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Solute Transport Model of the Tomhom Aquifer Basin, Northern Guam Lens Aquifer

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WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
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WERI Modeling Team

Jovic A. Caasi and Dr. Nathan C. Habana

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WERI Hydrology Lab

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) is Guam's primary drinking water source, with the Tomhom Aquifer Basin producing approximately 20 million gallons per day. Historical monitoring has shown increasing nitrate-N trends in production wells. A three-dimensional nitrate-N solute transport model of the Tomhom Basin was developed in Aquaveo's Groundwater Modeling System (GMS) using MODFLOW-USG/USG-Transport. The model integrates known and estimated parameters for aquifer properties, site hydrology and hydrogeology, and nitrate-N sources and transport. Three scenarios were simulated to visualize nitrate-N transport through groundwater, with emphasis on evaluating the potential impact of septic-system wastewater discharge on production wells. Simulated nitrate-N concentrations were compared with observed well concentrations. Results show the distribution and extent of nitrate-N plumes throughout the basin, with higher concentrations associated with greater septic-system density and plumes migrating toward nearby production wells. These results provide insight into the potential influence of septic wastewater on groundwater quality and may help refine regulations for development near production wells and septic-system density limits. The model provides stakeholders with a visualization tool to guide wastewater management, land-use planning, and protection of Guam's drinking water resources.

Keywords: Northern Guam Lens Aquifer, nitrate-N, solute transport model, Tomhom Aquifer Basin

Contents

FIGURES

1 INTRODUCTION

The Northern Guam Lens Aquifer (NGLA) is Guam's major utility water source, with the Tomhom Aquifer Basin as its largest productive basin, supplying approximately 20 MGD of groundwater (Zapata et al., 2024). With many production wells located within the basin, increasing nitrate-N concentrations are an important groundwater quality concern.

1.1 Water Quality Concern

Most of Guam's residential, commercial, military, and tourism-related development is atop the NGLA, increasing the potential for contaminating the aquifer. Increasing nitrate-N concentrations in production wells were documented by McDonald (2002) and Bulaklak et al. (2020) reported increasing concentrations in about half of 146 production wells. These impacts were attributed to direct discharge of wastewater into the aquifer such as leaky/overflowed sewer lines and dense use of septic systems and pits. Advisory council had requested the application of solute transport model analysis. Bautista et al. (2026) applied a nitrate-N solute model of the Swamp Road as a pilot study. The same analysis will be applied to the Tomhom Aquifer.

1.2 Goals, Purpose, and Specific Objectives

The goal is to expand the pilot study to the Tomhom Aquifer. The purpose is to visualize wastewater transport simulation into the groundwater for insights into the impact. The specific objectives were to:

1) collect and organize model inputs such as hydrologic and nitrate-N source data
2) develop a nitrate-N solute transport model for the Tomhom Aquifer and match with production well concentrations
3) conduct nitrate-N transport scenarios:
   - no production wells pumping, only natural and agricultural sources
   - pumping, and natural and agricultural sources
   - pumping, and natural, agricultural, and septic sources
4) evaluate and interpret the results of each modeling scenario and provide recommendations based on modeling outputs.

The scope is the Tomhom Aquifer Basin and the nitrate sources are from residential, agriculture, and legumes. Limitations, delimitations, and assumptions are the same as the pilot study.

1.3 Benefits

This model provides groundwater utility stakeholders information about nitrate-N within the Tomhom Basin. The results are insightful for determining areas that require attention such is the case for residential density and the need for treatment/development to reduce wastewater contamination of the sole source aquifer.

2 BACKGROUND AND RELATED LITERATURE

Understanding nitrate-N occurrence in the Northern Guam Lens Aquifer requires consideration of its sources, transformation, and transport, as well as observed trends in production wells. Previous research, including the Swamp Road pilot model, provides the scientific and modeling foundation for evaluating nitrate-N movement within the Tomhom Basin.

2.1 Nitrates

Nitrate (NO_3^-) is an indicator of wastewater contamination in groundwater, often reported as nitrate-nitrogen (NO_3^--N), mg/L or ppm. Routine sampling from Guam production wells are conducted quarterly. Over ingestion may result in methemoglobinemia, or "blue baby syndrome." USEPA set nitrate-N to 10 mg/L, MCL, in drinking water (Ward et al., 2018). Under the Safe Drinking Water Act, monitoring frequency increases when nitrate concentrations reach 50% of the MCL (McDonald, 2002).

The occurrence of nitrate in groundwater is a result of the nitrogen cycle, including amino acids and urea. McDonald (2002) identified sources that contribute to groundwater nitrate, including atmospheric deposition, nitrogen fixation by leguminous vegetation such as tangan-tangan (*Leucaena leucocephala*), fertilizer application, decomposition of plant and animal matter, livestock waste, and domestic wastewater. Nitrogen from these sources may be transformed through ammonification to ammonium and subsequently converted to nitrate through nitrification (Almasri, 2007).

Some nitrate is taken up by plants; however, excess nitrate may accumulate in the soil when nitrogen inputs exceed plant uptake, particularly in areas affected by anthropogenic activities. Because nitrate is highly soluble and weakly retained by soil, it can readily leach from the root zone into groundwater, where it remains relatively stable under oxic conditions until removed through biological or chemical processes (Oms et al., 2000).

2.2 Related Research

Several studies have contributed to the understanding of nitrate occurrence and trends within the NGLA. McDonald (2002) evaluated nitrate concentrations in production wells using linear regression to identify significant trends over time. Bulaklak et al. (2020) expanded this work by incorporating two additional decades of monitoring data and developing a ranking system to classify wells based on historical nitrate concentrations. Valerio et al. (2023) developed the *MAppFx: Northern Guam Lens Aquifer Production Well Nitrates*, an interactive visualization tool integrating production-well locations with time-series nitrate concentration data. As mentioned in Section 1, this research applies the pilot study modeling approach to the Tomhom Aquifer Basin.

