Nitrate-N Solute Transport Model of Swamp Road, Northern Guam Lens Aquifer

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WATER AND ENVIRONMENTAL RESEARCH INSTITUTE OF THE WESTERN PACIFIC

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<u>WERI Hydrology Lab</u>

Jezreelyn Bulaklak, Dannika Kate Valerio, Matt Wilson Zapata
Mary Clare Snaer, and Sydney Quintanilla

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Abstract

The Northern Guam Lens Aquifer (NGLA) supplies approximately 90% of Guam's municipal water, making development directly above this critical resource both practical and widespread. However, rising nitrate-nitrogen (nitrate-N) concentrations in production wells have raised concerns about the long-term impacts of continued development and associated wastewater discharge. To evaluate these concerns, a three-dimensional solute transport model of the Swamp Road area was developed using MODFLOW-USG within Aquaveo's Groundwater Modeling System (GMS). The model integrates known and estimated parameters for aquifer properties, site hydrology and hydrogeology, and nitrate-N fate and transport.

Four land-use scenarios were simulated to quantify nitrate-N loading from septic systems, agriculture, and leguminous vegetation. These scenarios span from pre-development conditions to present-day land use under Guam's non-sewered septic infrastructure, as well as a projected high-density residential development near the Swamp Road production wells.

The model was calibrated (matched) to observe nitrate-N concentrations and used to predict future contamination under continued residential expansion. Results delineate the spatial extent and migration of nitrate-N plumes, indicating increased risk of production well contamination under higher-density septic use. These findings provide critical insights for groundwater protection and support evidence-based land-use planning, particularly regarding septic system density and regulations near drinking water sources. This study underscores the value of solute transport modeling as a decision-support tool and serves as a pilot for future applications across other regions of the NGLA.

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CHAPTER 1

INTRODUCTION

This chapter establishes the hydrogeological context of Guam and examines a particular water quality concern. It further elaborates on the project's goals, purpose, and specific objectives, in addition to outlining its scope, limitations, delimitations, and assumptions.

1.1 Northern Guam Lens Aquifer

Guam is geologically divided by the Pågu-Adilok Fault, which separates the southern volcanic terrain from the northern limestone plateau. Beneath the northern plateau lies the Northern Guam Lens Aquifer (NGLA), an unconfined carbonate island karst aquifer composed of highly porous limestone that facilitates the capture, storage, and transmission of groundwater in economically significant quantities. The aquifer is divided into the vadose and phreatic zones. The vadose zone, located above the water table, plays a critical role in facilitating groundwater recharge. The phreatic zone below is fully saturated and contains the freshwater lens that floats atop the denser salt water (Dougher et al., 2019).

1.2 Water Quality Concern

The NGLA supplies over 90% of Guam's utility water, equivalent to approximately 40 million gallons per day (MGD). This vital resource supports the island's residential, military, and tourism sectors, while also sustaining ongoing urban development. As of 2020, Guam's population reached 153,836 (United States Census, 2021), and continued growth is expected to intensify development pressures on both land and water resources. Given the island's strong dependence on the NGLA for its drinking water, managing contamination is important.

The reliance on septic tanks for wastewater disposal is a primary factor contributing to potential groundwater contamination. When improperly maintained, these systems can release nitrate into the subsurface, adding to existing background levels (Figure1.2). McDonald (2002) first documented significantly trends of increasing nitrate-nitrogen levels in production wells two decades ago. More recently, Bulaklak et al. (2020) reported increasing nitrate-nitrogen concentrations in nearly half of 146 production wells. Their study also mapped septic tank densities alongside observed nitrate concentrations and trends, revealing areas of concern.

One area of concern that stands out is the Swamp Road area in Dededo, which was also noted as an area of concern by McDonald (2002). Here, households may be utilizing septic tank systems that range from well maintained and properly functioning, to poorly maintained and malfunctioning, to unmaintained and nonfunctioning, and to non-septic tanks, i.e., septic pits. The combination of unsewered residential areas and nearby production wells makes Swamp Road the chosen study site.

Notably, there are housing developments planned for the area (Parcel Map DLM, 2005). One major topic of debate is whether the new residences should be allowed to use septic tanks or required to connect to sewer lines. There is an acknowledged need to better understand the relative merits of these two alternatives. As a preliminary step, this study focuses on understanding the fate and transport of nitrate-nitrogen from septic systems, along with contributions from other potential nitrate-nitrogen sources.

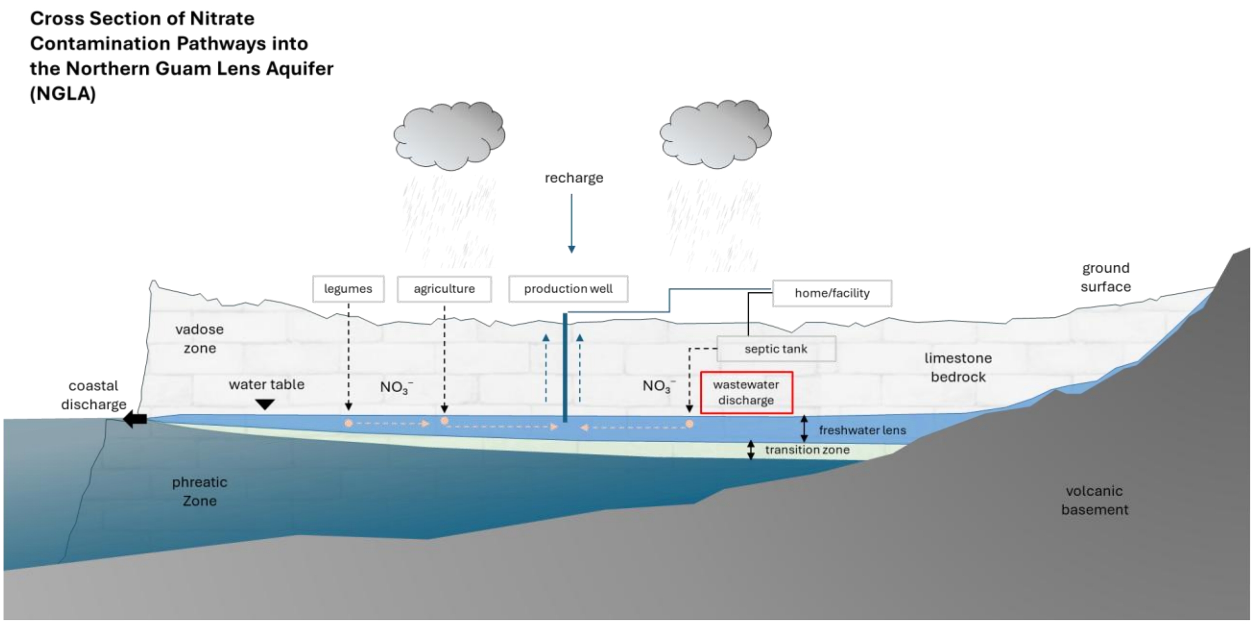

Figure 1.2. A cross-section showing how nitrate (NO_3^-) from potential sources such as legumes, farming, and septic tanks can contaminate production wells by percolating through the vadose zone into the phreatic zone, which contains the freshwater lens.

1.3 Goals, Purpose, and Specific Objectives

The goal of this project is to develop a comprehensive solute transport model for a selected section of the NGLA. The focus is on applying a numerical modeling approach to determine whether observed conditions can be replicated using simulated conditions based on known, measured, or estimated inputs. These include initial and boundary conditions, aquifer parameters, and estimated nitrate-nitrogen flux across the study area.

The resulting model will provide insight into the extent and intensity of nitrate-nitrogen plumes in groundwater and their potential impact on production wells. The outputs will be shared with agency partners and made publicly accessible to stakeholders. Results will serve as a valuable tool for research, land-use planning, and the management of groundwater resources.

The specific objectives for this project are:

1) The collection and organization of pertinent hydrologic and nitrate-N sources data.
2) Development of a 3-D groundwater and solute transport model of the selected domain and model calibration to the existing system.
3) Run modeling scenarios:
   - No-pumping scenario with natural and agricultural sources
   - Pumping scenario with natural and agricultural sources
   - Pumping scenario with natural, agricultural, and septic sources
   - Pumping scenario with natural, agricultural, septic sources, and proposed development

4) Interpret and discuss the results of each scenario.
5) Provide recommendations for future land development and wastewater management strategies based on modeling outputs.

1.4 Scope, Limitations, Delimitations, and Assumptions

1.4.1 Scope

Figure 1.4.1 shows the model domain, which spans from Machananao, Astumbo, Land Trust, and Old South Finegayan to the coast. This site was chosen as one of the recommended places for wastewater modeling, with special attention given to the water concerns mentioned above.

