APPENDIX VI

UPCOUNTRY MAUI GROUNDWATER FLOW AND NITROGEN TRANSPORT MODEL REPORT MAUI, HAWAII

Draft

Prepared by:
Hawaii Department of Health
Safe Drinking Water Branch
2385 Waimano Home Road
Uluakupu Building 4
Pearl City, Hawaii 96782

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SECTION 1 INTRODUCTION

As an important component of the Upcountry Maui Nitrate Investigation, a groundwater flow and transport model was developed of the study area. As is described below, the total nitrogen dissolved in the groundwater (referred to hereafter as groundwater nitrogen) rather than nitrate was the species that was modeled. This model served to fill in "data blanks" and increase understanding of the sources of nitrogen, the relative magnitude of nitrogen from the various sources, and estimate the distribution and magnitude of the groundwater nitrogen throughout the study area. Details of the Upcountry Maui investigation can be found in the *Upcountry Maui Groundwater Nitrate Investigation Report – Maui, Hawaii; Draft* (DOH, 2018) hereafter referred to as the Report.

Figure 1-1 shows the location of the study area. The study area is the west facing slope of the Haleakala Volcano down slope to the approximate centerline of the isthmus that connects eastern Maui to western Maui. Upcountry Maui is the general term used for the west facing slope of Haleakala above 1000 feet above mean sea level (ft msl) elevation and downslope of the land that is zoned for conservation. This includes the communities of Makawao, Pukalani, Kula, and Pulehu.

1.1 MODELING APPROACH AND PHILOSOPHY

The approach used was to develop a groundwater nitrogen flow and transport model using the best available hydrologic and nitrogen source data, and evaluate how the model results compared with measured groundwater nitrogen concentrations. As described below, the transport of groundwater nitrogen rather than nitrate, the contaminant of concern, was simulated. This was done since the model does not have the capability to simulate the series of transformations that dissolved nitrogen undergoes in the subsurface. Total nitrogen was one of the species analyzed for during the groundwater sampling which provides a criteria to evaluate how well the model replicated the actual groundwater nitrogen chemistry.

Commonly, groundwater flow and transport models are subjected to a rigorous calibration process that entails adjusting model parameters to get a better match between the simulated and measured values of groundwater elevation and/or contaminant concentrations. The primary focus of this modeling effort was to evaluate whether or not the assumed sources of groundwater nitrogen could account for what was measured by the groundwater sampling without extensive manipulation of the model. The calibration process can result in "forcing" the model results to a desired outcome. To prevent forcing the model results to a desired outcome, the calibration process for this investigation was kept to a minimum. The calibration involved adjusting hydraulic conductivity of the lava formations to get water table elevations beneath the upper slopes of the model that were consistent with those measured and refining the recharge polygons in the areas of high onsite sewage disposal system density (OSDS) to a size of approximately 500 meters (m) on a side. The actual process of incorporating the OSDS leachate into the model is described in Section 3.2.2.

1.2 PREVIOUS GROUNDWATER MODELS OF UPCOUNTRY MAUI

As part of the Source Water Assessment Program (SWAP), the University of Hawaii (UH), Water Resources Research Center, and the Department of Health (DOH), Safe Drinking Water Branch developed a groundwater flow model of east Maui to delineate zones of contribution to public drinking water wells (Whittier et al., 2004). This model only simulated freshwater flow and treated the interface between the fresh and saline groundwater as an impermeable boundary. As part of an assessment of the sustainability of groundwater resource for the Wailuku Area, the U.S. Geological Survey (USGS) developed a groundwater flow model of east-central and west Maui (Gingerich, 2008). This model simulated both the movement of fresh and saline groundwater using the density dependent groundwater flow model Sutra (Voss and Provost, 2010).

In 2014, UH and DOH published a report on the human health and environmental risks from OSDS leachate (Whittier and El-Kadi, 2014). This study included a groundwater flow and transport model of east Maui that evaluated the impact of OSDS on the groundwater and to critical receptors such as public drinking water wells and the coastal zone. This model indicated that it was likely that leachate from OSDS has significantly elevated the nitrate concentrations in the Upcountry Maui groundwater. However, there were no wells in the modeled areas of highest nitrate concentrations to validate the model results. Also, the model did not account for any natural attenuation of nitrate that might occur between the OSDS leachate being released to the shallow subsurface and the groundwater that was hundreds of feet beneath the OSDS.

1.3 DESCRIPTION OF THE STUDY AREA

1.3.1 Physical Setting

Maui is the second largest island of the Main Hawaii Islands (MHI) and lies near the southeast extent of the State of Hawaii. The Hawaiian island chain is formed as the Pacific Tectonic Plate passes over a mid-ocean hotspot. Maui, like most of the MHI, is made up of two volcanoes (Langenheim and Clague, 1987). Haleakala forms the eastern part of Maui that is separated from the West Maui Volcano by a central isthmus that provides a natural division between eastern and western Maui. Figure 1-2 is a map of east Maui showing the major geologic formations and features. The Haleakala Volcano, rises to 10,023 ft (3055 m) above sea level. Haleakala is much younger than the West Maui Volcano, with the shield building stage of this volcano ending between 0.93 and 0.97 million years ago (Gingerich, 1999a and b). Haleakala has three well defined rift zones, one radiating from the summit to the north-northwest, one to the east, and the third rift zone extends to west-southwest.

1.3.2 Regional Groundwater Hydrology

The precipitation that falls on Upcountry Maui is partitioned between surface runoff, evapotranspiration, soil moisture storage, and groundwater recharge. Recharge (the fraction of groundwater that reaches the water table) ranges from about 90 inches per year (in/yr) at the middle elevations of about 3,000 feet above mean sea level (ft msl) to less than 10 in/yr on the southwest flank of the Haleakala Volcano and along the coast (Johnson et al., 2014). When the recharge reaches the aquifer, it flows radially out from the central highlands to discharge areas along the coast. Figure 1-3 shows the boundaries of the study area, the recharge rate (Johnson et al., 2014), and water table elevation for east-central Maui. The water table elevations are those modeled by Gingerich (2008) in his groundwater flow model of central and west Maui.

In the subsurface, the groundwater becomes a lens of freshwater floating on the underlying saltwater with a water table elevation of less than 50 feet above sea level (Izuka et al., 2016). This Ghyben-Herzberg principal states that the thickness of the freshwater lens is 41 times the elevation of the water table above sea level (Freeze and Cherry, 1979, pg 375). This is only an estimation, however, and the actual thickness of the freshwater lens can deviate from this value due to factors such as non-horizontal flow and heterogeneous geology (Izuka and Gingerich, 1998). The mixing of the two waters at the bottom of the basal lens results in a sloping transition rather than a sharp interface between fresh and saltwater.

As the groundwater approaches the shoreline, it may encounter sedimentary deposits and formations that retard its flow. These formations, referred to collectively as caprock, have an effective hydraulic conductivity that is significantly lower than that of the thin bedded lavas forming the volcanic formations of the study area. This results in a thicker freshwater lens due to the flow impedance of the caprock that retards saltwater intrusion into the aquifer. The sediments in the central isthmus area between east and west Maui extend beneath the surface of the water table about 1 to 2 miles inland from the coast (Gingerich, 2008) and are deeper than 80 ft msl at the coast. The slopes of Upcountry Maui consist of a thick veneer of more recent Kula Volcanics overlying the shield building stage Honomanu Basalts (Izuka et al., 2016). Gingerich (2008) modeled the Kula Volcanics and the Honomanu Basalt as a single hydrogeologic unit. However, the Kula Volcanics are generally viewed as having lower permeability than the Honomanu Basalts (Stearns and Macdonald, 1942; Izuka et al., 2016). For groundwater transport, that has little bearing in the study area since the contact between the Kula Volcanics and the Honomanu Basalt is above the saturated zone (Gingerich, 2008). However, recharge infiltrating into the unsaturated zone may be influenced by the structure and lower permeability of the Kula Volcanics resulting in perched water and imparting a lateral downslope component to the infiltrating water.

The water transport characteristics of the various aquifer materials vary greatly along the flow path. In a groundwater model that included central Maui, Gingerich (2008) assigned horizontal longitudinal and transverse hydraulic conductivities of 11,083 and 3,694 feet per day (ft/d) respectively and a vertical hydraulic conductivity of 13.85 ft/d for the Kula/Honomanu Basalts in the Upcountry Maui area. For the sedimentary deposits, he used values of 17 and 0.38 ft/d for the horizontal and vertical hydraulic conductivity, respectively.

1.3.3 Land Use

In Upcountry Maui, the land utilization is predominantly agriculture with small urban centers and rural zones at the mid-elevations. Pineapple and sugar cultivation once dominated most of the study area, but have now ceased. However, residual fertilizer from past agriculture still likely add to the groundwater nitrogen load. Portions of this land remain fallow or have been converted to low density housing and diversified agriculture. The upper elevations are zoned as conservation land. Figure 1-4 shows the current land use zoning for East Maui (Hawaii Office of Planning, 2017). In East Maui irrigated agriculture exists on the central isthmus between the urban centers of Kahului and Kihei. Further upslope diversified agriculture dominates. Smaller residential communities exist on the western and windward slopes of Haleakala at the low to mid-level elevations. The middle to upper elevations of Haleakala are agricultural lands, and conservation land that is dominated by the Haleakala National Park.

1.4 UPCOUNTRY MAUI GROUNDWATER NITRATE AND NITROGEN

Nitrate in drinking water can interfere with the transport of oxygen in the bloodstream of young children. This condition, known as methemoglobinemia (or blue baby syndrome), results in blue color to the skin. Water used to make baby formula with as little as 12 mg/L of nitrate can result in this condition (Knobeloch et al., 2000). For this reason, the USEPA has established a Maximum Contaminant Level (MCL) of 10 mg/L for nitrate (as nitrogen) in drinking water. Nitrate in groundwater can naturally be reduced by denitrification (the biological conversion of nitrate to gaseous nitrogen), but this only occurs under anoxic conditions with dissolved organic carbon present. Most Hawaii drinking water aquifers are well oxygenated and denitrification is not expected to occur (Hunt, 2004). However, as described below the total nitrogen dissolved in the groundwater was modeled rather than nitrate alone.