3 METHODS

This section follows the modeling approach established in the Swamp Road pilot study, with refinements to the GIS datasets used to represent nitrate-N sources. These refinements include updates to land-cover and residential septic-system locations within the Tomhom Aquifer Basin.

3.1 Model Development

The model simulated the three nitrate-N transport scenarios described in Section 1 and refined the GIS input datasets used to define nitrate-N source areas. The preparation and refinement of these datasets are described in the following section.

3.2 Data Preparation

The GIS datasets incorporated into the model are summarized in Figure 3.1. The Guam Vegetation Land Cover dataset (Wen, 2006) was reviewed using recent satellite imagery and reclassified to identify land-cover types representing potential nitrate-N sources, including Leucaena stands, limestone forest, shrubland/grassland, scrub forest, and agricultural areas. All remaining land-cover types were designated as recharge zones: developed areas, buildings, housing, and roads.

Point source data were compiled from the septic tank survey map (Heitz & Habana, 2006) and the Guam Waterworks Authority (GWA) non-sewered water meter dataset and represents residential nitrate-N loading from septic systems. The datasets were reviewed to assess the spatial distribution of septic systems and identify duplicate records. Some residential properties were represented in both datasets, which would have resulted in duplicate septic sources and an overestimation of nitrate-N loading.

The point source dataset was refined using Google Earth and Street View. The GWA non-sewered water meter dataset was the main source to assign septic system points to each household. The septic tank survey map was used to verify existing septic system locations and identify duplicate records. Apartment buildings, commercial properties, and golf courses were excluded as their occupancy and water use vary.

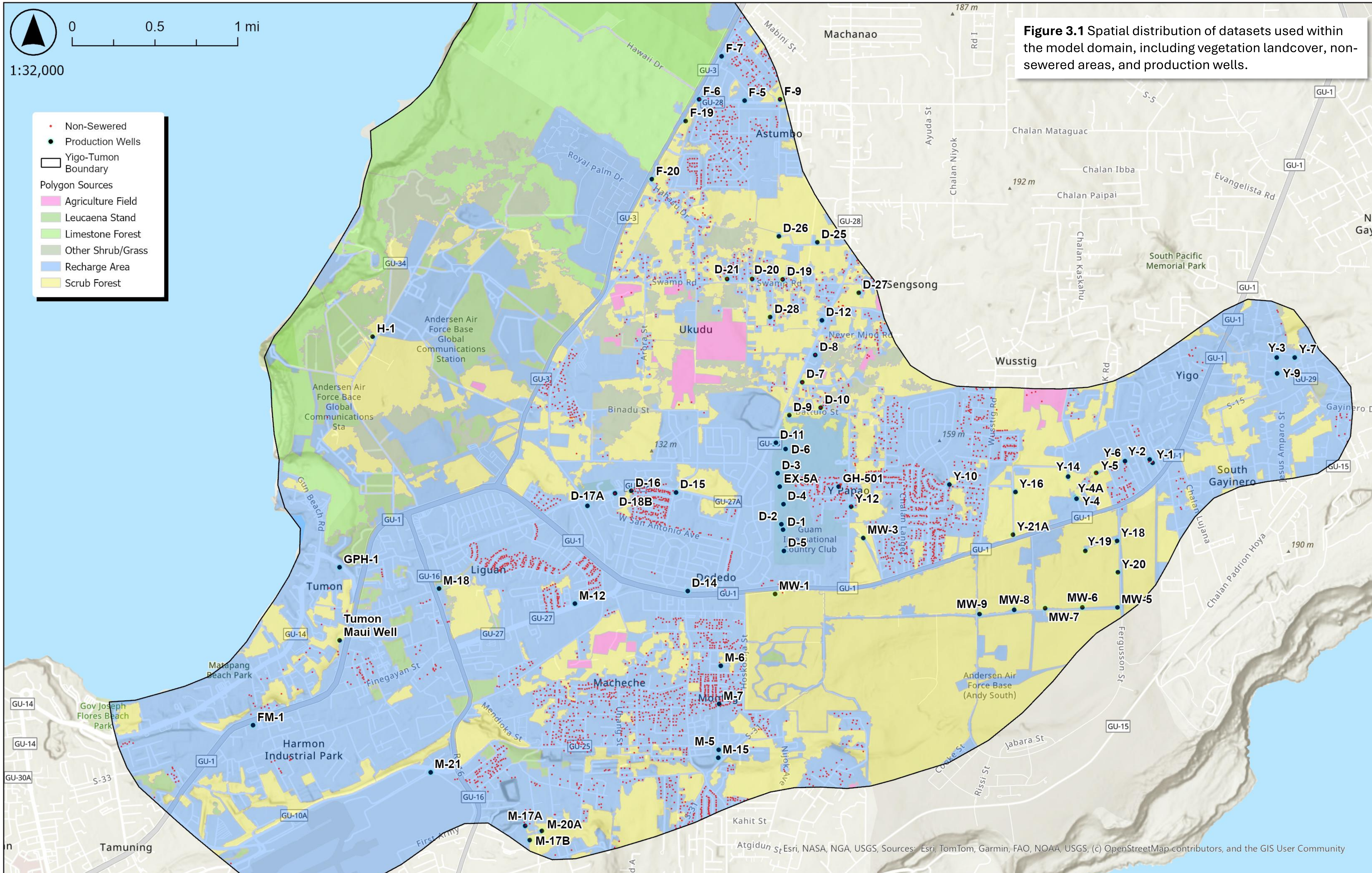

Figure 3.1 Spatial distribution of datasets used within the model domain, including vegetation landcover, non-sewered areas, and production wells.