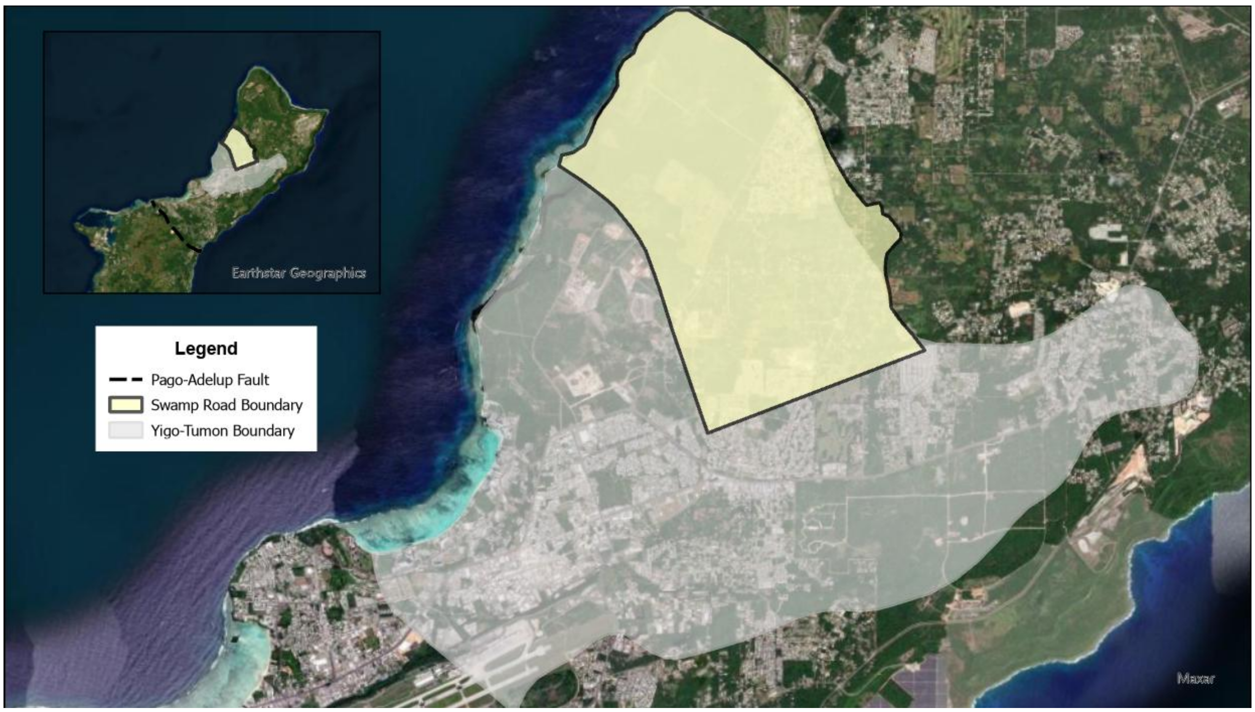

Figure 1.4.1 Geographic extent of the Swamp Road within the Tomhom Aquifer Basin. The model boundary (yellow) lies within the basin boundary (light gray) and is situated north of the Pågo-Adilok Fault.

1.4.2 Limitations

The availability of data is a limitation of this project, as nitrate concentrations were collected semi-annually to annually over the past 30 years and are further constrained by the limited number of wells and the instrumentation used. The model assumes Darcian flow to represent groundwater movement through the karst aquifer, which simplifies flow to behave uniformly through a porous medium. Karst aquifers are characterized by triple porosity, consisting of matrix pores, fractures, and conduits, which create highly variable flow conditions. The hydraulic properties of the limestone cannot be fully determined due to this heterogeneity. As a result, regional hydraulic conductivity values are used in place of local hydraulic conductivity. Additionally, the presence of nitrates in production wells and the occurrence of nitrate sources at the surface represent only an association and do not establish a causal relationship, as there could be confounding factors.

1.4.3 Delimitations

This study is fixed to existing data collected over 30 years, with no additional field data obtained as part of this project. The model simulates nitrate transport from non-sewered residential sources under uniform household loading and contributions from legumes and agriculture.

1.4.4 Assumptions

The following assumptions were made in the development of this model:

- **Groundwater condition:** It is assumed that the aquifer is oxic in which the nitrate-nitrogen remains stable and is not subjected to reduction processes.
- **Wastewater daily discharge:** Wastewater disposal per household is estimated based on an average household size of six people, with daily water use of approximately 60 gallons per person. This estimate is used to calculate the nitrate loading per septic system.
- **Legume daily discharge:** Discharge of legumes were estimated as recharge inputs. For an annual rainfall of 100 inches, it is assumed that 50% infiltrates to the aquifer. The resulting recharge was multiplied by the land area determining the volume per unit time.
- **Agricultural daily discharge:** A similar approach was applied for farming activities, with an additional irrigation input of 0.2 inches per day incorporated in the recharge calculation.

1.5 Benefits

This project will serve as a pilot study for future solute transport modeling to support effective groundwater management in Guam. The results will offer a scientifically informed foundation for land-use planning, regulatory development, alternative wastewater treatment strategies, zoning, and other decision-making processes.

The timing is appropriate for taking preventive action. Although nitrate-nitrogen (nitrate-N) concentrations in production wells remain below the U.S. Environmental Protection Agency's maximum contaminant level (MCL) of 10 mg/L, continued increases could pose a significant risk to public health. While other sewage-related contaminants have not been detected, a more comprehensive understanding of nitrate-N occurrence, spatial distribution, and transport behavior will enhance the ability to identify, predict, and manage risks associated with wastewater contamination.

The numerical solute transport model developed in this study will simulate the formation and migration of nitrate-N plumes. Supplemental benefits include improved understanding of the NGLA, identification of data needs for future monitoring and calibration, and evaluation of the modeling software's suitability for fate and transport applications.

CHAPTER 2

BACKGROUND AND RELATED LITERATURE

The following chapter explains nitrate as groundwater contaminant, summarizes prior studies on nitrates in Guam, and provides context on the modeling platform used.

2.1 Nitrates in Groundwater

Nitrate (NO_3^-) is a key indicator of groundwater contamination. Its concentration is reported as nitrate-nitrogen (NO_3^--N) in milligrams per liter (mg/L), which reflects only the nitrogen portion of the nitrate ion. The occurrence of nitrates in groundwater can be explained through an examination of the nitrogen cycle. Nitrogen (N) is the most abundant element in the atmosphere. However, it cannot be directly utilized by plants or animals. To become biologically available, it must first be transformed into reactive forms such as ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) through processes within the nitrogen cycle like ammonification and nitrification (Almasri, 2007). Not all nitrates are assimilated by plants, and the excess accumulates in soil. Much of this excess is linked to anthropogenic activities that have accelerated the natural rate of nitrogen deposition on land (Ward et al., 2018). Nitrate is highly soluble and weakly retained in soil. It can readily leach below the root zone into aquifers and surface waters. Once introduced into groundwater, it does not volatilize and remains until removed by biological or chemical processes (Oms et al., 2000).

High nitrate concentrations in drinking water pose health risks. In infants, ingestion may lead to methemoglobinemia, or "blue baby syndrome," which reduces the oxygen-carrying capacity of blood. The United States Environmental Protection Agency (EPA) established a maximum contaminant level (MCL) of 10 mg/L NO_3^--N (Ward et al., 2018). The Safe Drinking Water Act required monitoring frequency to be increased if concentrations reach 50% of the MCL (McDonald, 2002).

Given these risks, it is important to identify where nitrate in groundwater comes from. Natural sources include atmospheric deposition, rainfall, and nitrogen fixation by leguminous plants. One example of a leguminous plant that is widespread in northern Guam and grows on the limestone is tangan-tangan (*Leucaena leucocephala*). Nitrate can also enter the system through the breakdown of plant and animal matter, as well as waste from livestock and humans. Human activities add further inputs, with domestic wastewater and septic systems being major contributors. Fertilizer use is another significant source, which is commonly associated with golf courses and agricultural lands (Mink, 1976; McDonald, 2002).

2.2 Related Research

McDonald (2002) applied linear regression and compared the resulting correlation coefficients to critical values to determine which wells exhibited statistically significant trends in nitrate concentrations over time. For wells without significant trends, McDonald evaluated nitrate conditions using average and maximum concentrations across three five-year periods (1986–2000).

Bulaklak et al. (2021) expanded McDonald's analysis by incorporating two additional decades of nitrate data, extending the dataset through 2019. The study refined previously identified trends and introduced a ranking system that categorized wells based on historical nitrate concentrations.

A notable finding was the emergence of plateauing trends in several wells, which marked a shift from the trends reported in McDonald's earlier analysis.

More recently, Valerio et al. (2023) utilized the study done in Bulaklak et al. (2021) to develop an interactive visualization tool known as MAppFx: Northern Guam Lens Aquifer Production Well Nitrates. This platform presents nitrate concentration data as map-based spatial points linked to time-series graphs, allowing for user-friendly assessments of nitrate trends across the NGLA. The MAppFx tool supports interagency collaboration and decision-making by offering accessible insights into groundwater quality conditions.

2.3 Model Platform

Recent technological advancements have improved the simulation of complex groundwater systems. The modeling tools used in this study are the result of early developments by researchers at the United States Army Corps of Engineers and Brigham Young University. These foundational frameworks have since been expanded and refined by Aquaveo (2026), the current developer and maintainer of the Groundwater Modeling System (GMS).

Groundwater Modeling System (GMS) serves as the primary software platform for this work, integrating model packages (e.g., SEAWAT, FEMWATER, MODFLOW) to simulate water flow and solute transport. GMS is a graphical user interface for developing, running, analyzing, and visualizing groundwater models (MODFLOW USG for this case).

