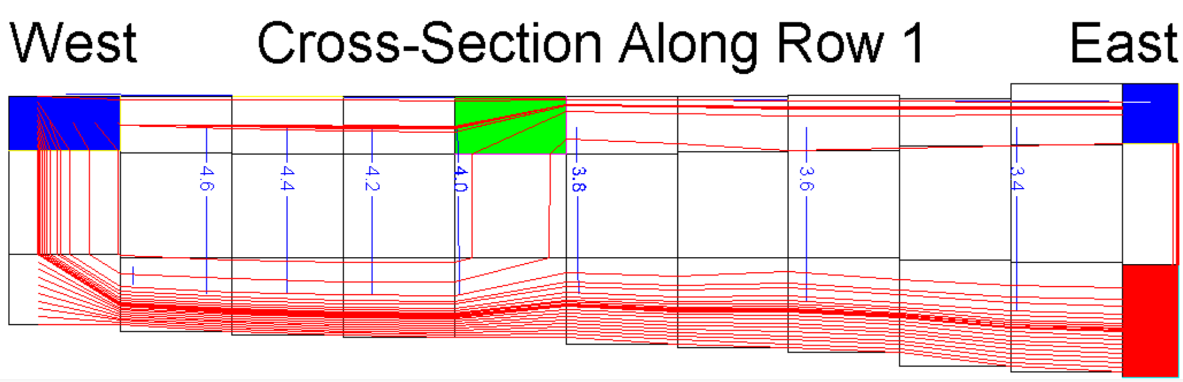


Figure 7. Simulated head contours (blue lines) (ft, NAVD88) and pathlines (brown lines) of the base run simulation.

As shown in Figure 7, the flow from the ENP is essentially along the model layers. Some deep groundwater seepage moves up from layer 3 to the canal.

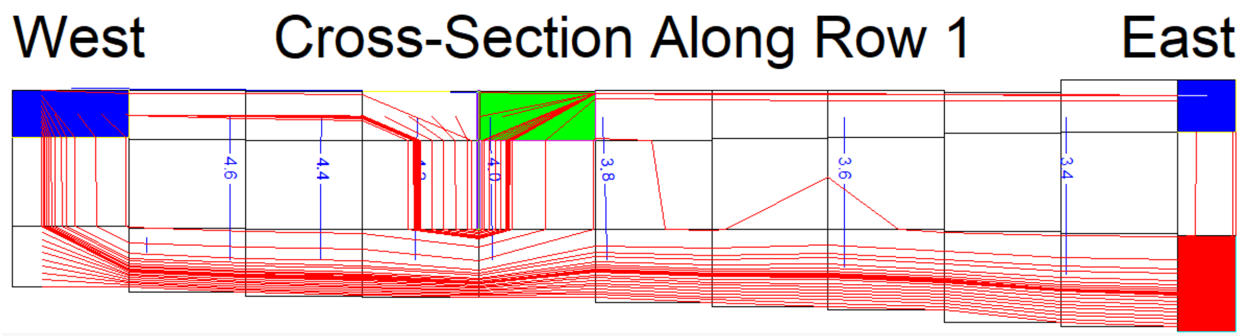


Figure 8. Simulated head contours (blue lines) (ft, NAVD88) and pathlines (brown lines) of the simulation with the wall.

As shown in Figure 8, the shallow seepage from the ENP is forced to move down to layer 3 due to the slurry wall. Once it passes the slurry wall, it will move upwards to the canal (layer 1). Some deep groundwater seepage may also move up from layer 3 to the canal, but most of the deep seepage will continue moving to the WWF area.

The Table below (**Table 2**) summarizes the seepage flowing into (Q_{in}) Column 5 and leaving (Q_{out}) Column 5 under the base run conditions and the slurry wall. Q_{in} represents the groundwater seepage from the ENP to Column 5 and Q_{out} represents the seepage from Column 5 flowing east towards the WWF area. Table 2 also contains the changes of seepage fluxes due to the construction of the slurry wall.