4 RESULTS AND DISCUSSION

Model results are presented by scenario, with plan-view showing the spatial distribution of simulated nitrate-N concentrations throughout the Tomhom Aquifer. Concentrations range from 0 mg/L (white) to 6 mg/L (purple), with scenario parameters summarized in each figure. Observed nitrate-N trends from Bulaklak et al. (2020), represented by the Linear Trend Group (LTG), are included for comparison with simulated concentrations. Production wells with significant increasing trends are shown as upward-pointing triangles and classified by observed nitrate-N concentration: cyan (≤2 mg/L), blue (≤3 mg/L), black (≤4 mg/L), orange (≤5 mg/L), and red (>5 mg/L).

4.1 Scenario 1: Agriculture and Natural (No Pumping)

Scenario 1 represents natural and agricultural nitrogen loading under conditions without groundwater pumping. Results shown in Figure 4.2 indicate simulated nitrate-N concentrations of approximately 1 mg/L in areas with leguminous vegetation and agricultural activity. Concentrations near 0 mg/L occur in areas without nitrate-N inputs, with recharge only. This scenario provides a baseline for groundwater conditions prior to the influence of septic systems.

4.2 Scenario 2: Agriculture and Natural (Pumping On)

Scenario 2 builds upon Scenario 1 by incorporating active groundwater withdrawal. As shown in Figure 4.3, nitrate-N concentrations remain largely unchanged. However, elevated nitrate-N concentrations remain concentrated around agricultural areas in both scenarios.

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

Scenario 3 builds upon Scenario 2 by adding septic systems as a source of nitrate-N loading. Figure 4.4a shows distinct nitrate-N hotspot zones throughout the basin, representing a noticeable shift from the relatively uniform concentration patterns observed in the previous scenarios. These elevated concentration areas generally correspond to locations with higher densities of septic systems.

Figure 4.4b provides a closer view of the northern portion of the basin to compare between the simulated nitrate-N concentrations and the nitrate-N trends reported by Bulaklak et al. (2020). The results show similarities between the model results and observed nitrate-N concentrations within this area. F series wells have observed nitrate-N concentrations

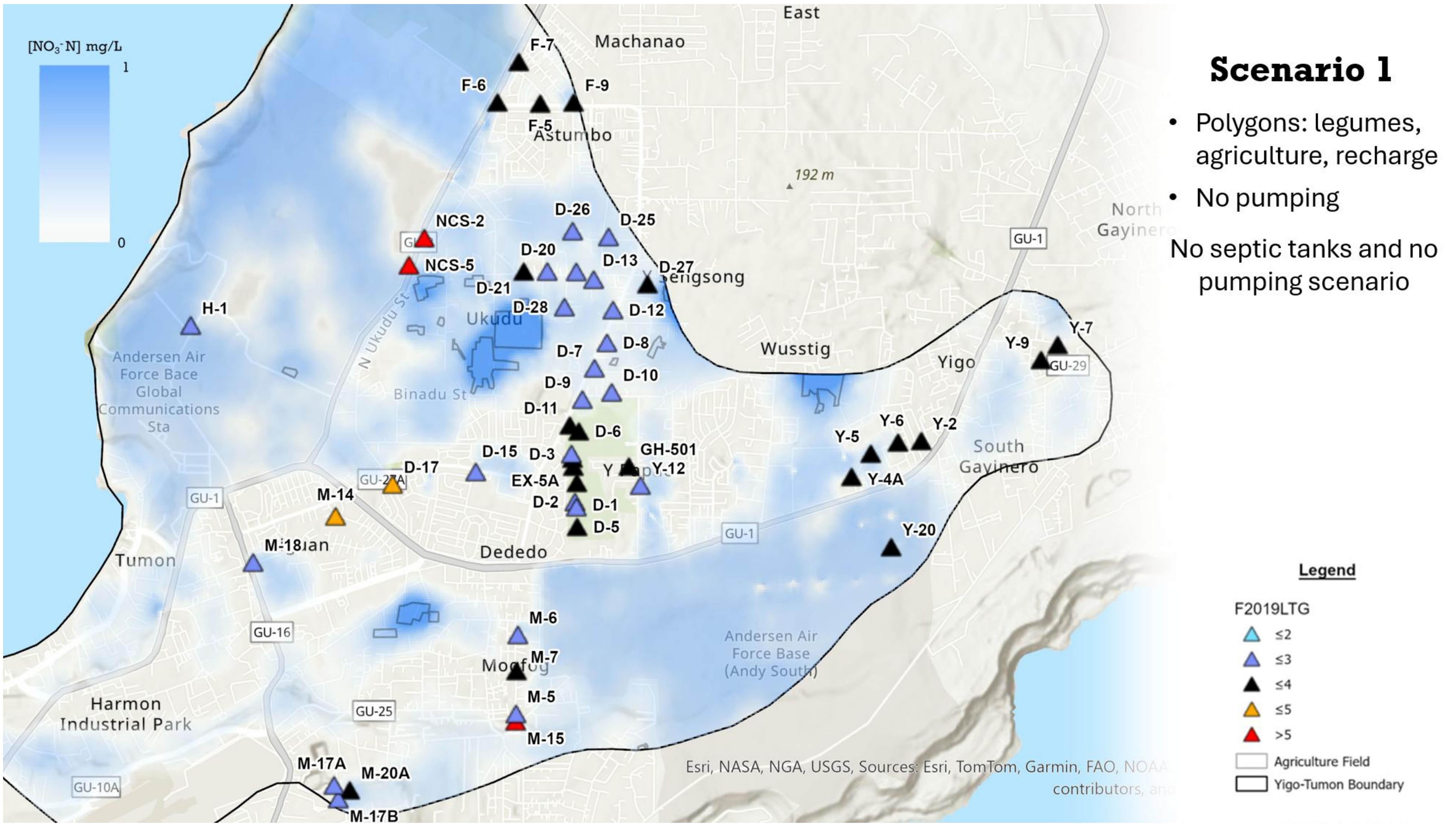

Figure 4.1 Plan-view simulation results for Scenario 1 after a 30-day simulation under natural and agricultural nitrate loading with no groundwater pumping. Production wells are symbolized according to the LTG classification developed by Bulaklak et al. (2020). Only production wells exhibiting increasing nitrate trends are shown.