As the research progressed, the MODFLOW-USG (USGS, 2017) framework was adopted to construct the solute transport model presented here. MODFLOW-USG was selected for its suitability, which featured unstructured grid that facilitates the representation of complex hydrostratigraphy, transport capabilities, more robust wetting and drying algorithm, and runs seamlessly with the flow model.

CHAPTER 3

METHODOLOGY

This chapter explains the development of the solute transport model to accomplish the objectives and goals mentioned in Chapter 1.

3.1 Model Concept

The conceptual model is modified across the scenarios described in Chapter 1 to capture different nitrate source inputs for pre-development, current, and future land-use conditions. Figure 3.1 corresponds to Scenario 3, representing current land-use conditions with active groundwater withdrawal and nitrate inputs from natural, agricultural, and septic sources.

To represent these inputs spatially, polygons and septic point features were overlaid onto the model mesh to define potential nitrate-loading areas. Production wells were represented by point features corresponding to their geographic locations within the study area. The MODFLOW-USG Wells Package was implemented to assign pumping rates to production wells and simulate nitrate loading by specifying discharge rates and associated concentrations. This approach treated nitrate sources as injection wells, enabling simulation of solute transport processes throughout the aquifer system.

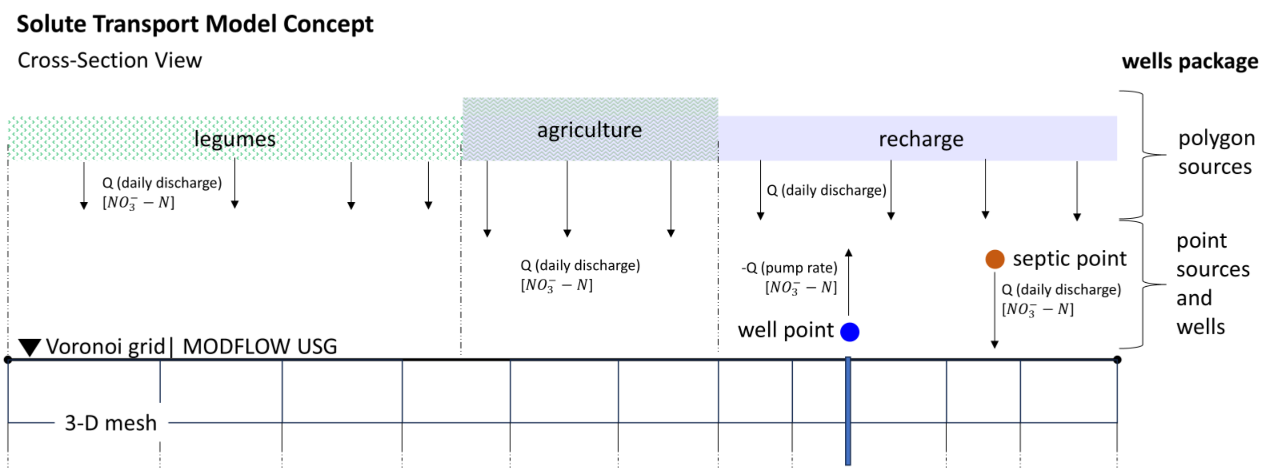

Figure 3.1. This figure presents the conceptual cross-section of the solute transport model representing current land-use conditions (Scenario 3). The diagram illustrates daily discharge (Q) from polygon and point sources under leguminous, agricultural, and recharge areas. Nitrate concentrations (NO_3^-–N) were assigned to these sources, excluding recharge zones. Production wells are shown as withdrawal points (–Q) receiving nitrate from the surrounding field.

3.2 Model Development

This section outlines the procedures and parameters used in constructing the solute transport model, which employs the same modeling approach to that used for the other scenarios. It describes the integration of spatial datasets and the configuration of MODFLOW-USG packages to simulate groundwater flow and nitrate transport.

3.2.1 Data preparation

Esri® ArcGIS Pro was used to collect, process, and prepare spatial datasets required for model development. The datasets incorporated into the model are shown in Figure 3.2.1. Geoprocessing tools within ArcGIS Pro were utilized to edit and organize the data layers before importing them into the model framework.

Production well locations obtained from the Guam Waterworks Authority (GWA) were extracted within the defined model boundary. Data from the Guam Vegetation Landcover dataset (Wen, 2006) were reclassified to identify land-cover types associated with nitrate loading, which served as the polygon source layers. These included leguminous vegetation, limestone forests, shrublands, and grasslands. Agricultural areas were refined through visual interpretation of satellite imagery. All remaining land-cover types not associated as nitrate loading were designated as recharge zones.

Point sources were compiled from the septic tank survey map (Heitz & Habana, 2006) and the non-sewered water meter dataset (Guam Waterworks Authority) and incorporated as septic point features. New housing developments were obtained from the parcel map provided by the Department of Land Management (2005) and were assumed to be served by individual septic systems under Scenario 4.

Each dataset was then assigned relevant hydrologic attributes for model integration. Production wells were assigned their respective pumping rates based on operational records, while approximate daily discharge rates were applied to the identified nitrate source areas.

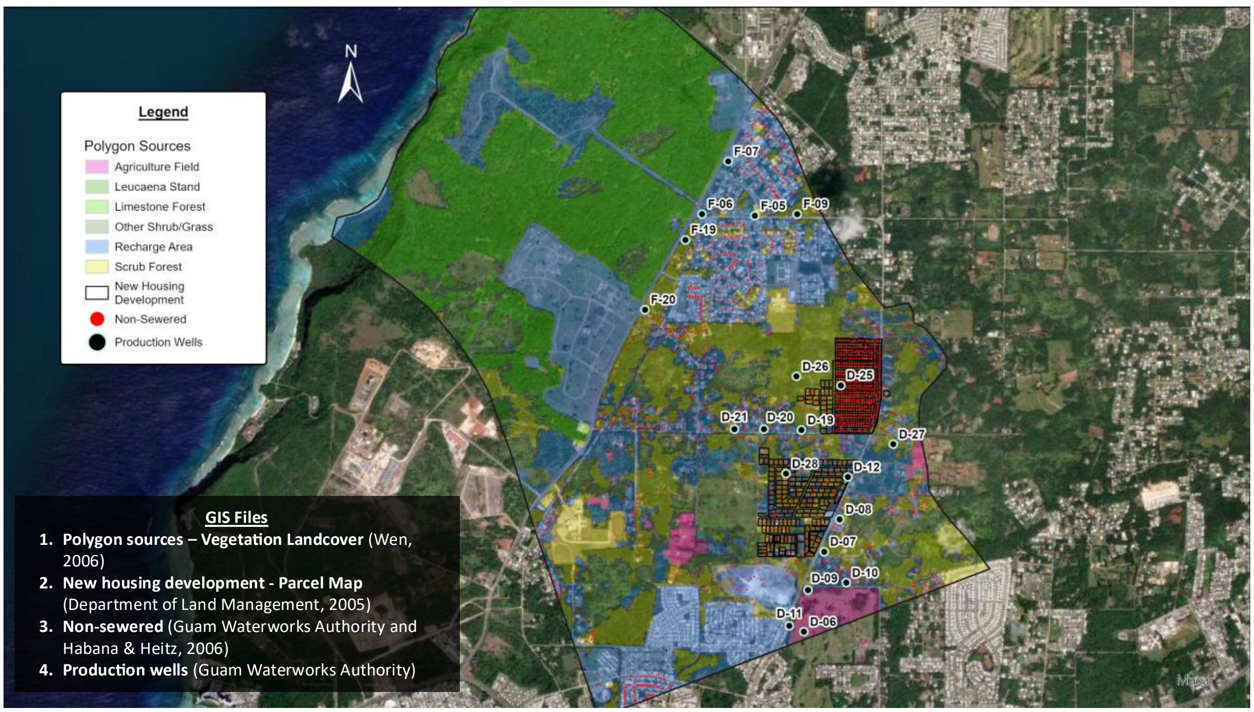

Figure 3.2.1. Spatial distribution of datasets used within the model domain, including vegetation landcover, non-sewered areas, new housing developments, and production wells.

3.2.2 Establishing the solute transport model

The solute transport model was constructed with guidance from Aquaveo's GMS tutorials. These resources are available through the Aquaveo website under Learning > Tutorials > MODFLOW > General and MODFLOW-USG Transport tutorial PDFs. These tutorials provided the foundational procedures for establishing boundary conditions, defining source inputs, and configuring solute transport processes within the MODFLOW-USG application.

3.2.2.1 Grid construction

GMS supports direct integration of spatial data through its compatibility with GIS shapefiles. After importing the necessary files, MODFLOW-USG/USG-Transport was selected as the numerical model to simulate groundwater flow. Multiple coverage layers were created within the conceptual model to define the model domain, boundary conditions, production wells, and nitrate source inputs (both polygonal and point features). Each coverage layer was assigned appropriate settings and mapped attributes. These coverages were consolidated into a single merged coverage and converted into an unstructured grid (UGrid), which was advantageous for mesh refinements around wells and irregular boundaries. The UGrid employed a three-dimensional Voronoi mesh consisting of 19 layers in the vertical (Z) dimension.