1.4.1 Nitrogen Chemistry

While nitrate is the contaminant of concern, nitrate is the result of a succession of transformations that nitrogen goes through (Manahan, 2004; WERF, 2009a). Figure 1-5 shows a representative transformation sequence of natural and anthropogenic nitrogen released to the subsurface. The most prevalent forms of nitrogen in the environment start as organic nitrogen or ammonium (NH_4^+). Common sources of organic nitrogen are the decay of organic matter, wastewater, or livestock wastes. Ammonium is common component of fertilizer and thus agriculture is a common source of ammonium. Also, ammonium results from a microbial mediated process called mineralization that converts organic nitrogen to ammonium. In the presence of oxygen, nitrifying bacteria convert ammonium to nitrate (NO_3^-). Nitrate is stable in water containing dissolved oxygen. The majority of Hawaii's drinking water aquifers contain sufficient dissolved oxygen to make nitrate a stable species in groundwater. This means that once the nitrogen transformation process reaches nitrate, it is the end species, thereby making nitrate a persistent contaminant. However, in anaerobic water (depleted of dissolved oxygen) that also has organic carbon, denitrifying bacteria uses nitrate as a respiration source and through a series of reactions convert nitrate to nitrous oxide or nitrogen gas, that is then lost from the subsurface water. This commonly occurs in soil beneath a leach field (WERF, 2009a) or when large amounts of wastewater are injected into the groundwater (Fackrell et al., 2016).

1.4.2 Groundwater Nitrogen in Upcountry Maui

The results of the Upcountry Maui groundwater sampling show that the transformation process to nitrate is not complete. Table 1-1 lists the Upcountry Maui sampling results by nitrogen species. In many cases nitrate only accounted for about half of the total nitrogen concentration with organic nitrogen accounting for the vast majority of the remainder. Organic nitrogen is assumed to be the total nitrogen concentration minus the inorganic species (ammonium, nitrite, and nitrate). In the Upcountry Maui groundwater, organic nitrogen is a significant fraction of the total nitrogen. Since the transformation to nitrate is not complete, total nitrogen rather than nitrate was modeled.

The concentration of groundwater nitrogen in Upcountry Maui varies from less than 0.7 mg/L to 12.9 mg/L. Commonly nitrate plus nitrite is the nitrogen species analyzed in groundwater samples. Nitrite is not stable in the environment and if detected is only at trace concentrations. So, frequently, the majority of the groundwater nitrogen data is nitrate only. For example in the 2001 National Water Quality Assessment study, the USGS only analyzed samples from 45 wells for nitrate plus nitrite, but only analyzed two of the samples for other nitrogen species due to the assumption that nitrate dominates the groundwater nitrogen (Hunt, 2004). In these two samples the non-nitrate concentrations were less than 0.1 mg/L, supporting the assumption that nitrate is the primary species of nitrogen in the groundwater. In the discussion that follows, nitrate concentrations are reported since that is the only data available and is generally representative of the total nitrogen in the groundwater. The nitrogen in groundwater from natural sources, usually measured as nitrate, is very low. A review of the DOH Safe Drinking Water Information System Contaminant Database (SDWIS-DB) that shows the vast majority of wells located in areas with little or human impact within the source's zone of contribution have nitrate concentrations less than 0.5 mg/L. However, there are exceptions to this general trend. In the Kaupulehu area of West Hawaii Island there are groundwater nitrate concentrations of greater than 2 mg/L (Fackrell et al. 2016a) and as high as 4.3 mg/L (SDWIS-DB, data extracted 1/26/2017). These nitrate concentrations are unexpectedly high since there are no identified anthropogenic source for the elevated nitrate in the Kaupulehu area. Predominantly, throughout the State, groundwater nitrate concentrations approaching the MCL of 10 mg/L are only associated with sugar cane cultivation and seed corn agriculture (Ling, 1996). While agriculture is viewed as the primary source on groundwater nitrate contamination, other sources including OSDS do contribute nitrogen to the groundwater.

In the area of Pukalani, Makawao, and Haliimaile, groundwater nitrogen concentrations as high as 12.9 mg/L were measured. Figure 1-6 is a map showing the measured nitrogen concentrations relative to the location of the nitrogen and nitrate sources. Using nitrogen concentrations greater than 8 mg/L as a baseline, elevated groundwater nitrogen concentrations occur from the BRE-1 and Maunaolu-Smith Well in the north and southward to the Waiohuli Observation Well in the south of the study area. The wells with significantly elevated groundwater nitrogen included; The Maunaolu-Smith, BRE-1, Omaopio-Esty, Pukalani Golf Course, and the Waiohuli Observation Wells. By contrast the Pookela and West Kuiaha Meadows Wells had groundwater nitrogen concentrations less than 1.0 mg/L. By visual correlation alone, the elevated groundwater nitrogen concentrations occur downgradient of areas with high OSDS populations.

Table 1-1. Dissolved nitrogen concentrations in the Upcountry Maui wells

Well Name	Well Number	Nitrite	Ammonium	Nitrate + Nitrite	Total Nitrogen	Organic Nitrogen
		(mg/L as N)				
Waiohuli Obs Well	6-4422-001	0.0	0.0	2.5	9.5	7.0
Maui Highlands Wells 2	6-4425-001	0.0	0.0	0.9	1.2	0.3
Omaopio-Esty	6-4821-001	0.0	0.0	5.0	10.9	5.9
Pukalani Golf Course	6-5021-001	0.0	0.0	5.8	12.9	7.1
Pookela Well	6-5118-002	0.0	0.0	0.4	0.9	0.5
Baldwin Ranch Estates 1	6-5220-002	0.0	0.1	4.0	9.1	4.9
Kaupakulua Well	6-5317-001	0.0	0.0	0.7	0.8	0.1
Hamakaupoko Well 1	6-5420-002	0.0	0.0	2.4	5.4	3.0
Hamakaupoko Well 2	6-5320-001	0.0	0.0	4.1	7.9	3.7
Maunaolu-Smith Well	6-5320-002	0.0	0.0	5.3	8.5	3.3
West Kuiaha Meadows Well	6-5418-002	0.0	0.0	0.7	0.7	0.1
Haiku Well	6-5419-001	0.0	0.0	1.9	4.7	2.8

1.5 POTENTIAL SOURCES OF NITRATE CONTAMINATION IN UPCOUNTRY MAUI

The purpose of this investigation is to determine the source of the elevated nitrate measured in current and future public drinking water wells. A review of land use and the list of potentially contaminating activities from Table 5-2 in SWAP (Whittier et al., 2004) indicate that the most likely sources of elevated nitrate and nitrogen contamination are:

- Confined animal feed operations, which may occur at the Haleakala Ranch lands,
- Former sugar cane agriculture,
- Former pineapple agriculture,
- Golf courses, and
- Onsite Sewage Disposal Systems (OSDS).

Figure 1-6 maps the locations of the potential sources of nitrate contamination relative to the location of to the total nitrogen concentrations measured during the Upcountry Maui nitrate sampling. Sugar cane agriculture, a known source of elevated nitrate in the groundwater water (Ling 1996; and Hunt, 2004), occurs predominantly downgradient of the sampled wells. Former pineapple cultivation does occur upgradient of some of the wells. However, elsewhere the nitrate concentrations in areas of pineapple cultivation are generally much lower than in areas where sugar cane is grown (Soicher and Peterson, 1996; Hunt, 2004; and Glenn et al., 2012). Other agriculture and golf courses, while sources of nitrate contamination, are only present over a small area. OSDS and confined animal feed operations (if these do occur on the Haleakala Ranch lands) are the most likely sources of elevated nitrate and nitrogen in the Upcountry Maui groundwater.