Table 2: Changes of Groundwater Seepages and L-31N Flow

(All values in cubic feet per day (cfd))

Base	Q_{in}	Q_{out}	**To Canal**
Layer 1	32,2545	167,713	549,776
Layer 2	2,320	1,283	
Layer 3	1,106,872	712,965	
Total	1,431,737	881,961	549,776

Wall	Q_{in}	Q_{out}	**To Canal**
Layer 1	55	162,347	464,219
Layer 2	126	1,266	
Layer 3	1,343,598	715,947	
Total	1,343,779	879,560	464,219

Changes	Q_{in}	Q_{out}	**To Canal**
Layer 1	-322,490	-5,366	-85,557
Layer 2	-2,194	-17	
Layer 3	236,726	2,982	
Total	-87,958	-2,401	-85,557

Most of the increased inflow for layer 3 goes back to the canal (layer 1) after passing the bottom of the slurry wall. This flow pattern is demonstrated in Figure 8. The overall seepage flow in layer 3 towards the WWF area increased only about 0.4%. The total outflow (Q_{out}) from Column 5 is reduced by only about 0.3% in groundwater seepage.

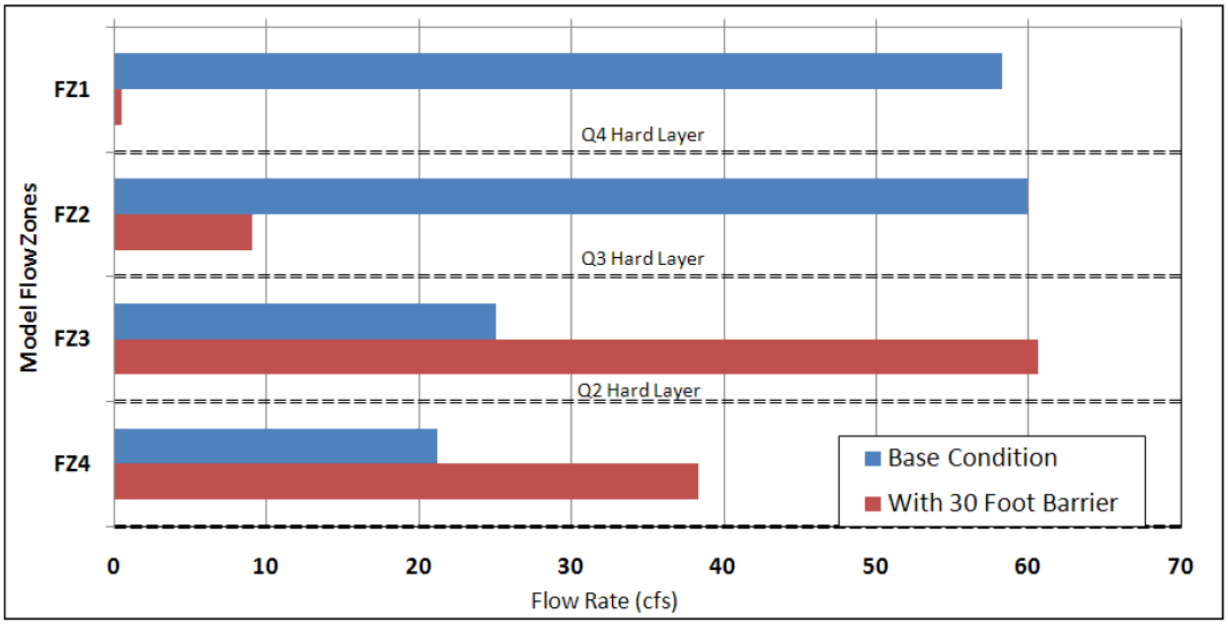
The total loss of seepage outflow from Column 5 (2,401 cfd) and the flow reduction to the canal is 87,958 cfd, which is about the same as the total loss of inflow from the ENP. In addition, the simulated seepage flow to the L-31N is reduced from 549,776 cfd to 464,219 cfd (about a 16% reduction from the base case) due to the construction of the slurry wall. This apparent reduction is caused by the slightly lower head in the cell containing the L-31N due to the fact that the slurry wall forces the seepage in the shallow layer travels longer distance to L-31N thus subjects to greater head loss. This reduction, 85,557 cfd, does not consider dynamic flow in the L-31N canal, and is just a small fraction of the total discharge of the L31N canal at this location. The mean flow rate of the L-31N at S-0229766 is 407 cfs or 35,164,800 cfd. This is consistent with the measured water levels in the L-31N canal that have not changed appreciably due to slurry wall construction.