3.2.2.2 MODFLOW configuration

The MODFLOW-USG/USG-Transport configuration was initiated following the generation of the UGrid structure. The USG Transport and Transient option was selected to represent stress periods as time intervals. The initial stress period was defined as steady state to establish baseline hydraulic conditions within the aquifer system. To ensure full model functionality, several packages were incorporated, including the Layer Property Flow (LPF), Solver Management (SMS), Block Centered Transport (BCT), Constant Head (CHD1), Recharge (RCH1), and Wells (WEL1) packages.

Following the setup of MODFLOW-USG/USG-Transport, the aquifer setting was defined. Elevation data for the Yigo–Tumon basin was interpolated from scattered topographic points and applied to the model domain to represent the area profile. The merged coverage was then mapped onto the MODFLOW domain. To initialize hydraulic conditions, a uniform starting head of 0.5 m was assigned in the global options. Hydraulic properties were then specified in the LPF package based on regional aquifer characteristics. These parameters included a horizontal hydraulic conductivity of 7,000 m/day, vertical anisotropy of 70, horizontal anisotropy of 1.0, specific storage of 0.0001, and specific yield of 0.1. The cell wetting option was enabled to allow simulation of dynamic fluctuations in the water table under transient conditions.

After establishing the hydraulic framework, the solute transport configuration was developed to simulate nitrate migration within the aquifer system. The BCT package was implemented to represent nitrate transport, incorporating both advection and dispersion processes. Dispersivity parameters were set to 61.0 m longitudinal and 18.3 m transverse, which is consistent with limestone aquifer values reported by Istok (1989). Initial nitrate concentrations at identified source zones were assigned to a baseline value of 0.0001 mg/L. Within the Wells Package, an auxiliary variable (AUX) labeled "C01" was created to store nitrate concentration data. The corresponding concentration values were then specified under the "C01" column for each respective nitrate source. Upon finalizing all configurations, the model was run.

3.3 Model Calibration

The model was calibrated (matched) using the MAppFx Production Well Nitrate-N platform (Valerio et al., 2023). Nitrate inputs under the AUX variable “C01” were adjusted until simulated concentrations matched observed values at production wells. The calibrated model provides a reliable basis for assessing nitrate transport and evaluating scenarios within the aquifer system.

3.4 Scenarios

Four simulation scenarios were developed to evaluate the impact of varying nitrate source inputs associated with pre-development, current, and projected future land-use conditions. Each scenario incorporated distinct nitrogen loading configurations to facilitate the analysis of nitrate transport dynamics and their effects on groundwater quality. The scenarios included:

Scenario 1: Agriculture and Natural Conditions
This scenario represents pre-development conditions, which incorporates agricultural activities and natural nitrogen sources. Production wells are turned off, and no septic sources were introduced.

Scenario 2: Agriculture and Natural Conditions with Wells On
Building on Scenario 1, this scenario introduces active production wells to simulate groundwater extraction.

Scenario 3: Agriculture, Natural Conditions, Septic Sources, and Wells On
This scenario expands upon Scenario 2 by introducing septic systems as additional nitrate sources. With production wells operating and septic inputs included, it represents present-day land-use conditions.

Scenario 4: Agriculture, Natural Conditions, Septic Sources, Wells On, and New Development

Scenario 4 expands on Scenario 3 by adding new residential or commercial areas that use septic systems. This setup helps evaluate how increased septic input could affect groundwater quality when combined with current conditions.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and interprets the results of the nitrate-N solute transport model for the Swamp Road study area, based on the scenarios developed in Chapter 3.

4.1 Model Output Interpretation

The model output for each scenario is presented as a plan view, with nitrate concentrations ranging from 0 mg/L (light blue) to 5 mg/L (purple), shown on the upper-left side of each figure. A summary box beside each figure outlines key scenario parameters. The MAppFx data visualization tool (Valerio et al., 2023) displays observed nitrate trends and concentrations from Bulaklak et al. (2020), as discussed in Chapter 2, and is used to compare modeled results with observed statistical trends. Nitrate trends are represented as follows: an upward-pointing triangle denotes a significant increasing nitrate trend, a downward-pointing triangle illustrates a significant decreasing nitrate trend, and a circle indicates no significant change.

4.2 Scenario 1: Agriculture and Natural (No Pumping)

Scenario one simulates conditions with natural and agricultural nitrogen loading and no groundwater pumping. Results shown in Figure 4.2. indicate ambient N-nitrate concentrations of about 1–2 mg/L where legumes or agriculture are present. Areas with near-zero concentrations reflect locations with no N-nitrate inputs and only natural recharge, representing conditions prior to the use of septic systems.

4.3 Scenario 2: Agriculture and Natural (Pumping On)

Scenario two builds upon Scenario one by introducing active groundwater withdrawal. It does not show difference in concentration, as illustrated in Figure 4.3a. However, a map comparing the two scenarios is provided in Figure 4.3b. The map indicates a minor change, with a maximum difference of approximately 0.1 mg/L occurring within the area highlighted by the red circle. This slight reduction may reflect a dilution effect induced by pumping being turned on. However, the influence is spatially limited and does not produce measurable changes across the broader model domain.

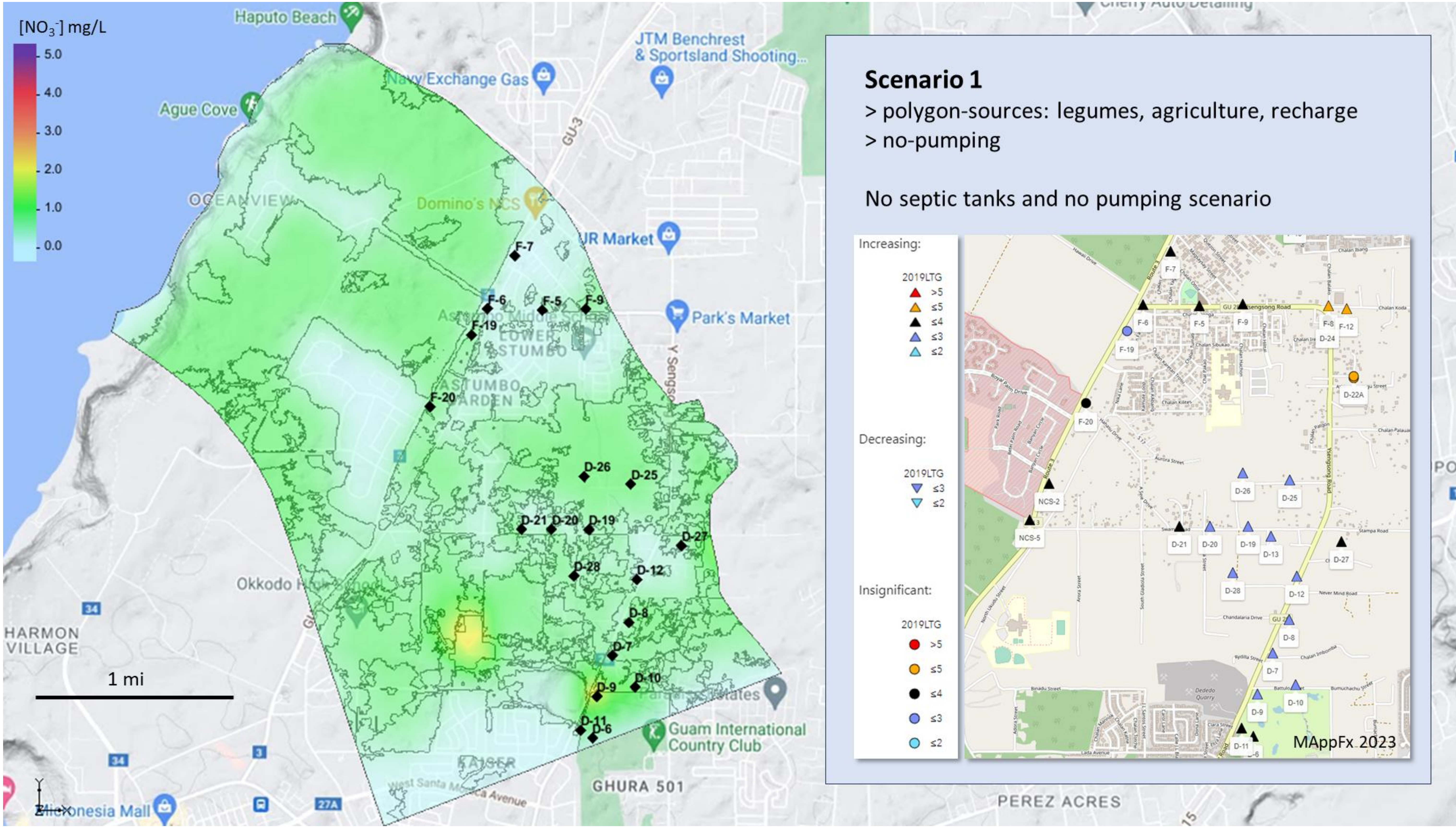

Figure 4.2. Plan view showing the modeled results for Scenario 1, which simulates nitrate discharge from natural and agricultural sources with no groundwater pumping.