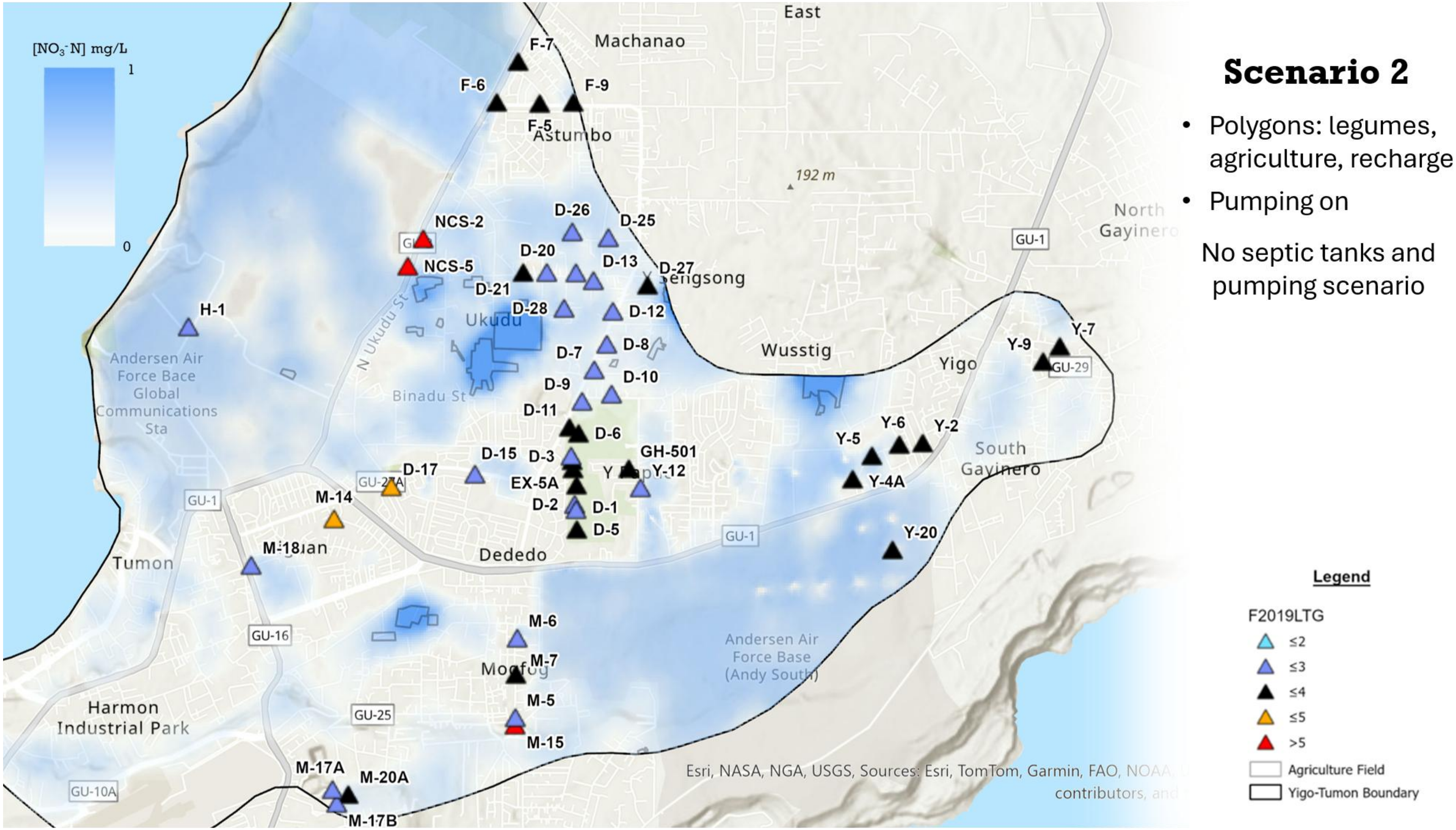

Figure 4.2 Plan-view simulation results for Scenario 2 after a 30-day simulation under natural and agricultural nitrate loading with groundwater pumping. Production wells are symbolized according to the LTG classification developed by Bulaklak et al. (2020). Only production wells exhibiting increasing nitrate trends are shown.