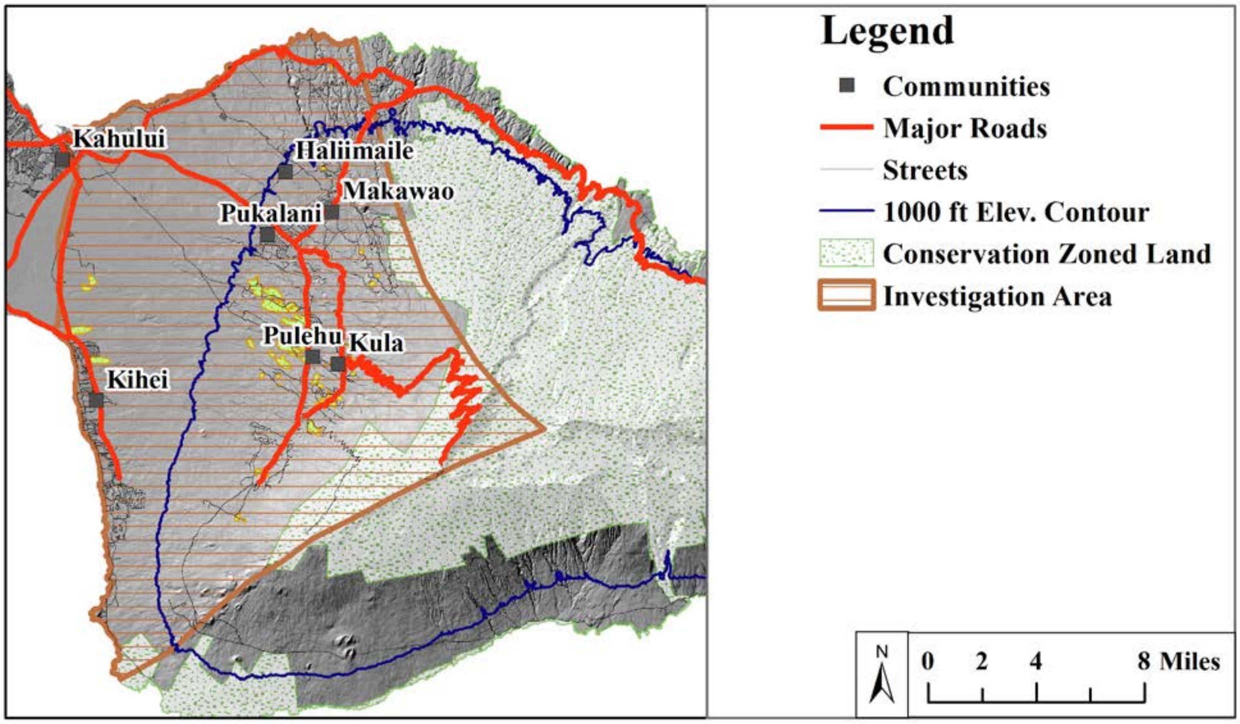

Figure 1-1. Map showing Maui and the location of the investigation area

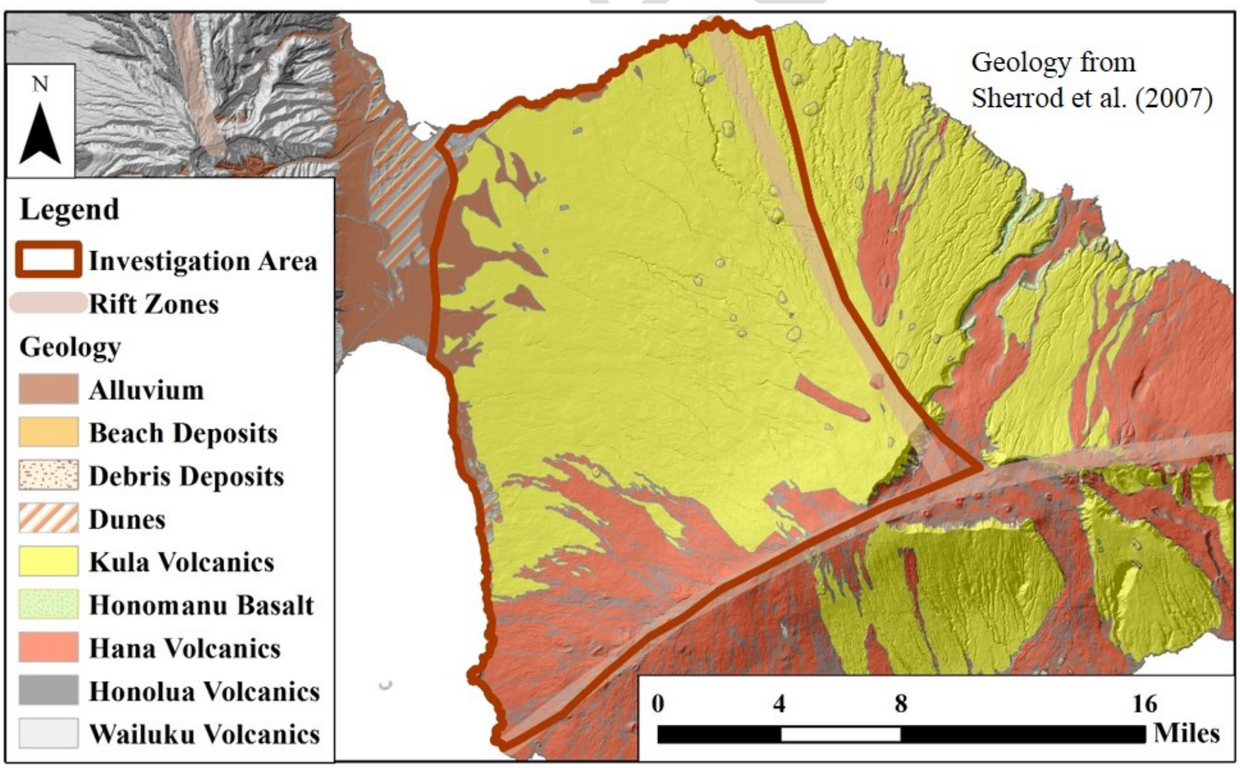

Figure 1-2. Geologic map of east Maui

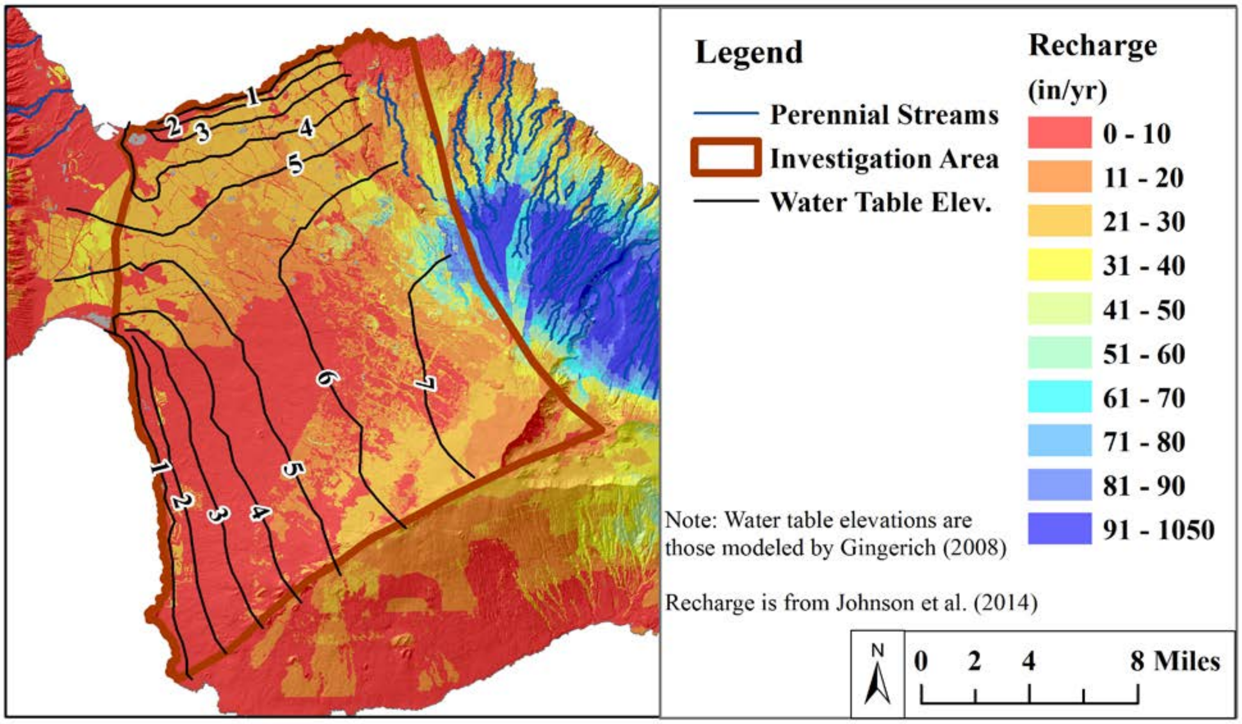

Figure 1-3. Groundwater recharge rates and groundwater surface elevation for east-central Maui

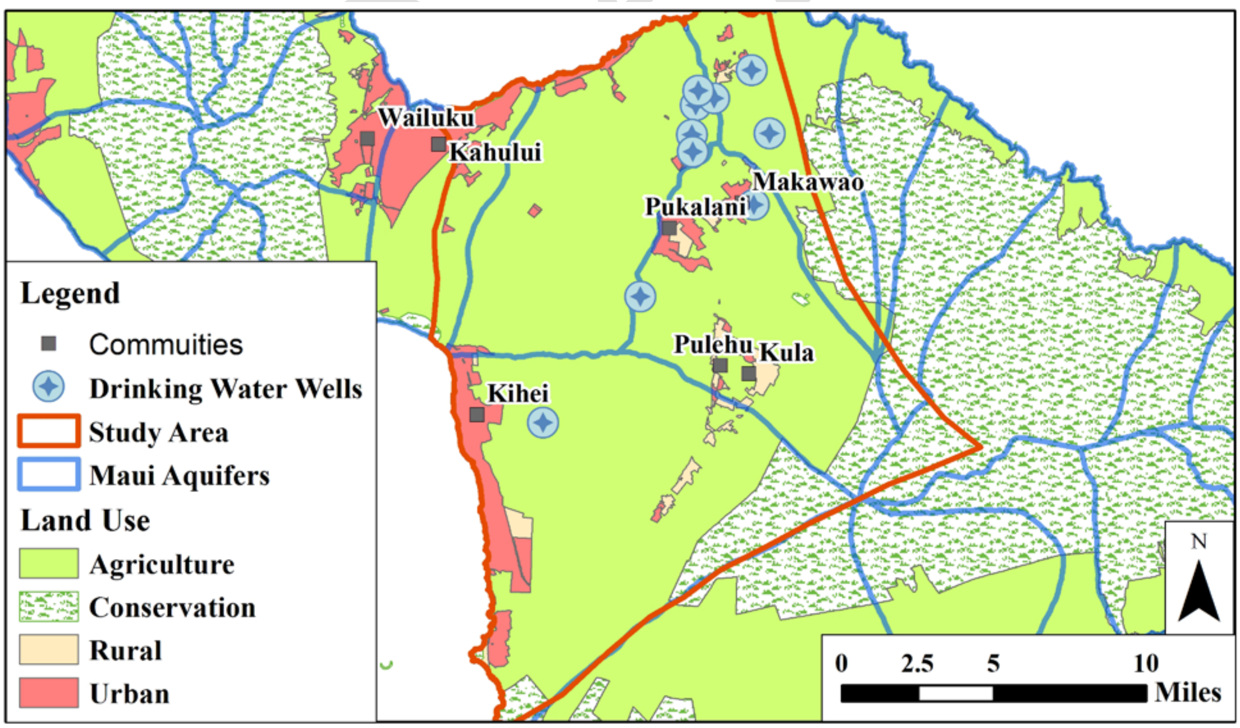

Figure 1-4. The aquifer boundaries and the land use designation for east-central Maui