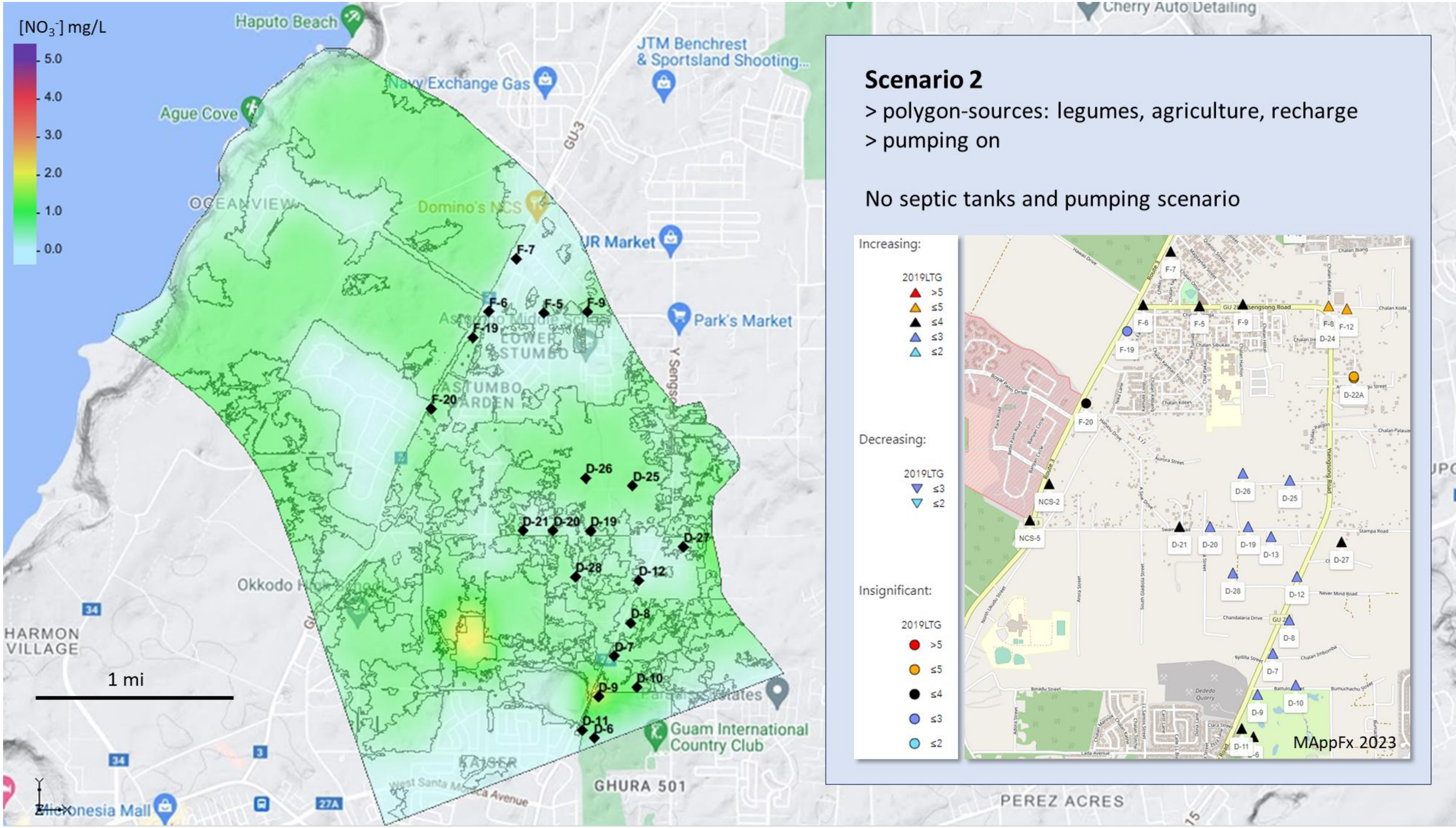

Figure 4.3a. Plan view showing the modeled results for Scenario 2 with pumping enabled. The outcome produced similar concentrations to those observed in Scenario 1.

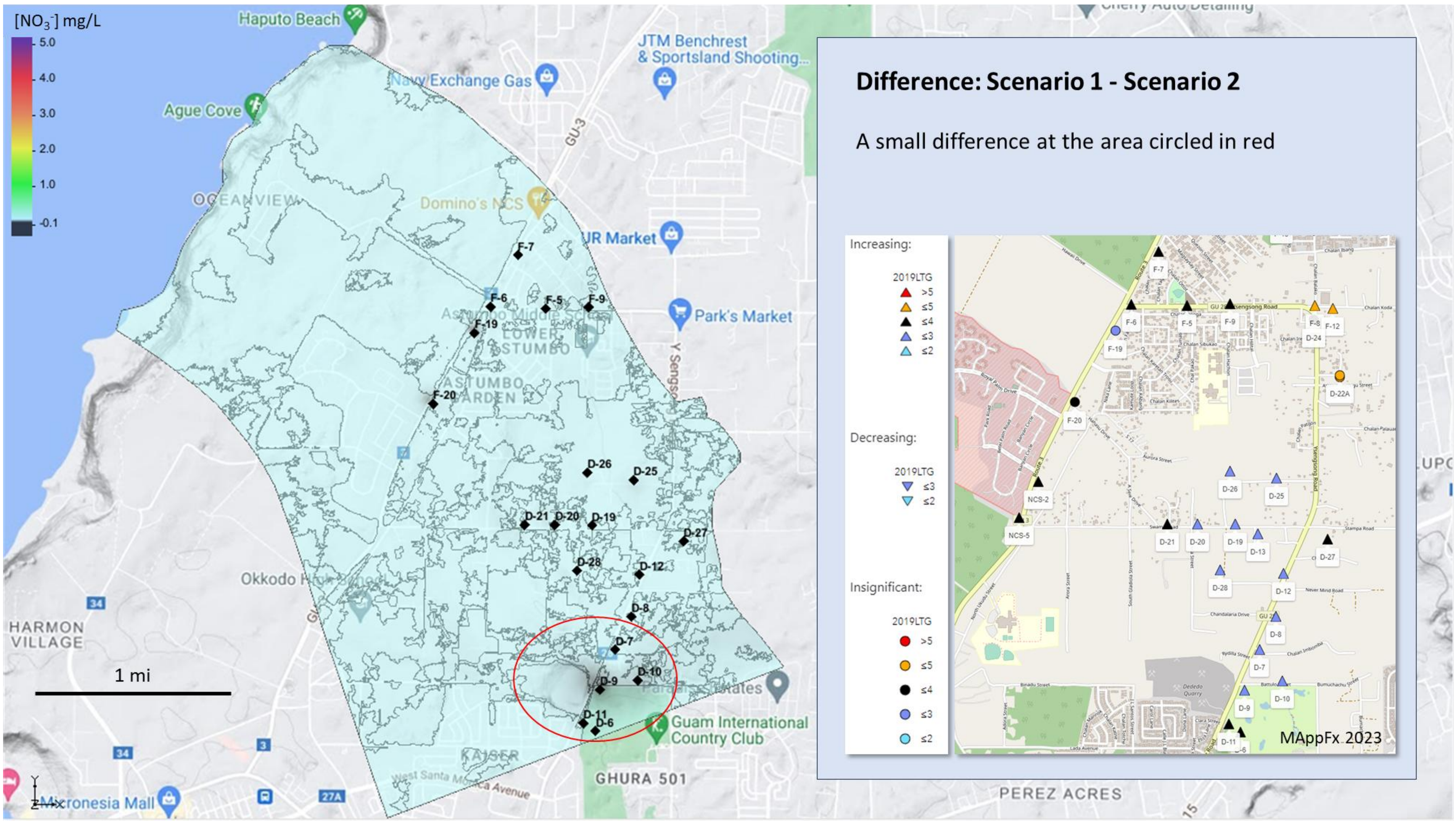

Figure 4.3b. Displays the difference between Scenarios 1 and 2, revealing a change of about 0.1 mg/L in the area circled in red.

4.4 Scenario 3: Agriculture, Natural, and Septic (Pumping On)

Scenario three builds upon Scenario two by incorporating septic tanks as an additional nitrate source. As shown in Figure 4.4a, the nitrate plume displays a distinct green-to-red-to-purple hotspots. These hotspot zones align with areas where septic systems are more concentrated, indicating elevated nitrate loading.

A closer review of the D-series production wells in Figure 4.4b indicates that most wells are consistent with observed groundwater trends reported in MAppFx, where nitrate-N concentrations are typically ≤3 mg/L. However, wells D-7, D-8, D-6, D-11, and D-27 show discrepancies between modeled and observed concentrations. MAppFx data indicate that wells D-6, D-11, and D-27 have observed nitrate-N concentrations of ≤4 mg/L, whereas the model simulates lower concentrations of 1.0 mg/L at these locations. In contrast, wells D-7 and D-8 exhibit observed concentrations of ≤3 mg/L, while modeled concentrations are elevated, reaching 4–5 mg/L.

Another area of interest includes the F-series production wells, with modeled results shown in Figure 4.4c. Observed nitrate-N concentrations are generally ≤4 mg/L, whereas modeled concentrations at nearby wells are approximately 1–2 mg/L. A high-concentration hotspot near the top of Figure 4.4c is attributed to clustered non-sewered water meter data from GWA, which results in a misrepresentation of nitrate loading and elevated simulated concentrations. Further refinement of nitrate loading inputs is warranted.