Based on the total fluxes shown in Table 2, the total simulated seepage from the ENP (Q_{in}) is reduced by about 6.14% due to the construction of the slurry wall. The total reduction of flow to the L-31N canal is 16% but the total reduction of simulated seepage to the WWF area is only 0.3%.

The flow of seepage per unit width beneath L-31N prior to the construction of the slurry wall, is about 536 cfd/ft of levee, which is comparable to the estimate from Nemeth et al. (2000), who modeled seepage rates between -200 and 500 cfd per foot of levee.

MFL (2011) conducted a modeling study of the performance of the slurry wall between the ENP and the L-31N canal before the slurry wall was actually constructed. They developed a three-dimensional, ten-layer MODFLOW groundwater flow model to study the potential impacts of the slurry wall to the groundwater seepage. The model, which represents the Biscayne aquifer, includes four flow zones. The L-31N canal was modeled using MODFLOW River package in their model. The model was calibrated for 3,288 days from 1/1/2000 to 12/31/2008. Different configurations of the slurry wall, from 18 ft to 30 ft deep with various lengths, were evaluated. A constant vertical anisotropy of 10:1 was applied to all the flow zones. It is not clear what permeability was used for the slurry wall in their model. It is also unclear whether or not the slurry wall fully penetrated to the third flow zone (FZ3).

MFL (2011) found that the slurry wall 30 feet deep would reduce the horizontal flow to the L-31N canal in shallow flow zones (Zones 1 and 2) but would increase the seepage flux in the deep flow zones. They estimated the total flow from the ENP would be reduced by approximately 33.5% (as shown in **Figure 9**) from 164 cubic feet per second (cfs) to 109 cfs due to the construction of a 7-mile long 30 ft deep slurry wall along the west side of the L-31N canal.



Model Result: Average annual flow through the four flow zones at the eastern boundary of ENP with and without a 30 foot deep 7-mile long barrier.

Figure 9. Changes of groundwater fluxes due to the construction of a 7-mile-long 30-ft-deep slurry wall (MFL, 2011).

The flow reduction of 33.5% due to the slurry wall, estimated by MFL (2011), is about 5 times higher than the estimate from this study (6.14%). The MODFLOW models used by MFL and GTI are quite different in many aspects. One of the key factors might be vertical anisotropy. In the USGS county-wide model, the horizontal and vertical hydraulic conductivities were set as equal while the vertical hydraulic conductivities for the flow zones were set as 1/10 of the horizontal hydraulic conductivities in the MFL (2011) model.

MacVicar Consulting, Inc. (MacVicar 2021) also performed a modeling study to evaluate the effectiveness of a slurry wall in reducing seepage from the ENP and mitigating flooding at the Las Palmas community that is to the south southwest of the WWF. The results were presented in a report dated January 28, 2021 (MacVicar 2021). Using a model that was similar to the model used for the MacVicar 2011 study, MacVicar simulated the reductions of seepage from the ENP for 14 different scenarios (Table 2 in the MacVicar 2021 report). Scenarios labelled as Base13_W10b and Base 13_W10b_K10x0.5 included a slurry wall of similar depth as the slurry wall being considered for the capture zone analyses. The scenario labelled Base 13_W10b_K10x0.5 was the same as Base 13_W10b except that the hydraulic conductivity values were reduced by 50%.

Results of the simulations are summarized in Table 4 of the MacVicar 2021 report. Results of scenario Base13_W10b indicate that the slurry wall reduced the simulated seepage by between 18% (Segment D) and 56% (Segment B) along the slurry wall. Locations of Segments B, C, and D are shown on Figure 8 of the MacVicar 2021 report. For scenario Base13_W10b_Kx0.5, the reduction of simulated seepage varied from 18% (Segment D) to 30% (Segment B) along the slurry wall. The differences in reductions of seepage rates are likely due to the directions of groundwater seepage along the various segments. These reductions in simulated seepage are also considerably higher than estimated using the GTI's cross-sectional model.