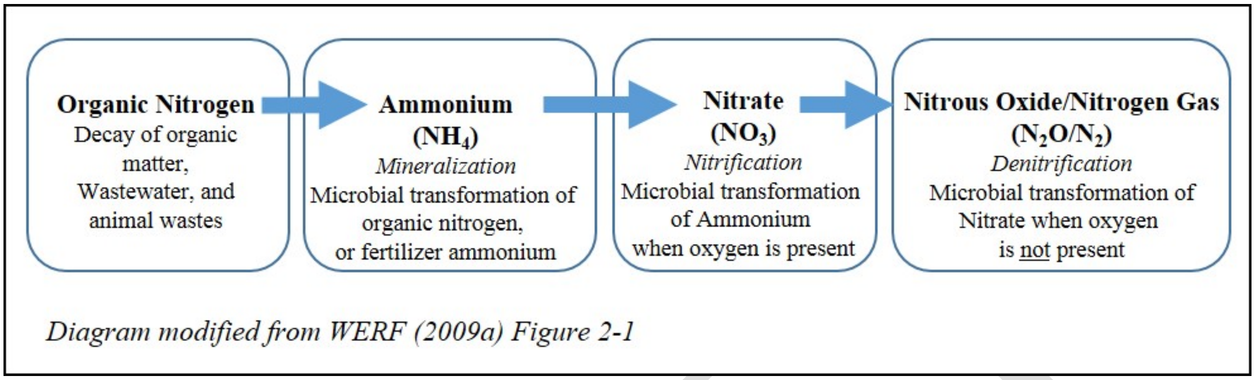

Figure 1-5. Nitrogen transformation sequence

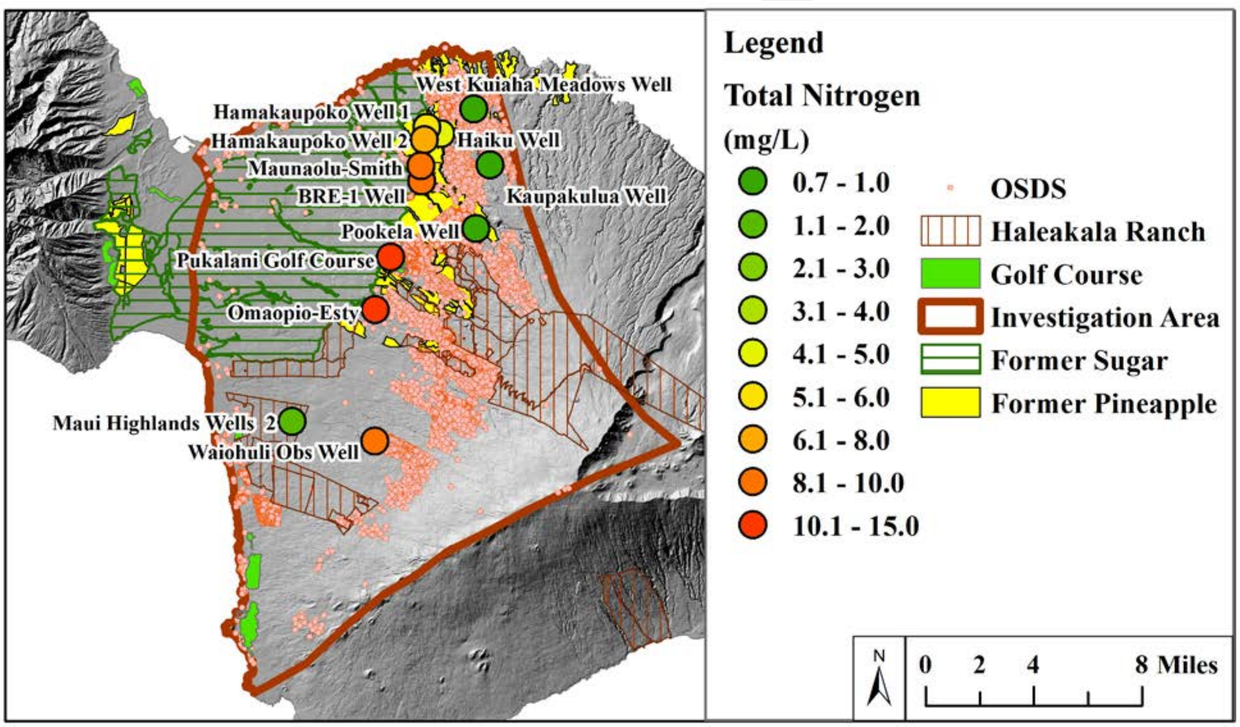

Figure 1-6. The total nitrogen concentrations in the Upcountry Maui wells relative to the sources of nitrogen

SECTION 2 UPCOUNTRY MAUI GROUNDWATER FLOW MODEL

2.1 INTRODUCTION

A groundwater flow and transport model was developed for the study area to test hypotheses about the sources of groundwater nitrate and to “interpolate” the distribution of groundwater nitrogen throughout the study area aquifers. Accomplishing this task requires two fundamental tasks: first, developing a groundwater flow model that simulates the groundwater flow regime in Upcountry Maui; and second, to use the resulting groundwater flow paths to simulate the distribution and concentration of dissolved nitrogen in the groundwater from the primary terrestrial sources.

The modeling approach was to develop a groundwater flow model based on available data. These data included existing pumpage, recharge studies, geologic maps, and water level data from records maintained by various agencies including the USGS, DOH, and the Department of Land and Natural Resources (DLNR) Commission On Water Resource Management (CWRM). Minimal model calibration was done due to the sparseness of data. Also, excessive calibration can lead to nudging the model toward a desired result. The adjustments done to the model following the initial model construction were:

- Adjusting the hydraulic conductivity of the lava formations so that the simulated and actual water levels in upper elevations of the model were in reasonable agreement;
- Refining the recharge polygons to more precisely replicate the distribution of OSDS in the study area; and
- Adding observation coverages to layer 2 of the model grid since the majority of the well screens or open intervals were at a depth more consistent with layer 2.

The goal of the modeling effort was to test assumptions made about the groundwater flow paths and distribution of nitrate sources. A reasonable agreement between the measured and modeled distribution of groundwater nitrogen would indicate that the modeling assumptions are valid.

The Upcountry Maui flow model borrowed from the results of the USGS groundwater flow model of central and west Maui (Gingerich 2008) to define the bottom of the freshwater aquifer and to better constrain the groundwater elevations at the upslope extent of the model domain. The USGS model simulated both fresh and salty groundwater flow using the density dependent modeling code SUTRA (Voss and Provost, 2010) and thus provided the downward extent of the freshwater aquifer.

2.1.1 Purpose of the Model

The purpose of the groundwater flow model was to produce the numerical groundwater flow solution that the transport model needs to simulate the transport and distribution of dissolved nitrogen in the Upcountry Maui groundwater.

2.2 GROUNDWATER FLOW MODEL

2.2.1 Modeling Code Selected

The groundwater flow model was done using the USGS groundwater modeling code MODFLOW 2005 (Harbaugh, 2005). MODFLOW is considered an international standard for simulating groundwater flow. To simulate groundwater flow, MODFLOW uses the finite difference method where the model is represented by a grid of cells in three dimensions. The groundwater flow calculations are done to calculate water movement between adjacent cells. The model code is divided into modules that communicate with each other to do numerical calculations specific to the modules. These modules include packages for well pumpage, recharge to groundwater, and boundary conditions such as specified head, stream groundwater interaction, and other hydraulic conditions.

2.2.2 Boundary Conditions

Boundary conditions are those parameters specified at the "edges" or the boundary of the model. The general philosophy for establishing model boundaries is that they are far enough from the area in interest in the model so that inaccuracies in the boundary conditions will not significantly impact the model results in the area of interest. Also, to the extent possible the boundaries should follow some accepted physical or chemical boundary that exists in "real life." For the Upcountry Maui model, the boundaries were as follows:

- The northeast lateral boundary (Figure 2-1) is defined by the approximate axis of Haleakala's northwest rift zone (Sherrod et al., 2007). Dike intrusions in the rift zone constrain groundwater to higher elevations than that in the basal aquifer. For this reason, the axis of the rift zones are generally viewed as groundwater divides making them groundwater flow boundaries (Lau and Mink, 2006, page 16; and Stearns and Macdonald, 1942). For this reason, the northeast boundary is assigned a no-flow condition meaning that water neither flows out of or into the model across this boundary.
- The southeast lateral boundary (Figure 2-1) is defined by the approximate axis of Haleakala's southwest rift zone (Stearns and Macdonald, 1942). This boundary was also assigned a no-flow condition.
- The western boundary (Figure 2-1) is defined across the approximate north-south mid-point of the isthmus between east and west Maui. The groundwater elevation was fixed at this boundary and the values assigned were those simulated by Gingerich (2008).
- The northwest and southwest model boundaries (Figure 2-1) were the shoreline and were assigned specified head conditions similar to the western model boundary. The value of the specified head condition was based on the hydraulic head simulated by Gingerich (2008) at the shoreline.
- The upper boundary of the numerical model, that performs the groundwater flow calculations, is the surface of the water table since MODFLOW only simulates saturated groundwater flow. The boundary condition assigned is that of specified flux where the amount of water entering the upper model boundary is defined. The specified values were the average groundwater recharge for 2001 to 2010 estimated by the USGS (Johnson et al., 2014).
- The bottom boundary of the model uses the sharp interface approach that assumes the mid-point of the freshwater/saltwater transition zone is a no-flow boundary representing the bottom of the freshwater aquifer. The mid-point transition zone depth was taken from that simulated by Gingerich (2008).

2.2.3 Model Geology

The model considered two different geologic types (Figure 2-1). These were sedimentary formations and the lava flows of the Kula and Honomanu formations. The sedimentary deposits are only present in the in the north and south areas of the isthmus near the coast. The depth and extent of the sedimentary deposits beneath the water table were based on the elevation of the contacts observed in boreholes as interpolated by Gingerich (2008). The vast major of the modeled area consists of the lavas of the Kula and Honomanu formations. While having differing water transport characteristics, the Kula and the Honomanu formations were modeled as a single unit. While the Kula Volcanics dominate the surface topography of the study area, it only forms a veneer on top of the Honomanu Basalts and exists almost entirely above the water table. Since the model only simulates saturated groundwater flow, the Kula Volcanics play a very limited role in groundwater flow. This was also the approach taken by Gingerich (2008). Table 2-1 below lists the hydraulic parameters used for the geologic units for this model.

Table 2-1. Geology and Parameters Values Used

Geologic Formation	Horizontal Hydraulic Conductivity (ft/d)	Vertical Anisotropy[1] (Kh/Kv)	Porosity (percent)
Kula and Honomanu Formations	1,300	200	15
Sedimentary formations	17	45	30
[1]Vertical anisotropy = [Horizontal hydraulic conductivity]/[vertical hydraulic conductivity]			

2.2.4 Well Withdrawals

Pumping well distribution and withdrawals were taken from data provided by CWRM for the period from January 2010 through October 2017. There are 23 Public Drinking Water Wells and 41 other wells for other uses, primarily irrigation and crop processing, in the study area. Total pumpage by wells within the model domain was 116 mgd.

2.2.5 Recharge

Groundwater recharge is the volume of water that reaches the water table from precipitation, irrigation, and other infiltration. This is also the specified flux for the upper boundary of the model. The recharge used for this model was taken from the USGS water budget for the island of Maui (Johnson et al., 2014). The spatial resolution of the USGS recharge coverage was much finer than the model grid, so larger recharge polygons were developed for the model. The USGS calculated recharge was converted to a network of points spaced 100 meters apart. The total recharge for each model polygon was calculated from the sum of recharge of each point that fell within the polygon. Figure 2-2 maps the recharge distribution for the Upcountry Maui groundwater flow model.