4.5 Scenario 4: Scenario 3 and New Development Plan

Scenario four addresses a key question raised by Ms. McDonald regarding the use of septic systems in a planned residential development within Swamp Road. This simulation incorporates newly proposed residential parcels, where the top portion of the study area is one-eighth acre lot and the bottom portion is 0.44-acre lot (less than half an acre), as shown in Figure 4.5a. This scenario applies the same parameters used in Scenario 3, with the additional assumption that each parcel is served by an individual septic system.

Results presented in Figure 4.5b indicate that increased housing density poses a significant threat to groundwater quality. Nitrate-N concentrations reach up to 5.0 mg/L in areas with one-eighth acre lot and up to 4.0 mg/L in areas with 0.44-acre lot. These results highlight the strong influence of residential density and septic system on nitrate loading to the aquifer.

Figure 4.5c shows the 1,000-ft buffer zones around production wells and the difference in modeled results between Scenarios 3 and 4. Buffer zones are intended to limit surface activities within 1,000 ft of each well. However, these zones are not enforced, as indicated by the presence of existing non-sewered residential development within the buffer areas. An exception is observed at well D-26, where the buffer zone illustrates the effectiveness of maintaining adequate separation distances between production wells and surrounding land-use activities.

Moreover, the comparison between Scenarios 3 and 4 demonstrates the effect of introducing septic systems within the proposed residential parcels, which may lead to increased simulated nitrate-N concentrations at production wells D-7, D-12, D-25, and D-28. These results suggest increased vulnerability of production wells to contamination and highlight the need to consider alternative wastewater management strategies for residential parcels with lot sizes of one-eighth acre and less than one-half acre.

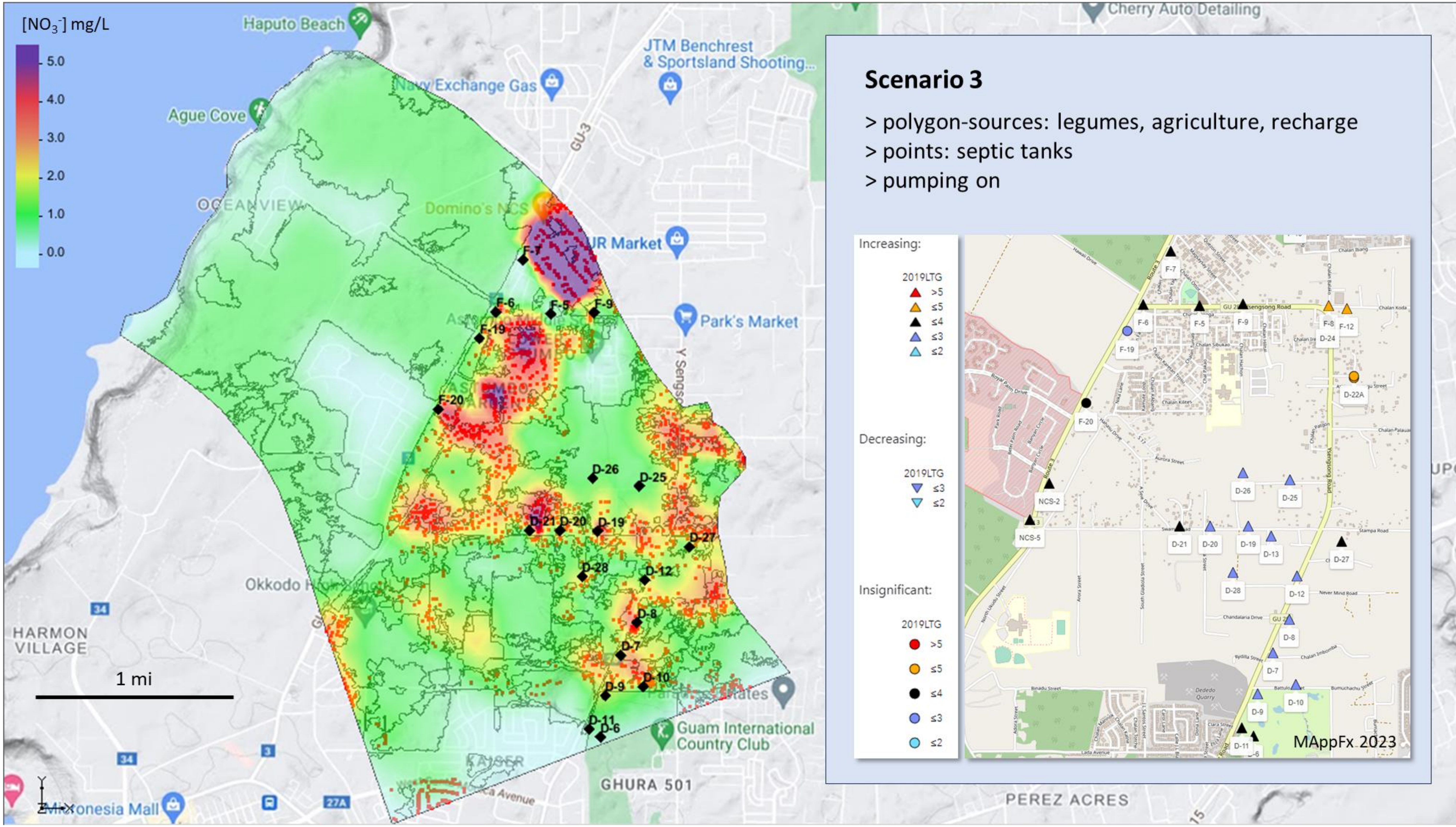

Figure 4.4a. Plan view showing the modeled results for Scenario 3, in which septic tanks are included as an additional nitrate source.

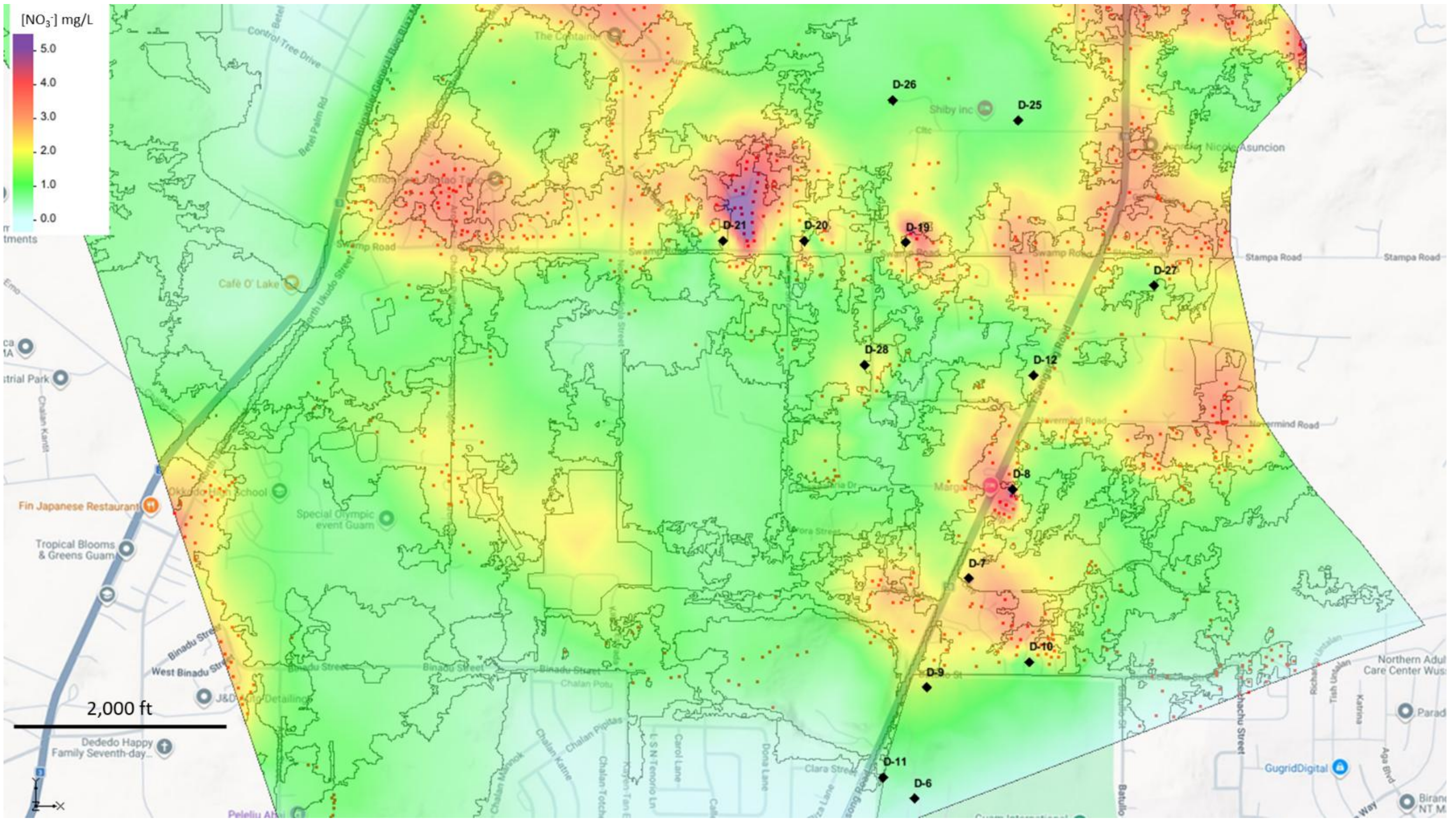

Figure 4.4b. A close-up view of nitrate-N concentrations near the D-series wells.