The simulated seepage reductions due to the slurry wall, estimated by MFL (2011), are significantly different than those estimated by GTI using the cross-sectional model. However, all models indicate a significant reduction of simulated seepage in the shallow zones and an increase in seepage in the deep zones. The quantitative differences in seepage flow are due to the differences in model construction and hydrologic property input values. The model input data used by GTI are based those used by the USGS in their calibrated county-wide model while those used by MFL (2011) and MacVicars (2021) were determined by MFL.

Sensitivity Analysis of Vertical Anisotropy (kv=0.1*Kh)

A sensitivity analysis simulation was performed using the GTI's cross-sectional model to test the vertical anisotropy values with respect to the modeling results. In this run, a 1/10 vertical anisotropy (i.e., Kv=0.1*Kh) was applied to all layers while everything else remained unchanged.

Figure 10 shows modeled head contours and pathlines from the base simulation without the slurry wall when Kv=0.1*Kh for all layers. **Figure 11** shows modeled head contours and pathlines from the simulation with a slurry wall penetrating layers 1 and 2 when Kv=0.1*Kh for all model layers.

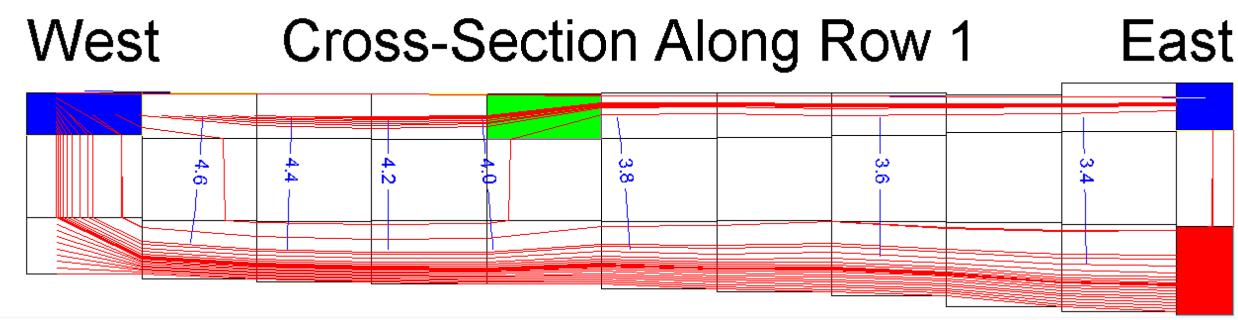


Figure 10. Head contours (blue lines) (ft, NAVD88) and pathlines (brown lines) of the base run simulation (Kv=0.1*Kh).

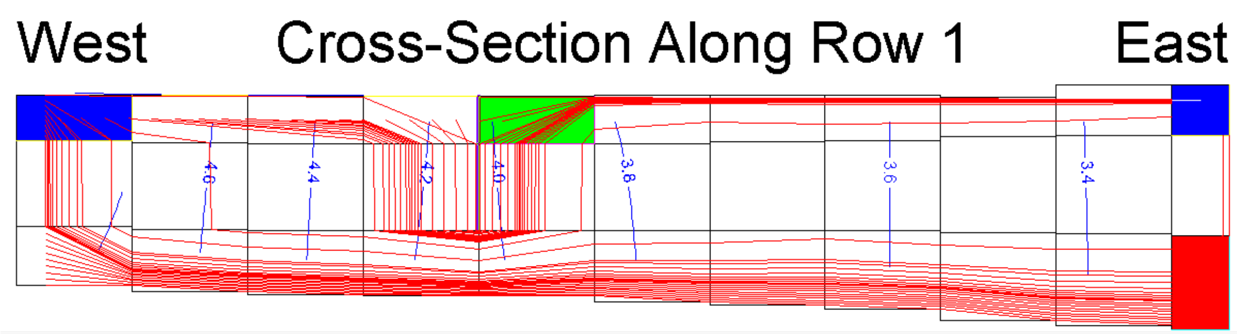


Figure 11. Head contours (blue lines) (ft, NAVD88) and pathlines (brown lines) of the simulation with the wall (Kv=0.1*Kh).

Table 3 summarizes modeled fluxes through Column 5 containing the river cell and the net changes before and after the construction of the slurry wall. These values are based on the model simulations assuming kv=0.1*kh.