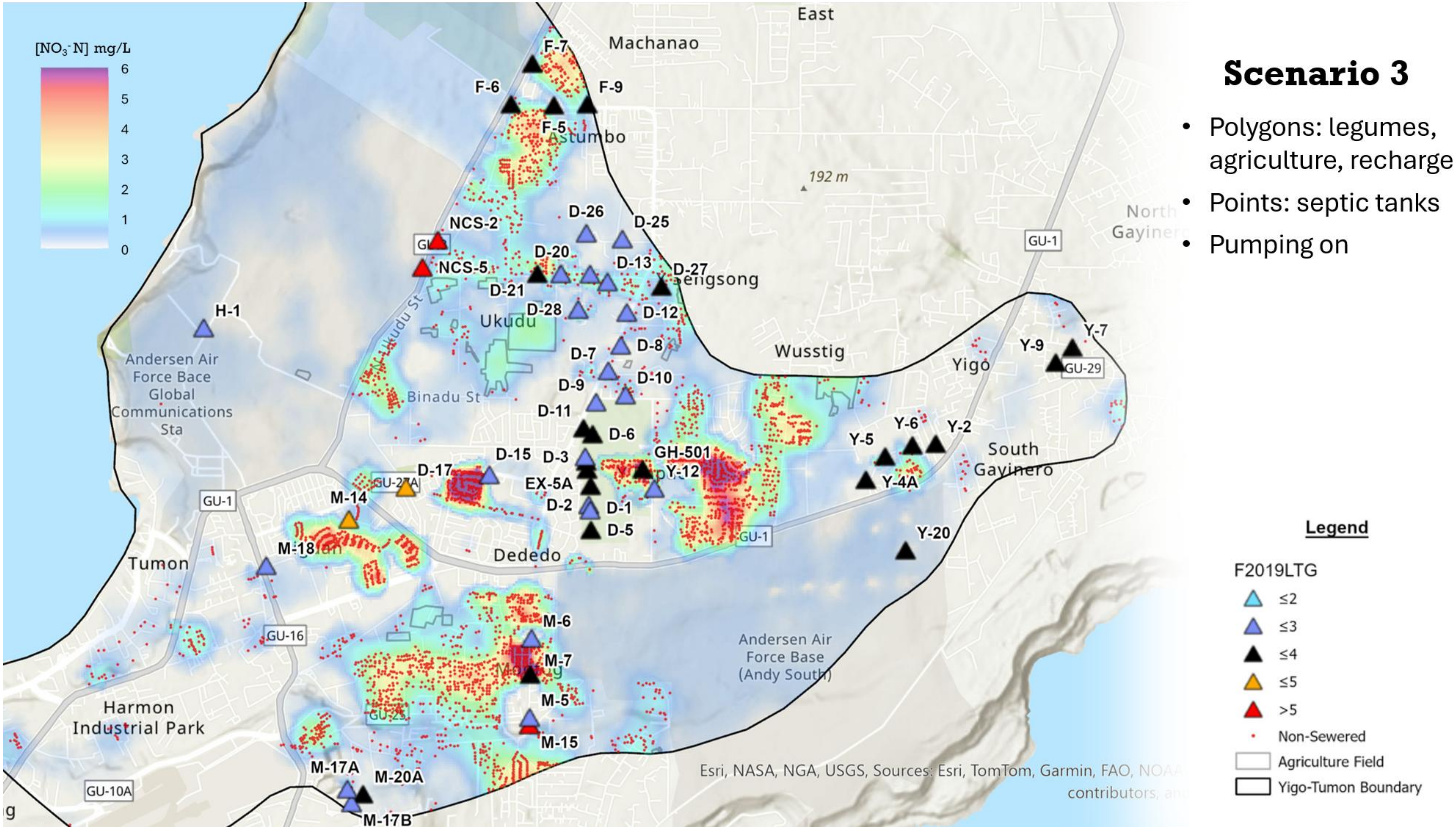

Figure 4.3 Plan-view simulation results for Scenario 3 after a 30-day simulation under natural and agricultural nitrate loading, septic system loading, and groundwater pumping. Production wells are symbolized according to LTG classification developed by Bulaklak et al. (2020). Only production wells exhibiting increasing nitrate trends are shown.