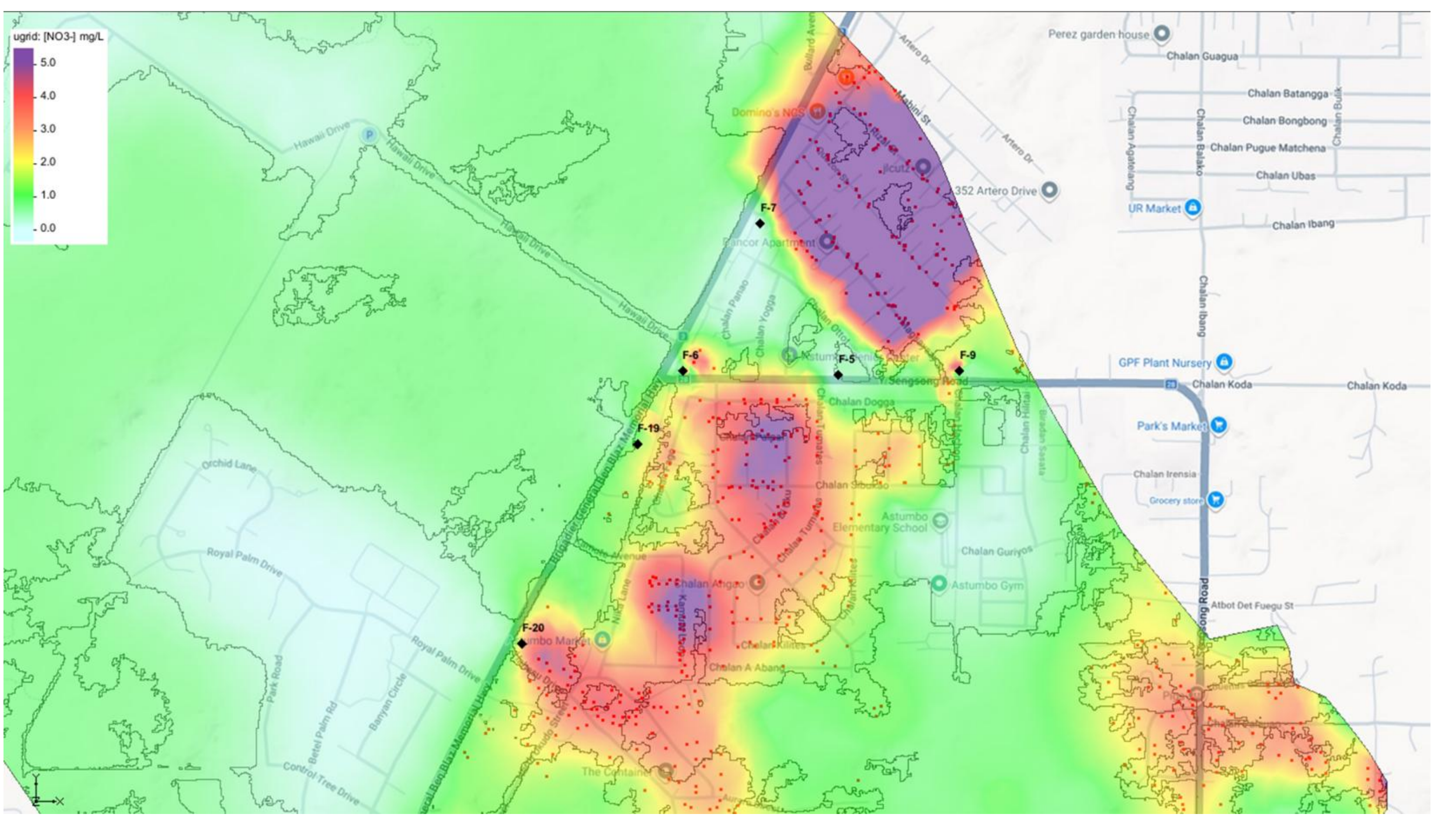

Figure 4.4c. A close-up view of nitrate-N concentrations near the F-series well.

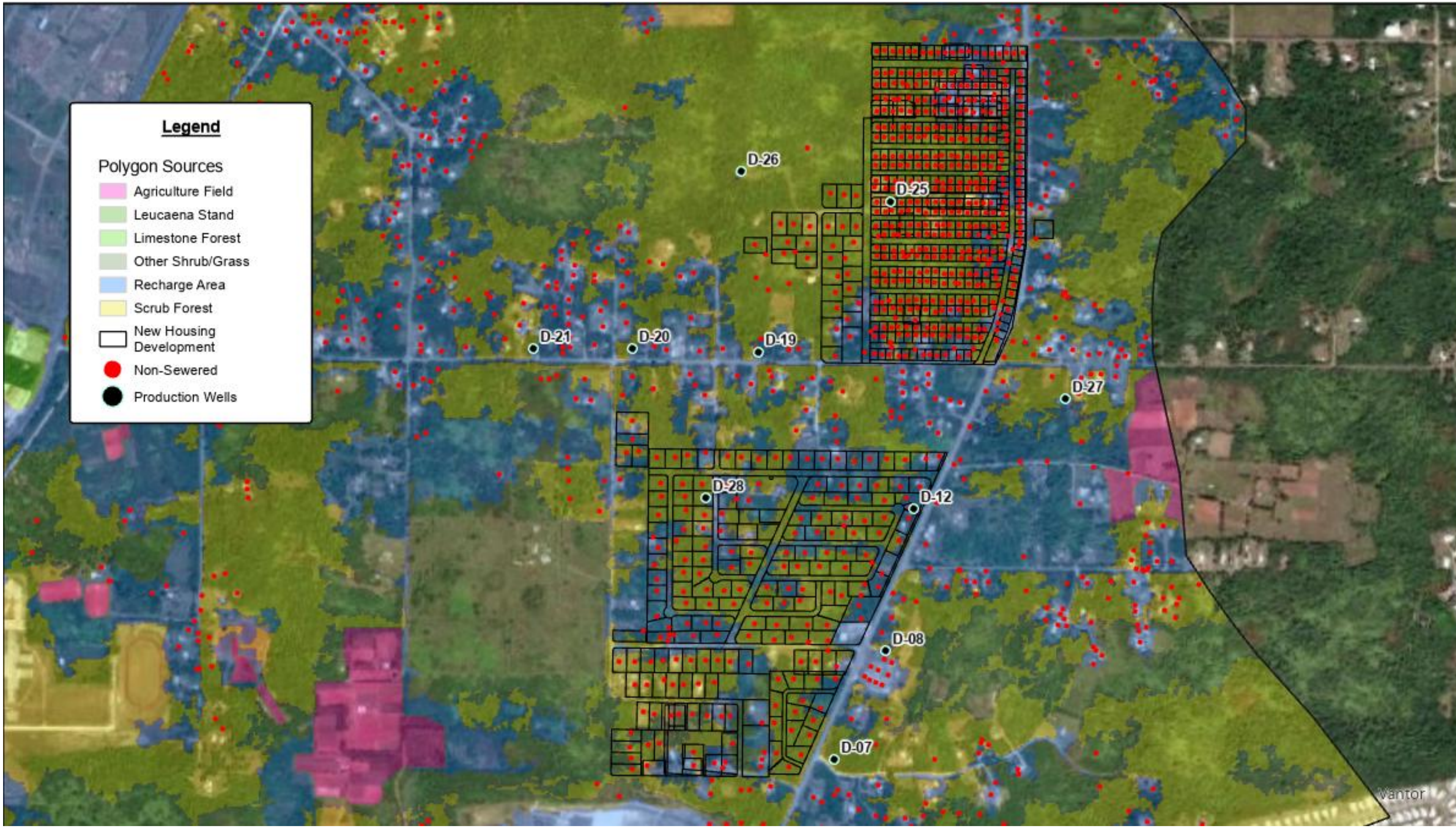

Figure 4.5a. Proposed residential parcels within the study area, with one-eight-acre lots shown in the upper region and 0.44-acre lots (less than one-half acre) shown in the lower region. Each parcel is assumed to be served by an individual septic system.