Table 3: Changes of Groundwater Seepages based on Kv=0.1*Kh

(All values in cubic ft per day (cfd))

Base_kv0.1	**Q_{in}**	**Q_{out}**	**To Canal**
Layer 1	309,693	133,155	377,456
Layer 2	2,096	1,175	
Layer 3	951,196	733,797	
Total	1,262,985	868,127	377,456

Wall_Kv0.1	**Q_{in}**	**Q_{out}**	**To Canal**
Layer 1	86	107,524	249,607
Layer 2	127	1,118	
Layer 3	1,133,842	775,805	
Total	1,134,055	884,447	249,607

Changes	**Q_{in}**	**Q_{out}**	**To Canal**
Layer 1	-309,607	-25,631	-127,849
Layer 2	-1,969	-57	
Layer 3	182,646	42,008	
Total	-128,930	16,320	-127,849

Based on the simulation results shown in Table 3, the simulated seepage reduction from the ENP (Q_{in}) is approximately 10.2% due to the construction of the slurry wall. However, the simulated seepage available to the WWF (Q_{out}) area increases by approximately 1.9%. The seepage flow to the WWF area in the deep layer (Layer 3) increased by 5.7% while the flow through layers 1 and 2 is reduced by 25,631 cfd (or 19.2%) and 57 cfd (or 4.9%) respectively. The flow to the L-31N canal is reduced by 33.9% because of slurry wall construction.

Conclusions and Recommendations

The groundwater flow model (or the USGS wellfield model) developed by the USGS (Brakefield et al., 2013) and used for the wellhead protection area delineation of the Miami-Dade's Northwell field (NWWF) and WWF used a comprehensive boundary to represent two hydrological features: the ENP and the L-31N canal. However, this one-layer model cannot be used to simulate the partially penetrating slurry wall constructed along the western levee of the L-31N canal.

Quantifying the hydraulic impacts of the slurry wall to the seepage of groundwater from the ENP is challenging. A simplified approach is applied here in this study. There are no published studies found for the impact due to the slurry wall construction to the groundwater seepage to NWWF and WWF after the slurry wall construction was completed in 2016.

The analysis presented here provides an estimate that can be used to adjust the river leakance for the L-31N canal to account for the change in groundwater seepage from the ENP due to the slurry wall when applying the USGS wellfield model for wellhead protection area delineation of the NWWF and WWF.

A one-dimensional cross-section groundwater flow model was constructed based on the USGS county-wide three-layer groundwater flow model (Hughes and White, 2014). The cross-sectional model was used to estimate the net change of simulated seepage from the ENP towards the WWF from the base condition to the condition with a slurry wall penetrating layers 1 and 2 under steady-state conditions.

The GTI's modeling results indicate that the partially penetrating slurry wall reduces the simulated groundwater seepage from the ENP along the length of the slurry wall (Q_{in}) by 6.14%. The slurry wall also reduces the simulated groundwater discharge to the L-31N canal along the length of the slurry wall by 15.6%. However, the modeling results also indicate that the slurry wall has an insignificant impact to the deep seepage to the WWF area (0.3%).

If a 10:1 vertical anisotropy was applied to the model, as in the model developed by MFL (2011), the groundwater seepage from the ENP would be reduced by approximately 10.2% and the flow to the canal would be reduced by 33.5% along the length of the slurry wall.

This study found the slurry wall has no appreciable effect on groundwater seepage from the ENP/L-31N canal to the WWF area. The simulated seepage to the WWF area (as Q_{out}) based on the GTI's cross-sectional model decreased by only by approximately 0.3% where for kv=kh. This value increased to 1.9% with a 10:1 vertical anisotropy.

Although the quantitative reductions in simulated seepage estimated by MFL (2011) and MacVicars (2021) are significantly higher than estimated by GTI in this study, all models indicate a significant reduction of simulated seepage to the L-31N canal in the shallow zones and an increase in seepage in the deep zones. Values determined by MFL (2011) and MacVicars (2021) are analogous to the Q_{in} values determined by GTI. The values determined by GTI are different from those determined by MFL (2011) and MacVicars (2021) because model input parameters used by GTI are consistent with those used by the USGS for their calibrated county-wide model whereas the MFL (2011) and MacVicars (2021) used input parameters developed by MFL.