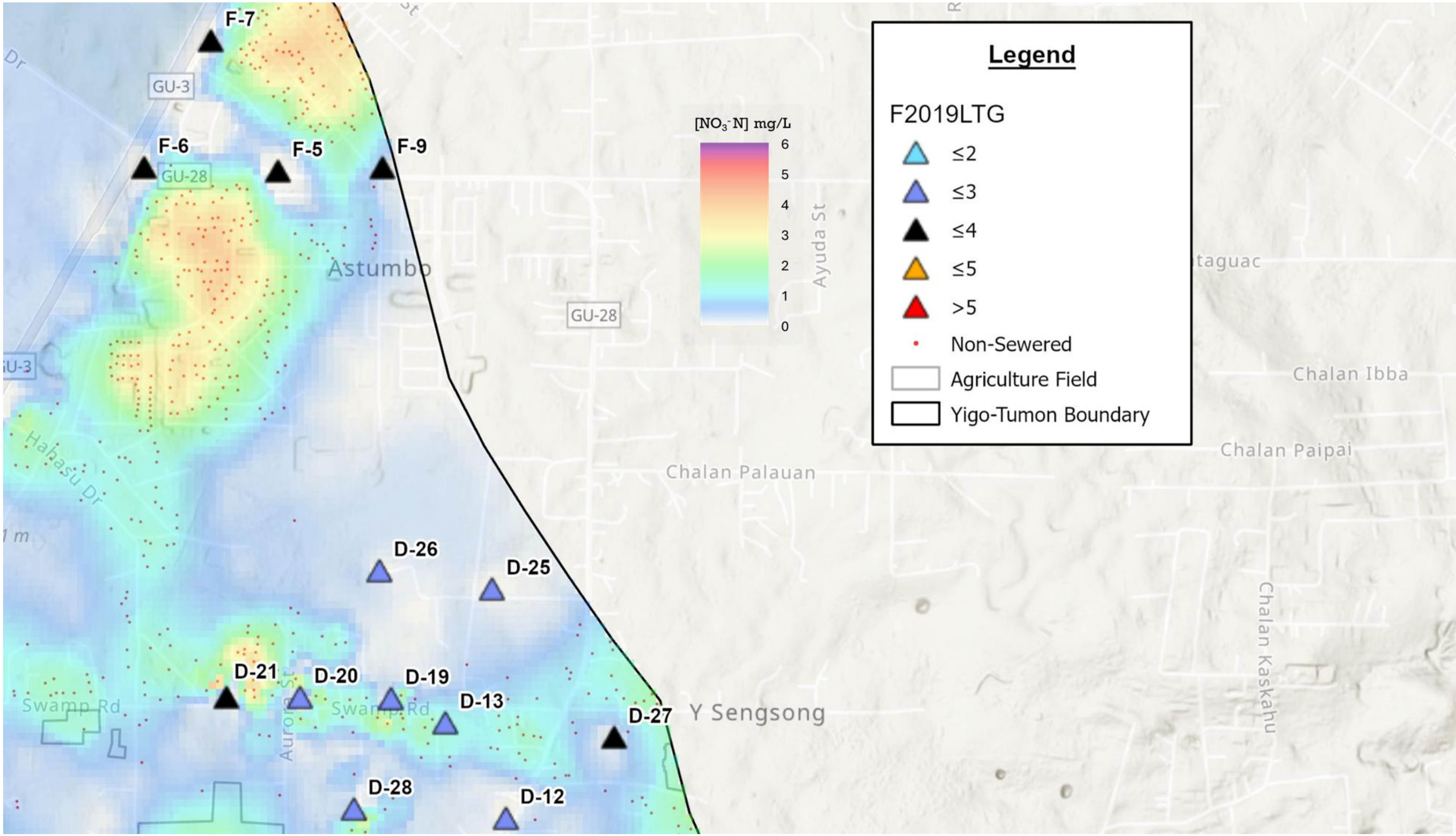

Figure 4.3b Closer view of the northern portion of the Tomhom Basin under Scenario 3.

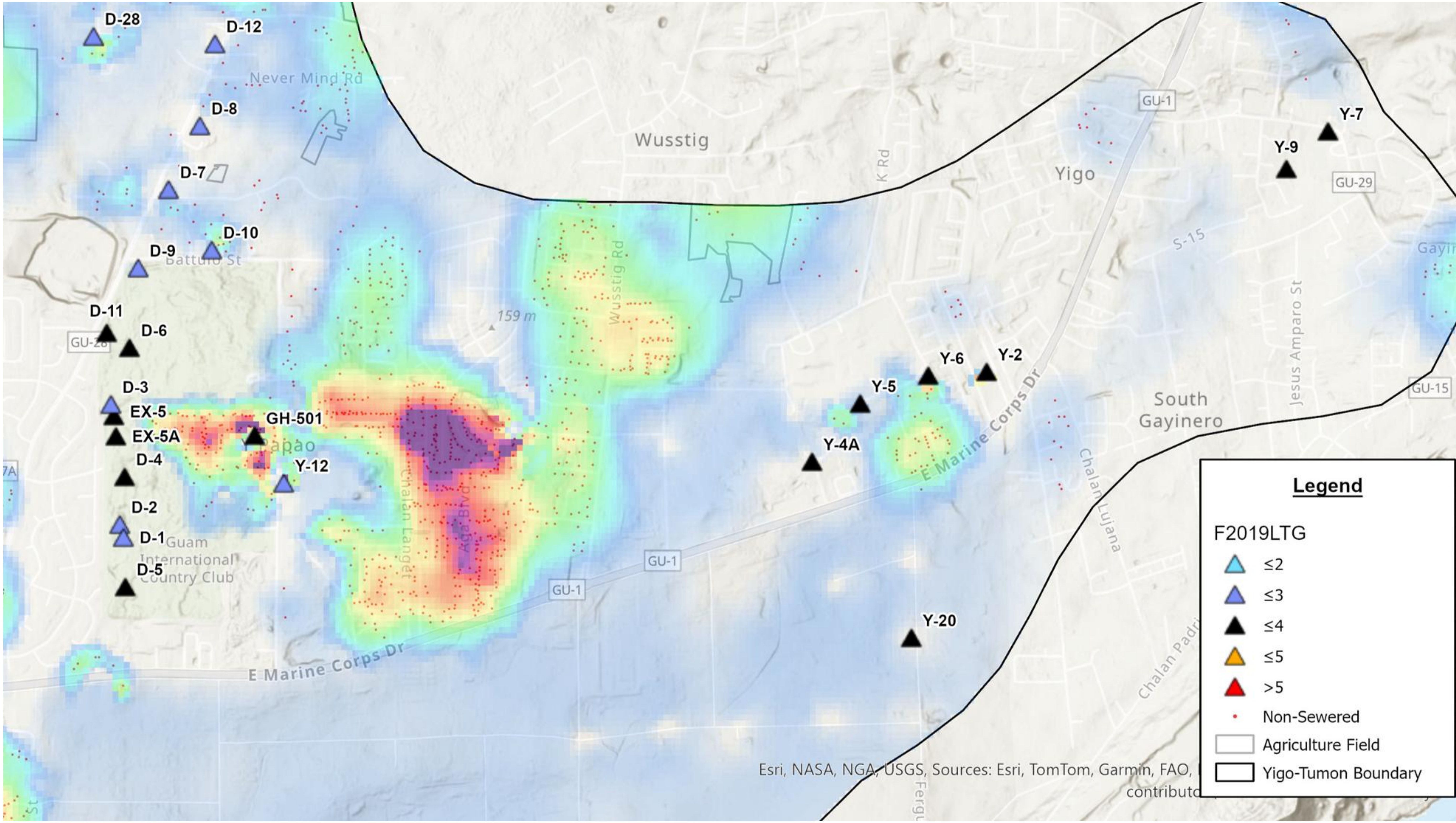

Figure 4.3c Closer view of the central portion of the Tomhom Basin under Scenario 3.