2.2.6 Numerical Model Grid

The numerical model grid represents the structure of the model where the groundwater flow and transport calculations are performed. MODFLOW used a finite difference approach to calculating groundwater flow between adjacent cells. This is done using a complex array with each element of the array representing a cell in model grid. The Upcountry Maui groundwater flow model consisted of 141,960 cells arranged in 210 rows, 169 columns, and 4 layers. The model grid forms a rectangular prism, while the model domain itself has an irregular shape. The cells within the rectangular prism, but falling outside of the model domain, are inactive. Calculations were only done for the 63,340 cells that fell within the model domain with the remainder being inactive cells. Figure 2-3 shows the numerical model grid in plan view and in cross-section that bisects the model grid. The cross-section has vertical exaggeration of five (5) times the horizontal scale. The blue line on the cross-section shows the approximate water table. While the top of the grid extends to the topographic surface, the groundwater flow calculations are only done for that zone between the water table and the bottom boundary. Thus, the vertical extent of model profile where groundwater flow calculations are done is from the water table to the mid-point of the freshwater/saltwater transition zone that is the bottom boundary of the model.

2.2.7 Simulated Water Levels

The simulated water table, as expected, was highest in the upland areas and declined going toward the coast. Figure 2-4 shows the simulated water table. The best water table elevation data set available to validate the model results were measured by the USGS on May 17, 2005 for a groundwater modeling study of central and west Maui (Gingerich, 2008, Figure 26). It must be noted that this is only a general comparison since the water levels were measured in 2005 and the period represented by the model are not consistent. Other water level data available include water levels measured during installation of new wells and two observation wells that are now routinely gaged by CRWM. These other data sets do not represent a temporally consistent-regional set of water level measurements and thus are not as reliable for characterizing the surface of the water table. This makes the USGS May 17, 2005 water level data set the most reliable for evaluating how well the model results reflect the actual groundwater surface. Figure 2-4 graphs the observed water levels from Gingerich (2008) on the x axis versus the model simulated water levels on the y axis. Observation wells where large simulated groundwater pumpage occurred were excluded from the comparison since the measured water levels reflect a pump off condition. The average difference between the measured and simulated water levels was -0.1 ft.

2.2.8 Simulated Water Budget

The modeled input to the groundwater flow systems was 161 mgd of recharge based on a water budget developed by the USGS for the island of Maui (Johnson et al., 2014). Groundwater withdrawals were 116 mgd based on the average reported pumpage for the period from 2010 through 2016 (CWRM, 2017 data delivered 10/26/2017). The remaining 45 mgd was simulated as freshwater discharge to the coastal wetlands or to the ocean.

2.2.9 Simulated Groundwater Flow Paths

The groundwater flows from the recharge zones in the upper elevations down gradient to wells or the coastal zone. At the lower elevations the groundwater flow lines diverge to the north and south to the coastal and wetland discharge zones. The path lines were simulated using the USGS particle tracking code MODPATH (Pollock, 2016). Figure 2-4 shows the simulated groundwater flow paths.

2.3 GROUNDWATER FLOW MODEL SUMMARY

The Upcountry Maui groundwater model was developed to provide the groundwater flow solution that the transport model requires to simulate the magnitude and distribution of nitrogen in the aquifer within the study area. The models used data from existing sources including the results of the USGS recharge and groundwater modeling studies (Johnson et al., 2014; and Gingerich, 2008). The groundwater flow model produced good agreement with the available measured water level data and produced the requisite groundwater flow solution for the transport model.

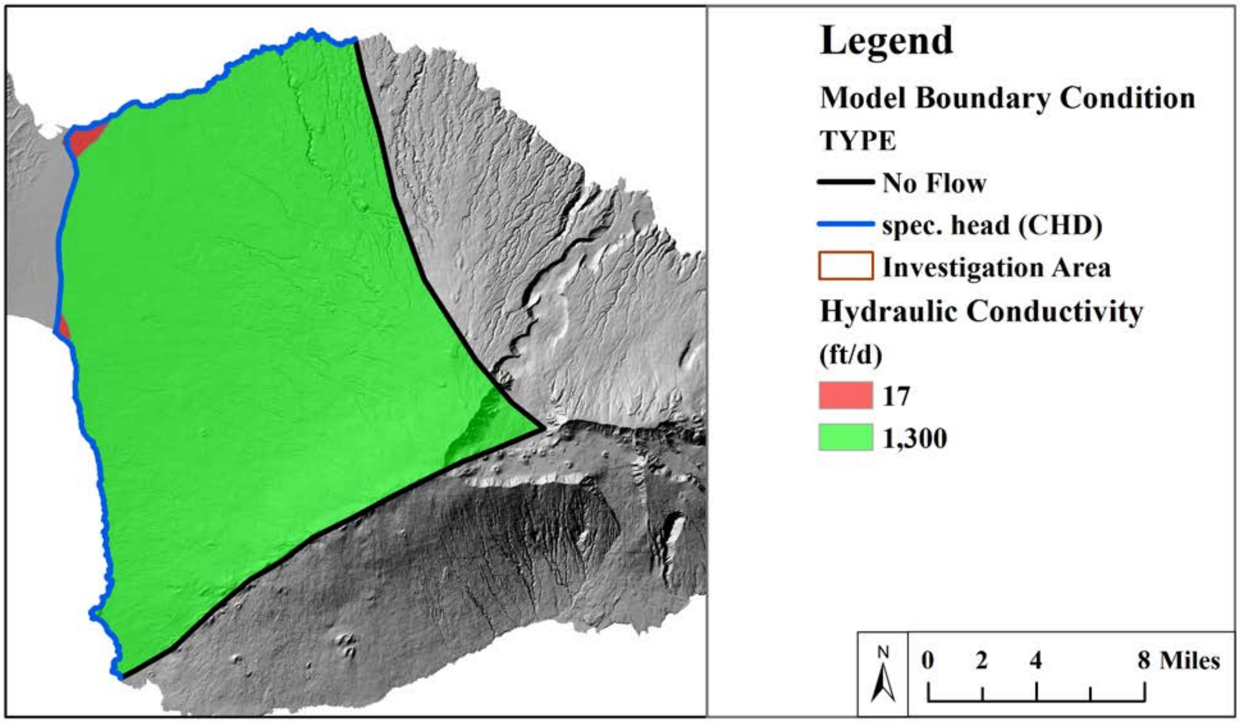

Figure 2-1. A map of the model domain, lateral boundary conditions, and hydraulic conductivity

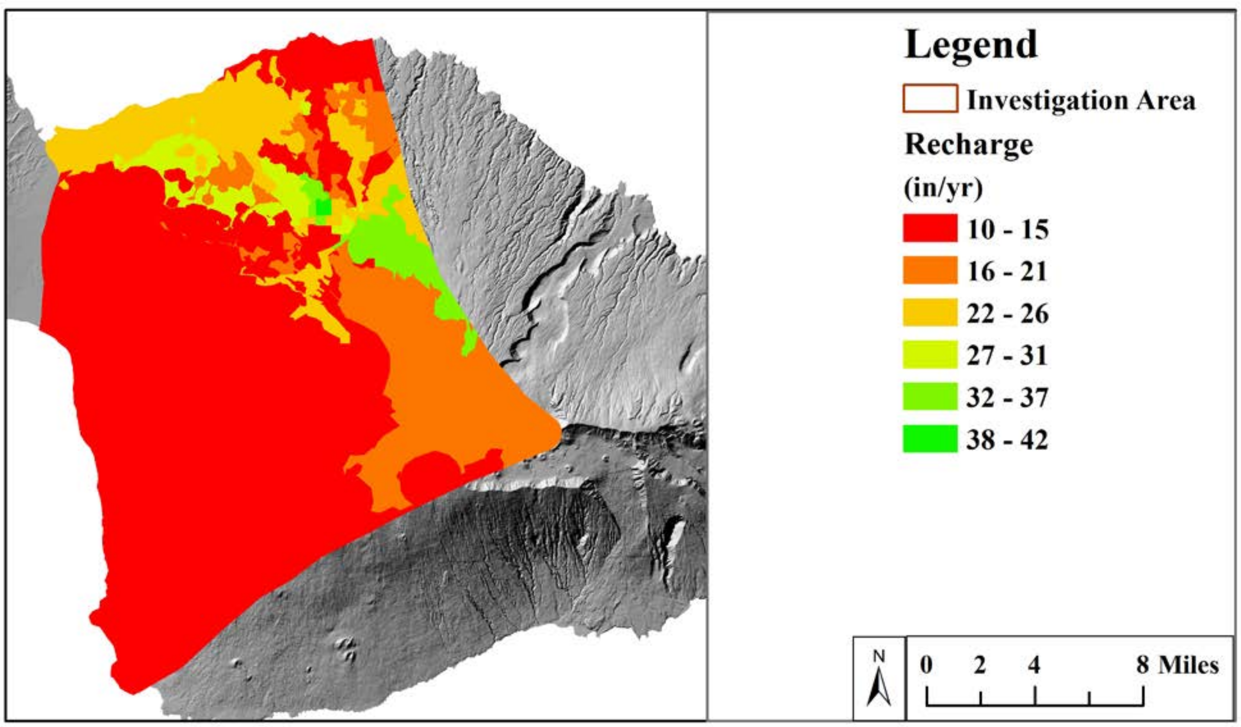

Figure 2-2. A map of the recharge distribution for the Upcountry Maui groundwater flow model