Use of the estimated simulated seepage available to the WWF (Q_{out}) determined by GTI with kv=kh (0.3%) is recommended for use in revising the river cell conductivity for the River package for modeling wellfield capture zones. This value was determined using input parameters from the USGS county-wide model. The reduction in simulated seepage (33.5%) determined by MFL (2011) might be considered and used for sensitivity analysis. In addition, a sensitivity analysis should be performed using the decrease in simulated seepage (Q_{in}) value determined by GTI where Kv=0.1*kh (10.2%). This Q_{in} value is analogous to the result determined by MFL. Although these values are not estimates of the seepage changes from the ENP/L-31N canal to the WWF area due to the slurry wall, we will assume that these seepage changes prevail to the east side of the L-31N canal for the purpose of sensitivity analyses. These adjustments should be applied for the 5-mile segment of the L-31N canal from US-41 to approximately SW 88th Street. The capture zones from the sensitivity analysis simulations should be compared to the simulated capture zone using the 0.3% reduction and considered in the determination of wellhead protection area delineations.

Although the study was focused on the impact of slurry wall to the WWF area, similar conclusion can be applied to the NWWF area. The impact of the slurry wall to the NWWF is expected to be even smaller due to the longer distance from the slurry wall to the wellfield. The numerous mining lakes and canals in proximity to the NWWF should also help damp the impacts from the slurry wall.

References

Amec Foster Wheeler Environment & Infrastructure, Inc. 2012. AS-BUILT REPORT PHASE 1 SEEPAGE BARRIER LEVEE L-31N, for Miami-Dade Limestone Products Association, Inc., Miami, Florida, 1029 p.

Amec Foster Wheeler Environment & Infrastructure, Inc. 2016. AS-BUILT REPORT – PHASE 2 SEEPAGE BARRIER LEVEE L-31N, for Miami-Dade Limestone Products Association, Inc. Miami, Florida, 1562 p.

Brakefield, L., J. D. Hughes, C. D. Langevin, and K. Chartier, 2013. Estimation of Capture Zones and Drawdown at the Northwest and West Well Fields, Miami-Dade County, Florida, Using an Unconstrained Monte Carlo Analysis: Recent (2004) and Proposed Conditions, USGS Open-File Report 2013–1086.

Brown, C. 2015. An assessment of seepage into the L-31N canal Northeast Everglades National Park, Florida, USA., Environmental Earth Sciences, 73: 5747-5759.

Harbaugh A.H, E. R. Banta, M. C. Hill, *and* M. G. McDonald. 2000. Modflow-2000, The U.S. Geological Survey Modular Ground-Water Model User Guide To Modularization Concepts and The Ground-Water Flow Process, U.S. Geological Survey, Open-File Report 00-92.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Hsieh, P.A., and Freckleton, J.R., 1993. Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey modular three- dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 92-477, 32 p.

Hughes, J. D. and Jeremy T. White 2014. Hydrologic Conditions in Urban Miami-Dade County, Florida, and the Effect of Groundwater Pumpage and Increased Sea Level on Canal Leakage and Regional Groundwater Flow, Scientific Investigations Report 2014–5162 Version 1.2, July 2016.

MacVicar, Fedrico & Lamb, Inc. (MFL) 2011. Evaluating the performance of a partial penetrating seepage barrier between Everglades National Park and the L-31N Canal, Appendix A: Results and analysis of computer simulation of various seepage barrier configurations, August 29, 2011, prepared on behalf of the Miami-Dade Limestone Products Association.

MacVicar Consulting, Inc. 2021. Evaluating the Performance of a 2.3-Mile Seepage Barrier between Everglades National Park and the Las Palmas Community, Results of Computer Simulation of Various Seepage Barrier Depths, prepared by MacVicar Consulting, Inc. 4524 Gun Club Road, Suite 201 West Palm Beach, FL 33415.

Nemeth, M. S. Walter M. Wilcox, and Helena M. Solo-Gabriele, 2000. Evaluation of the Use of Reach Transmissivity to Quantify Leakage beneath Levee 31N, Miami-Dade County, Florida, USGS Water-Resources Investigations Report 00-4066.

Wilcox, M. W., Helena M. Solo-Gabriele, Leonel O'Reilly Sternberg, 2004. Use of stable isotopes to quantify flows between the Everglades and urban areas in Miami-Dade County Florida, J. of Hydrology, 293: 1-19.