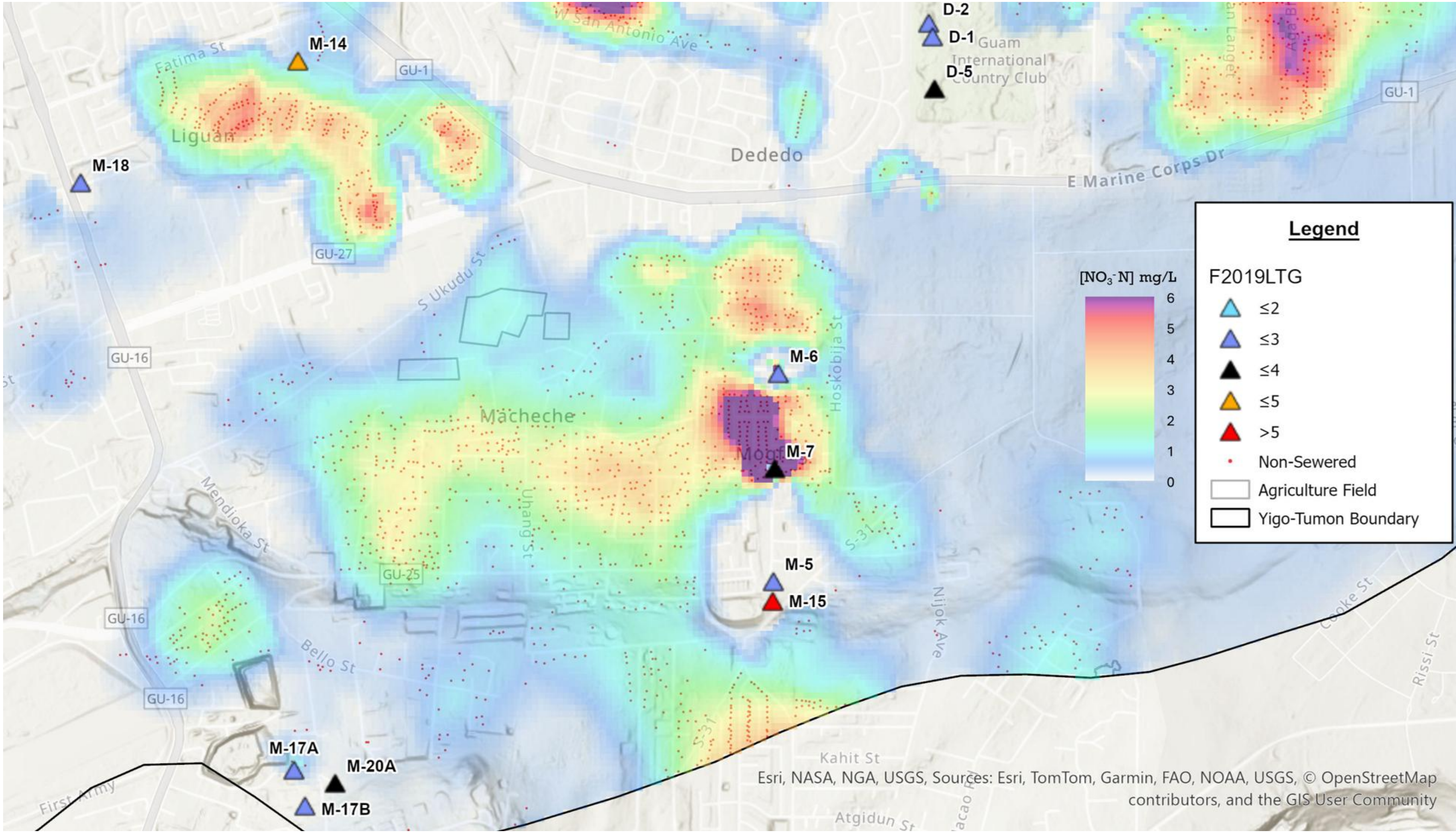

Figure 4.3d Closer view of the southern portion of the Tomhom Basin under Scenario 3**.**

below 4 mg/L and are located within a simulated plume containing concentrations of approximately 2–3 mg/L. Similarly, wells D-20, D-19, and D-13 are associated with observed concentrations below 3 mg/L and occur within areas where simulated concentrations are relatively low.

Figure 4.4c shows the central portion of the basin, with a pronounced nitrate-N plume observed near wells GH-501 and Y-12. In contrast, no significant plume is simulated near the production wells located west of GH-501 and Y-12. This result is expected, as the golf course was represented as a recharge area in the current model and potential nitrate-N contributions associated with golf course management practices were not included.

Figure 4.4d focuses on the southern portion of the basin, particularly the M-series wells. Although the model simulates several areas of elevated nitrate-N concentrations, the resulting plume patterns do not fully correspond with the trends reported by Bulaklak et al. (2020), suggesting that additional refinement of source-loading assumptions, hydraulic properties, and other parameters may be necessary to better represent nitrate-N transport and distribution within the southern portion of the basin.

5 CONCLUSION AND RECOMMENDATIONS

This nitrate-N solute transport model provides useful information on nitrate-N within the Tomhom Aquifer through three nitrate-N scenarios. This section summarizes the findings and provides recommendations for groundwater management and future model improvement.