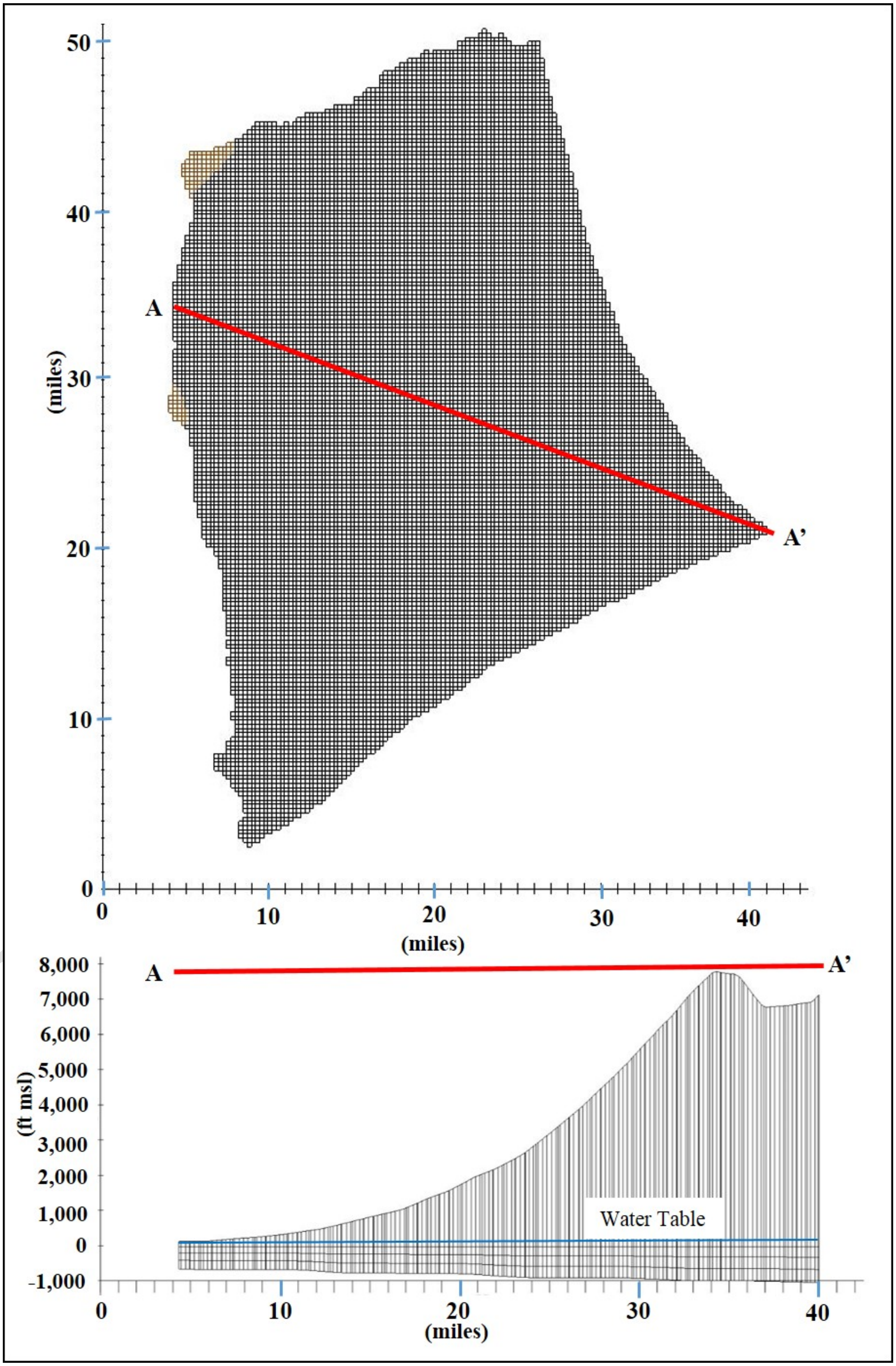

Figure 2-3. The numerical model grid in plan view and cross section

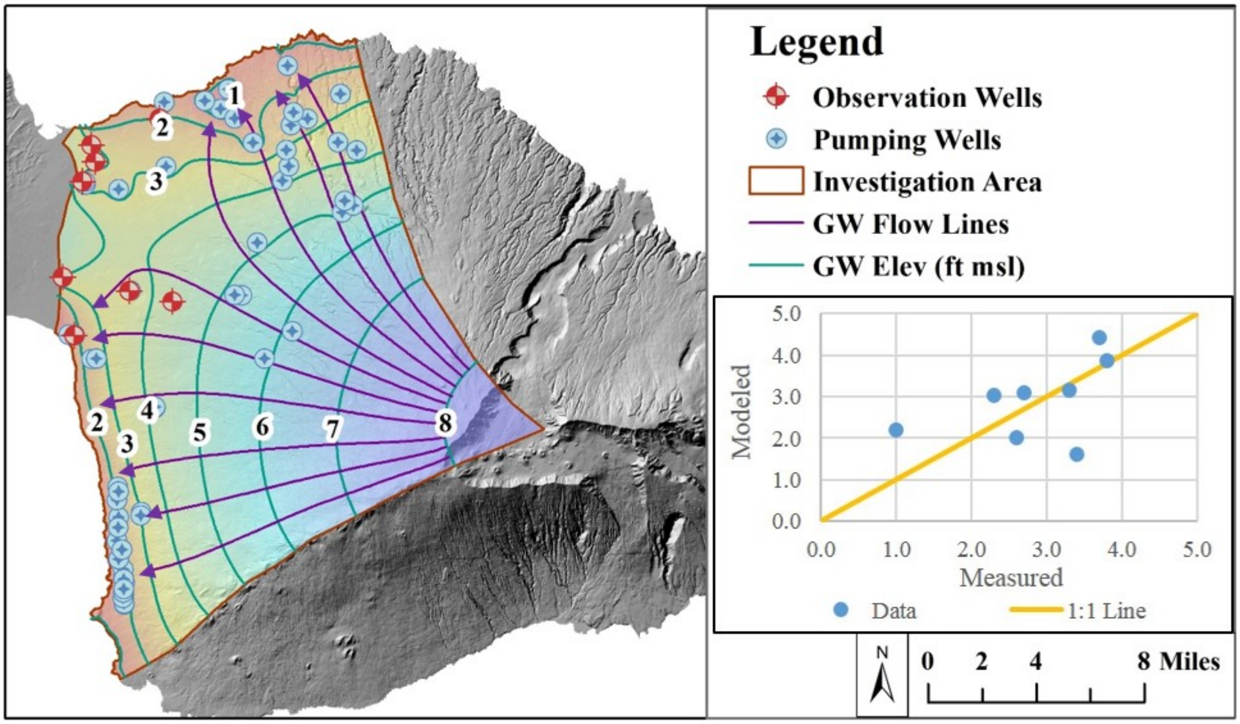

Figure 2-4. A map of the simulated water table, pumping and observation wells, and calibration graph

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SECTION 3 UPCOUNTRY MAUI NITROGEN TRANSPORT MODEL

3.1 INTRODUCTION

A groundwater transport model was developed to test if the assumed sources of groundwater nitrogen would produce simulated concentrations in the groundwater consistent with that measured by the Upcountry Maui Groundwater Nitrate Investigation. The assumed sources were: golf course irrigation with recycled water, former pineapple cultivation, former sugar cane cultivation, and OSDS leachate. It was further assumed that livestock operations at the Haleakala Ranch upgradient of the some of the sampled wells was not a significant source of nitrogen to the groundwater. Section 3.4 of the Report provides the rational for this assumption in more detail.

Nitrogen isotopes were used by the Upcountry Maui Groundwater Nitrate Investigation to link the nitrate in the wells to potentially contaminating activities occurring in the zone of contribution to the well. Wastewater and animal wastes are enriched in nitrogen-15, the heavy isotope of nitrogen. The groundwater samples with high nitrate concentrations were also enriched in nitrogen-15, expressed as a ratio of the nitrogen-15 enrichment ($\delta^{15}N$) relative to the abundance of the common isotope, nitrogen-14. While the 7,000 plus cesspools in Upcountry Maui are suspected to be the primary cause, leaching of animal wastes from Haleakala Ranch operations could also account for the elevated $\delta^{15}N$ values. For example, the Pukalani Golf Course and Omaopio-Esty Wells with high nitrate and $\delta^{15}N$ values, are downgradient of the Haleakala Ranch properties where there are livestock operations. During the field portions of this study, no large concentrations of animals were observed, but the investigation was limited to what could be observed from the road. Reasonable agreement between the simulated and measured groundwater nitrogen concentrations using the assumed nitrogen sources would strongly indicate that the assumed sources of nitrogen are in fact the primary sources of groundwater nitrogen.

3.1.1 Rationale for Simulating Total Nitrogen

Total dissolved nitrogen rather than nitrate was modeled since nitrogen in wastewater is predominantly ammonium and dissolved organic nitrogen (DON), and ammonium is major component of fertilizer. The sampling results show the total groundwater nitrogen concentration was significantly greater than the sum of the nitrate, nitrite, and ammonium concentrations. This indicates that a significant fraction of the groundwater nitrogen is organic nitrogen and the transformation to nitrate is not complete. Section 1.4.1 discusses the groundwater nitrogen chemistry in more detail. MT3D does not do the nitrogen transformation analysis making the modeling of nitrate fate and transport difficult. Simulating the total dissolved nitrogen load rather than nitrate alone, removes the requirement to do the nitrogen transformation analysis. Groundwater nitrogen simulation results can be compared with the measured groundwater nitrogen chemistry without having to account for the completeness of the nitrogen species transformations.

3.2 TRANSPORT MODEL DESCRIPTION

3.2.1 Transport Modeling Code Selected

Transport modeling codes simulate the distribution and concentration of selected dissolved species in groundwater. The modeling code selected was the Modular Three-Dimensional Multi-species (MT3D) transport model for simulation of chemical movement and dispersion in groundwater systems (Zheng and Wang, 1999; and Zheng, 2010). MT3D uses the MODFLOW groundwater flow solution to simulate the movement of dissolved contaminants in the groundwater. MT3D simulates the movement of contaminants due to the flow of groundwater (advection), the spreading of the plume due to small scale heterogeneities in the aquifer (dispersion), and chemical decay. MT3D can simultaneously simulate the transport of multiple species and this study took advantage of that capability by modeling the different nitrate sources as separate species. These species were nitrogen from natural sources, former sugar cane cultivation, former pineapple cultivation, application of recycled water applied to the Pukalani Golf Course, and OSDS leachate.

3.2.2 Simulated Nitrogen Flux to the Groundwater

All nitrogen input into the aquifer was incorporated into the recharge. Recharge into the model was that estimated by the USGS (Johnson et al., 2014). The recharge polygons were assigned a representative nitrogen concentration to account for the mass nitrogen flux from the various sources. The nitrogen recharge concentrations for former sugar and pineapple were assigned to produce a groundwater nitrogen concentration comparable to those measured in west Maui wells located in similar agriculture settings (Figure 3-1). A review of the west Maui groundwater nitrate data (Glenn et al., 2012; and DOH, 2017) showed that wells located in former pineapple fields had nitrate and total nitrogen concentrations in the range of 0.5 to 1.5 mg/L. Wells located in former sugar cane fields had nitrate and total nitrogen concentrations of 1.5 to 3.5 mg/L.