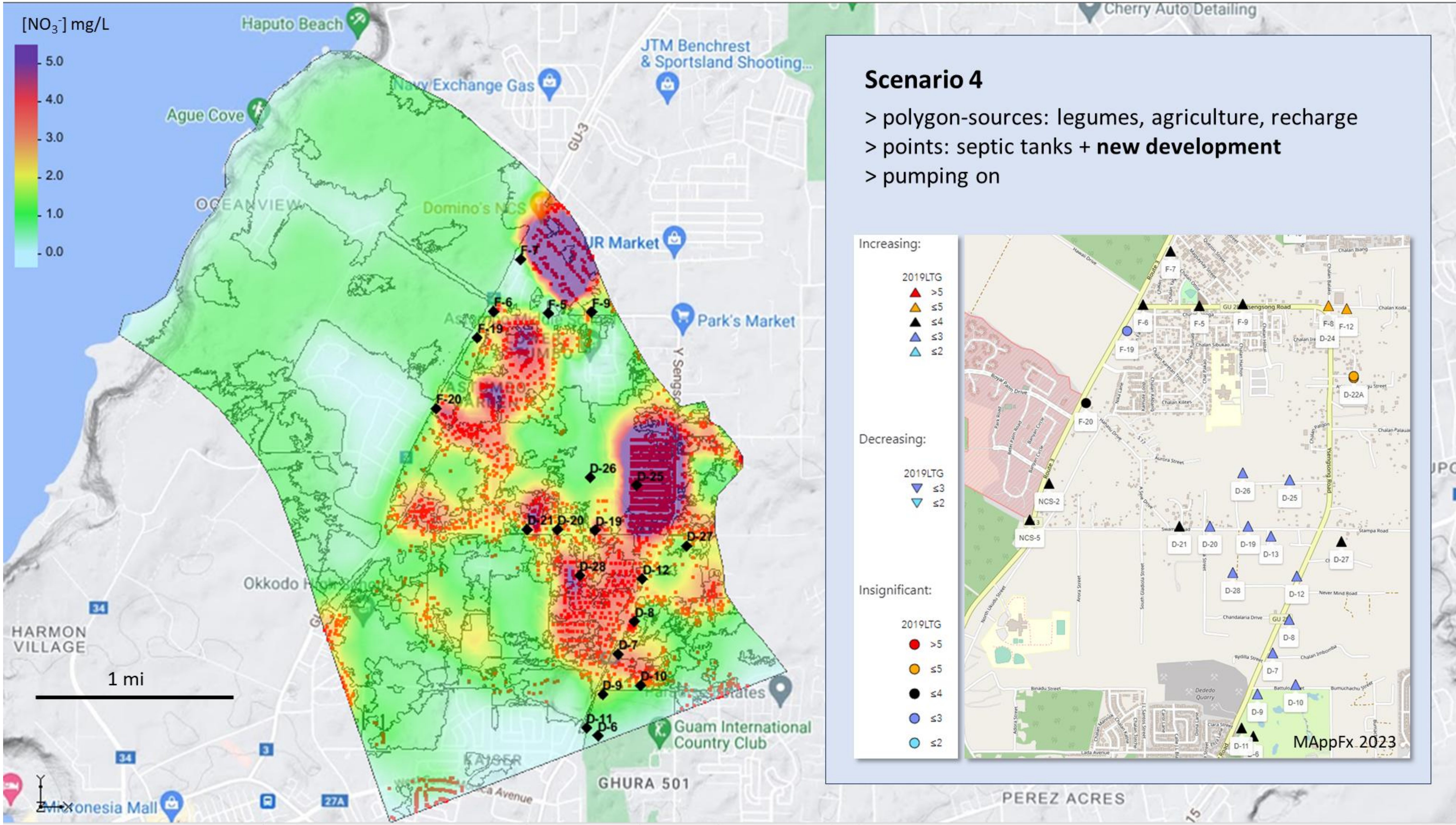

Figure 4.5b. Plan view showing the modeled results for scenario 4, which evaluates the effects of septic system use in a planned residential development within the Swamp Road area.

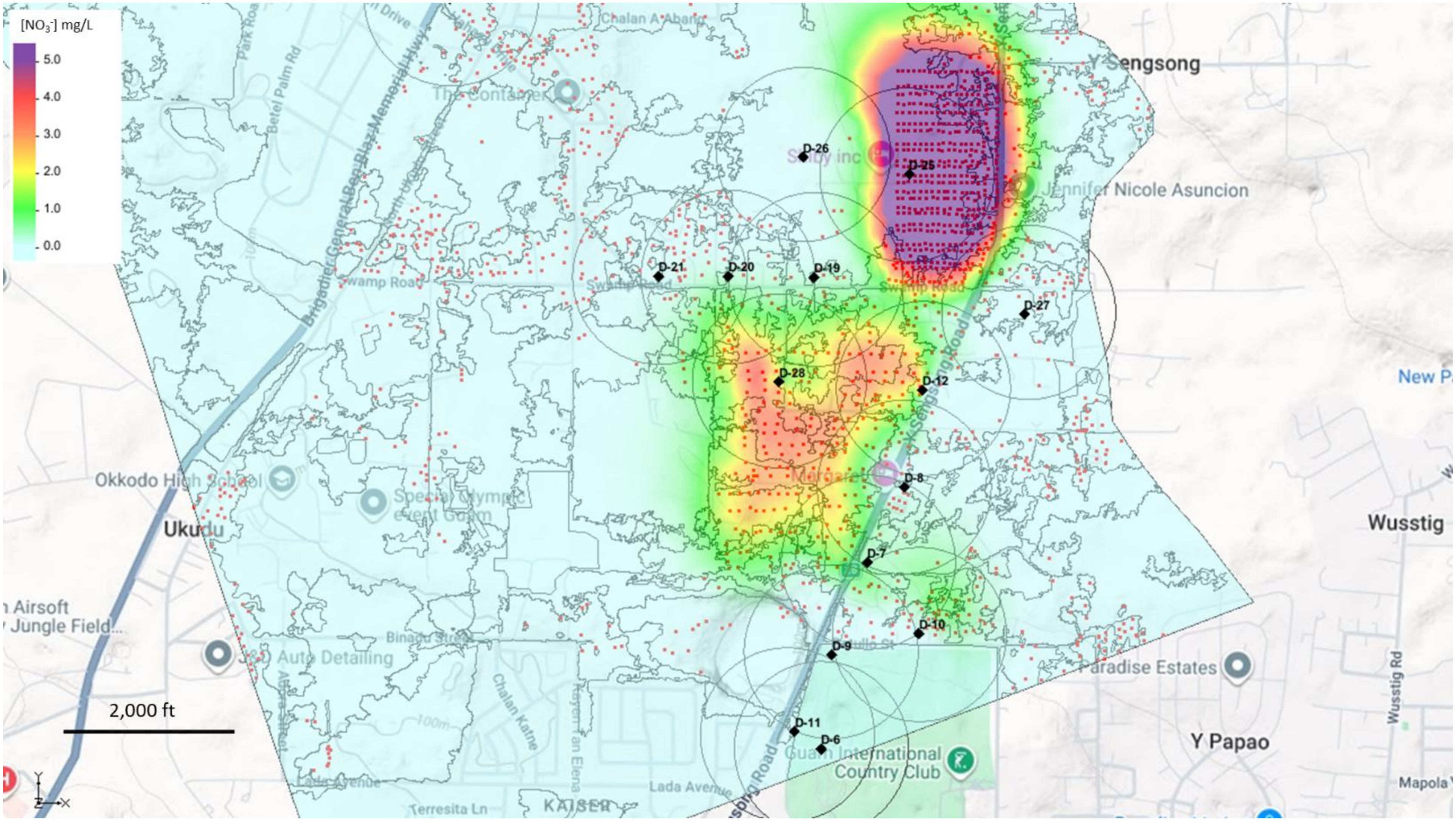

Figure 4.5c. Close-up view of the 1,000-ft buffer zones around the D-series production wells and the difference in modeled results between Scenarios 3 and 4.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This study presents the first comprehensive solute transport model of nitrate contamination in Guam's aquifer system, addressing critical knowledge gaps in groundwater management. The model meets the study's objectives and provides insight into how land use and wastewater practices influence groundwater quality. This chapter summarizes the key findings and presents recommendations for future research and policy considerations.

5.1 Conclusion

Scenario one simulates conditions influenced by natural and agricultural nitrogen sources, resulting in nitrate-N concentrations ranging from 1 to 2 mg/L. These concentrations are primarily associated with leguminous vegetation and agricultural activity. Scenario two builds upon Scenario one by incorporating groundwater pumping and results in only minor changes in nitrate-N concentrations (approximately 0.1 mg/L), indicating limited dilution associated with induced flow.

Scenario three reflects current development conditions and exhibits localized nitrate-N hotspot zones associated with areas served by septic systems. Scenario four incorporates high-density residential housing based on parcel data and assumes continued reliance on individual septic systems. Under this scenario, nitrate-N loading increases markedly, particularly near production wells, where simulated concentrations rise by up to 5 mg/L at vulnerable locations such as well D-25. Additionally, maximum simulated concentrations reached approximately 18 mg/L under Scenarios 3 and 4, in the 1/8-acre lot division.

5.2 Future Directions and Recommendations

This study demonstrates the influence of septic systems on nitrate-N concentrations in groundwater, particularly under high-density development areas. While centralized or advanced wastewater treatment systems may reduce localized nitrates compared to septic systems, wastewater effluent is still discharged into the water source. Nitrate treatment systems may lead to the perception of reduced wastewater impacts to the freshwater source.

As discussed in Chapter 1, the model is subject to limitations that warrant further refinement. Results from this study highlight the need for updated datasets, particularly land-cover data, which are currently outdated and may not accurately represent present-day conditions. In addition, non-sewered Guam Waterworks Authority (GWA) data are derived from water meter locations and may lead to overestimation of nitrate loading in areas where meters are spatially clustered. Future model improvements should prioritize refinement of datasets to enhance model reliability and strengthen its application as a decision-support tool for groundwater management and land-use planning. This modeling approach can be extended and adapted for application in the Yigo–Tumon Basin.

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