5.1 Conclusion

The goal, purpose, and objectives in Section 1.2 were accomplished by organizing hydrologic and nitrate-N source data, developing and matching the model to nitrate-N concentrations in production wells, simulating three scenarios, and evaluating and interpreting the results. Scenarios 1 and 2 included leguminous and agricultural sources and produced concentrations of up to approximately 1 mg/L. The similarity between the two scenarios showed that pumping had minimal effect on the overall nitrate-N distribution under these source conditions. Scenario 3 included septic sources and produced localized dispersion and advection of elevated nitrate-N concentrations. The plumes extended from residential areas with higher densities of non-sewered households toward nearby production wells, particularly in the Ypaopao Estates of the Tomhom Basin, suggesting that septic systems contribute to increased nitrate-N concentrations. While the septic/non septic determination was based on GWA data, there is a possibility that this is backwards and close residential areas near sewer lines are most often connected to the sewer main.

5.2 Future Directions and Recommendations

Proper septic system maintenance, increase in nitrate well sampling, and sewer infrastructure improvements should be prioritized in areas where modeled nitrate-N plumes are near production wells. A density map and accurate residential sewer system status needs updating and verification. This was noticed in the Kaiser area where sewered homes were listed non-sewer in the water meter data set.

The available land-cover and non-sewered residential datasets provided a useful basis for model development. As updated data become available, they should be incorporated to better represent nitrate-N source areas and septic loading. Sewer connections should especially be verified as some residences classified as non-sewered were found to be connected to the sewer system (see Appendix 1).

The current model provides a foundation for continued evaluation of nitrate-N transport and can support interagency wastewater management, land-use planning, and protection of Guam’s drinking and utility water resources.

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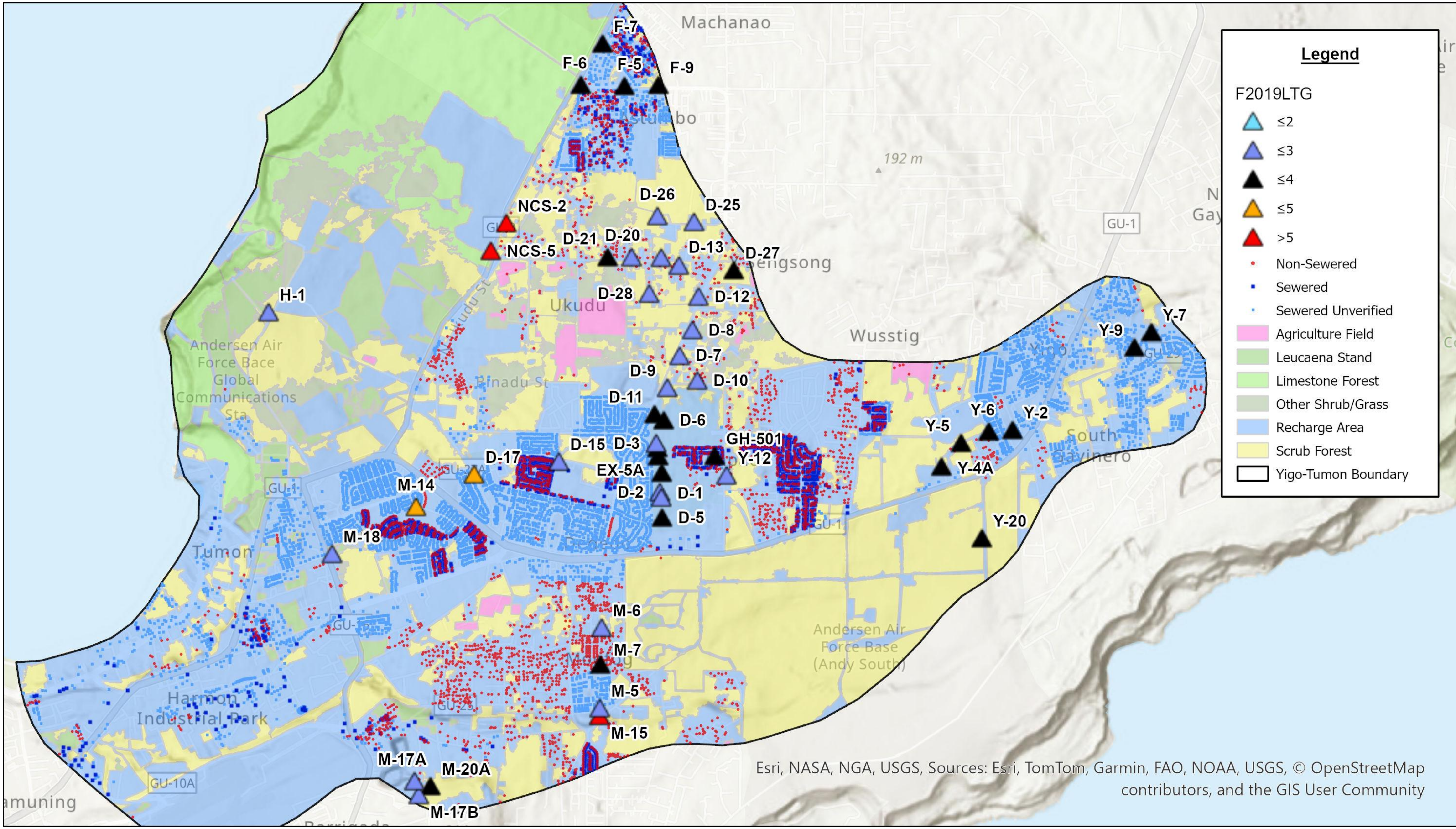
APPENDIX

Appendix 1



Appendix 1 Land-cover classifications and wastewater infrastructure within the Tomhom Basin. The identified discrepancies between the non-sewered residence dataset and verified sewered residences highlight the need for continued verification of wastewater infrastructure data for future model refinement.

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