There are more than 10,000 OSDS with the model domain. An OSDS is any wastewater system that discharges effluent within the parcel where it was generated (e.g., cesspools, septic systems, aerobic treatment units, advanced contaminant removal systems). It was beyond the capability of the computer resources available to simulate the nitrogen input from each OSDS separately. The OSDS nitrogen load was incorporated into the recharge coverage. Where the zone of OSDS density was equal to or greater than 100 units per square mile, the recharge polygons were refined to an approximate size of 500 m (1,640 ft) on each side. In ArcGIS the total nitrogen mass flux from OSDS within each recharge polygon was summed and a concentration computed that would input the appropriate daily mass of OSDS nitrogen into the model. The equation below shows how the OSDS leachate concentrations were computed.

$$[N_{OSDS}]=\text{N-LOAD}_{OSDS}/\text{RCHG-VOL}*(1/1,000)$$

$[N_{OSDS}]$ = nitrogen concentration in the recharge from OSDS (mg/L)

N-LOAD_{OSDS} = sum of the daily N load from the OSDS within the recharge polygon (kg/d)

RCHG-VOL = recharge volume for the recharge polygon (m^3/d)

(1/1000) = factor to convert units of kilograms and cubic meters to milligrams and liters

Table 3-1 lists the OSDS loading rates and the simulated recharge concentration of nitrogen for each of nitrogen sources. The nitrogen removal rates for septic systems with leach fields are for silty clay and loam type soils (Tasato and Dugan, 1980; and WERF, 2009b). These soil types are prevalent in Upcountry Maui (Figure 3-2). No attenuation of nitrogen was assumed for cesspools since the depth of the cistern is well below the zone of evapotranspiration where plant uptake could reduce the amount of wastewater leaching to the groundwater. Figure 3-3 shows the major sources of groundwater nitrogen and the nitrogen concentrations assigned to the recharge coverage.

Table 3-1. Nitrogen concentrations used to model the Upcountry Maui study area

Nitrogen Source	Quantity	Nitrogen Conc. (mg/L)	Comments
OSDS within the model domain:	Effluent rate assumed 70 gal/day/person and 1.5 persons per bedroom		U.S. EPA, 2002
Cesspools	8,924	87	Septic influent nitrogen concentration (WERF, 2009a, Table 3-3)
Septic to Seepage Pit	464	58	Assumed 33 percent nitrogen removal rate in septic tank (WERF, 2009b, Table 3-3)
Septic to Soil Treatment	2,644	34	Assumed 41 percent nitrogen removal rate in silty clay and loam soils (Tasato and Dugan, 1980, Table 6; and WERF, 2009a, Figure 2-8)
Former Pineapple	2,800 hectares [1]	1.5	Adjusted recharge concentration so nitrogen concentration beneath pineapple fields was about 1 – 2 mg/L
Former Sugar Cane	14,700 hectares	5	Adjusted recharge concentration so nitrogen concentration beneath sugar cane field was about 2 – 5 mg/L
Recycled Water Application to the Pukalani Golf Course	370 hectares	7	Accounts for golf course fertilizer and the additional nitrogen in the recycled water
Soil Nitrogen	70,000 hectares	0.3	Applied to entire model domain to simulate the assumed background nitrogen concentration of 0.3 mg/L

Note: [1] hectare = 2.471 acres or 10,000 square meters

3.2.3 Transport Model Parameters

The primary transport model parameters are dispersivity, porosity, and chemical decay. Dispersivity is a parameter used to account for the spread of a dissolved plume. There are two major processes that cause the plume spreading. The first is referred to as hydrodynamic dispersion where the multiple pathways taken by the solute result in different transport velocities and small scale deflections in travel direction. The second process is molecular diffusion caused by a concentration gradient. However, hydrodynamic dispersion is the dominant plume spreading mechanism and molecular diffusion is frequently not considered as was done for this model (Freeze and Cherry, 1971, pgs 392-393; Fetter, 1993, pgs 54-56). Dispersivity is assigned a value of length that is applied to the model calculated groundwater velocity to compute the degree of spreading as the simulated solute moves from grid cell to grid cell. The dispersivity value used for this was the best fit value of 25 m used by Glenn et al. (2013) when modeling a tracer test done to track wastewater injection in west Maui. Transverse and vertical dispesivities were assigned values of 2 m and 0.2 m respectively.

The porosity of the geologic formations will affect the velocity at which the plume spreads and the simulated concentration of the nitrogen in the aquifer. The porosity represents the fraction of the rock that is interconnected pore space through which groundwater and dissolved nitrogen travel. The porosities assigned were the same as those used by Gingerich (2008) and were 0.15 for the Kula/Honomanu Lavas and 0.30 for the sedimentary materials.

Nitrogen in the wastewater gets transformed to nitrate when it enters an aerobic environment. Nitrogen loss due to treatment in the septic tank and leachfield was taken into account in the assigned loading rate. No other transformations of decay are assumed and nitrogen is otherwise treated as a conservative contaminant, meaning that it does not sorb (attach) to the aquifer matrix or decay to another species.

Since cesspools are the dominant OSDS this assumption could lead to an overestimation of the groundwater nitrogen concentration.

As with the groundwater flow model, boundary conditions were assigned to the transport model. The primary boundary condition assigned was a specified flux of nitrogen at the top boundary as described in Section 3.2.2. Figure 3-3 shows the nitrogen concentrations assigned to different recharge polygons relative to the primary sources of nitrogen to the groundwater. The other boundary condition was a default specified concentration assignment at the lateral and bottom boundaries of the model.

3.2.3.1 Upcountry Maui Groundwater Nitrogen Model Results

Figure 3-4 maps the simulated groundwater nitrogen concentration relative to that measured during the Upcountry Maui groundwater sampling. Figure 3-4 uses identical color shading for modeled and measured groundwater nitrogen concentrations. So in essence, if the model assumptions are correct, the groundwater nitrogen background color (modeled concentration) and the color of symbols (measured concentration) should be similar or the same. This does seem to be the case indicating good spatial correlation between the modeled and the measured total nitrogen. Figure 3-5 graphs the measured groundwater nitrogen versus that simulated by the transport model. Both the map (Figure 3-4) and the graph (Figure 3-5) show good agreement between the modeled and measured data. In Figure 3-5, the modeled values follow the trend of the 1:1 correspondence line (in a perfect model fit all data points would fall on the 1:1 line), but generally fall below the line. This indicates that the model under predicts the groundwater nitrogen. The average error between the modeled and measured groundwater nitrogen values was -2.2 mg/L. The BRE-1 and Omaopio-Esty Wells had the largest error, where the model significantly under-predicted the groundwater nitrogen concentration. Two (2) wells, the Omaopio-Esty and BRE-1 Wells had measured groundwater nitrogen concentrations significantly greater than those simulated (as indicated by the points falling below the 1:1 line). These wells are on the lower edge of the nitrogen plume where there is a sharp gradient and a short distance down gradient from areas where the model predicted significantly elevated groundwater nitrogen concentrations. The model over predicted the concentration in the West Kuiaha Meadows Well. Similar to the BRE-1 and Omaopio-Esty Wells, this well located a short distance down gradient from an area with a very low simulated groundwater nitrogen concentration. One modeling assumption is that the infiltration path from the ground surface to the water table is strictly vertical. In reality, the slope of the lava bedding will tend to offset the infiltrating water downslope. The net effect would be that the infiltrating nitrogen plume would reach the water table downslope from that modeled. This offset downslope of the infiltrating groundwater would tend to increase the agreement between the simulated and measured nitrogen concentrations in the Omaopio-Esty, BRE-1, and West Kuiaha Meadows wells.

As stated above, the primary purpose of the Upcountry Maui groundwater flow and transport model was to test the hypothesis that former sugar cane and pineapple cultivation, golf course irrigation and fertilizers, and OSDS leachate were the sources of the elevated groundwater nitrogen concentrations. The good agreement between the measured and modeled groundwater nitrogen concentrations do support this hypothesis.

The contaminant of concern is nitrate rather than total groundwater nitrogen. The distribution of nitrate in the groundwater was estimated by multiplying the modeled groundwater nitrogen by the average fraction of measured groundwater nitrogen that was nitrate. Figure 3-6 maps the distribution of the nitrate in the groundwater based on the simulated groundwater nitrogen concentrations. It is important to note that the drinking water MCL for nitrate of 10 mg/L appears to be exceeded in the northern part of the study area between the Pookela and Pukalani Golf Course Wells.

3.2.4 Groundwater Nitrogen from the Different Sources

To evaluate the relative contribution of each groundwater nitrogen source, the groundwater from the major nitrogen producing activities were modeled as different species. So, a model product was the simulated distribution of groundwater nitrogen from each designated source. Figure 3-7 shows the simulated distribution of groundwater nitrogen from golf courses (a), former pineapple (b), former sugar cane cultivation (c), and OSDS (d). Since nitrogen from natural sources was uniformly applied over the model, no map was generated for this source. The groundwater nitrogen contribution from golf courses and former pineapple cultivation were minor with the maximum nitrogen concentration from each of about 1.5 mg/L. Leaching of past applications of fertilizer in areas of former sugar cane agriculture are estimated to produce groundwater nitrogen concentrations of up to about 5.1 mg/L in the lower elevations of the study area. As described in Section 3.2.3 the low nitrogen concentrations in the area of former sugar cane agriculture near the western boundary of the model domain was due to the zero concentration condition imposed by the model at this boundary. Based on this groundwater nitrogen transport model, leachate from OSDS accounts for a majority of the groundwater nitrogen in mid-elevations of Upcountry Maui. This is particularly true where in the areas of high OSDS density (shown as areas where the OSDS density is 500 units per square mile or greater). Also, in the southern part of the study area, leachate from OSDS in the Maui Meadows development results in significantly elevated groundwater nitrogen. While this does not pose a drinking water issue it may result in aggressive algae growth in the shallow coastal areas where the nitrogen contaminated water discharges to the ocean. The groundwater nitrogen from natural sources is not shown since its contribution was evenly distributed throughout the model.

3.3 SUMMARY AND CONCLUSIONS

This study simulated the sources of dissolved nitrogen to the groundwater and the distribution of groundwater nitrogen through the groundwater in east-central Maui. Groundwater nitrogen rather the nitrate, the contaminant of concern, was simulated since dissolved nitrogen comes in a variety of species with transformation between species occurring during the infiltration and groundwater transport process. The sources of groundwater nitrogen simulated were:

- Natural sources with an assumed infiltration concentration of 0.3 mg/L;
- Former sugar cane cultivation with an assumed infiltration concentration of 5 mg/L;
- A golf course where recycle water was applied for irrigation with an assumed nitrogen concentration of 7 mg/L;
- Former pineapple cultivation with an assumed nitrogen concentration of 1.5 mg/L; and
- OSDS with the recharge concentration varying based on OSDS type, mass nitrogen discharge flux, and the recharge rate (refer to Table 3-1 and Figure 3-3).

The goal of the transport modeling was to evaluate whether or not nitrogen leaching from these five (5) sources could account for the distribution and magnitude of groundwater nitrogen measured by the Upcountry Maui groundwater nitrate investigation.

The groundwater nitrogen transport model produced good agreement with distribution of groundwater nitrogen with the model results where the relative magnitude of the simulated concentration tracked well from the most northerly wells to the most southerly wells. However, overall the model under predicted the measured concentration of groundwater nitrogen. This is attributed to the water being deflected somewhat downslope during the infiltration process rather than strictly vertical as the model assumed. Offsetting the simulated plume downslope would result in a better quantitative agreement between the simulated and measured groundwater nitrogen concentrations. No downslope adjustment was attempted because there is no reliable method to evaluate the degree downslope the infiltrating water would be offset.

The model results indicate that in the western portion of the study area that former sugarcane is the primary source of groundwater nitrogen with concentrations up to about 5 mg/L. The groundwater nitrogen concentrations resulting from irrigating the Pukalani Golf Course with recycled water and from former pineapple cultivation were both about 1.5 mg/L. Leachate from OSDS dominate the groundwater nitrogen with peak concentrations about 20 mg/L. The combined groundwater nitrogen concentration from all sources reached about 22 mg/L. Of this at least half would be in the form of nitrate meaning that there are likely areas in groundwater beneath Upcountry Maui where the drinking water Maximum Contaminant Level of 10 mg/L for nitrate is exceeded.

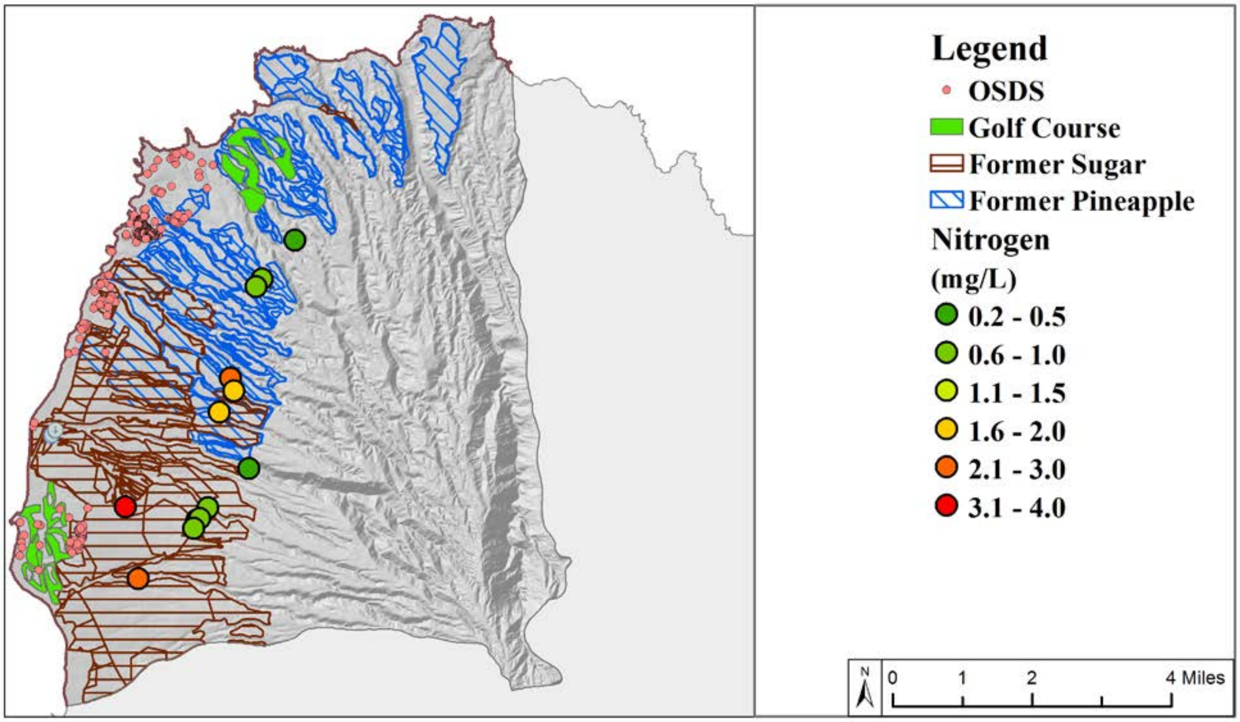

Figure 3-1. Groundwater nitrogen in west Maui with similar agricultural setting to Upcountry Maui

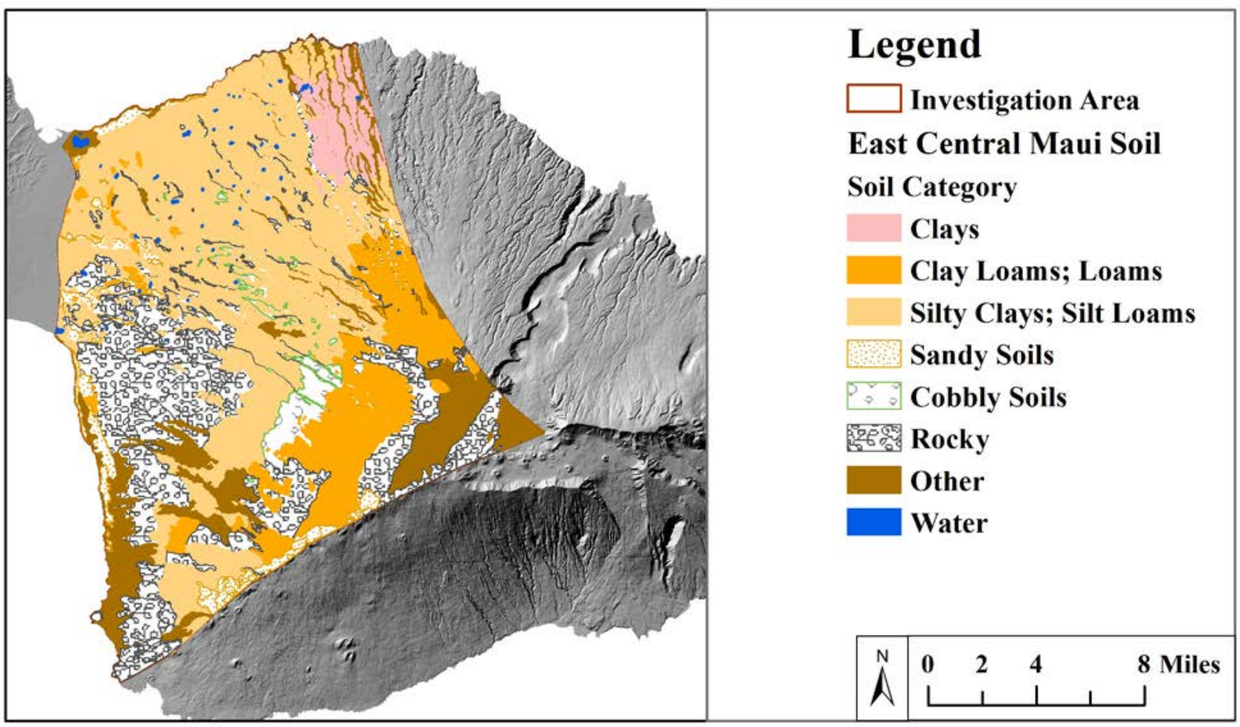

Figure 3-2. A map of the soil type categories in east-central Maui

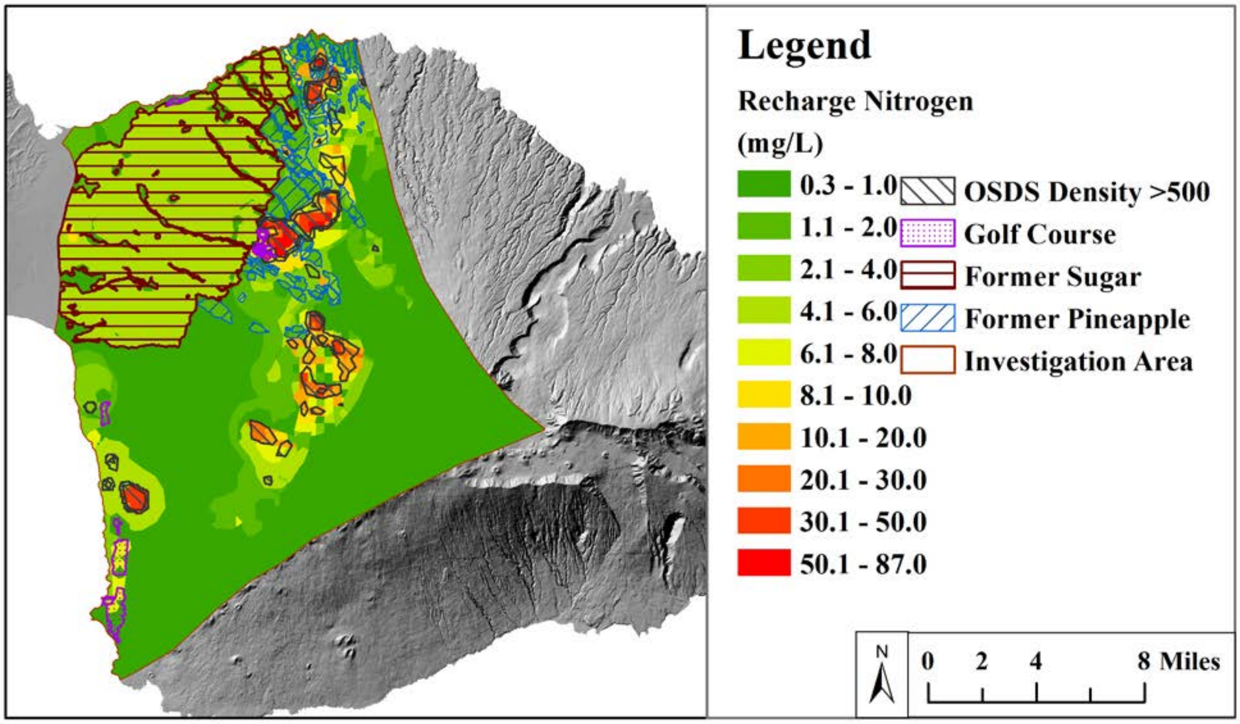

Figure 3-3. The nitrogen recharge concentrations and sources of groundwater nitrogen

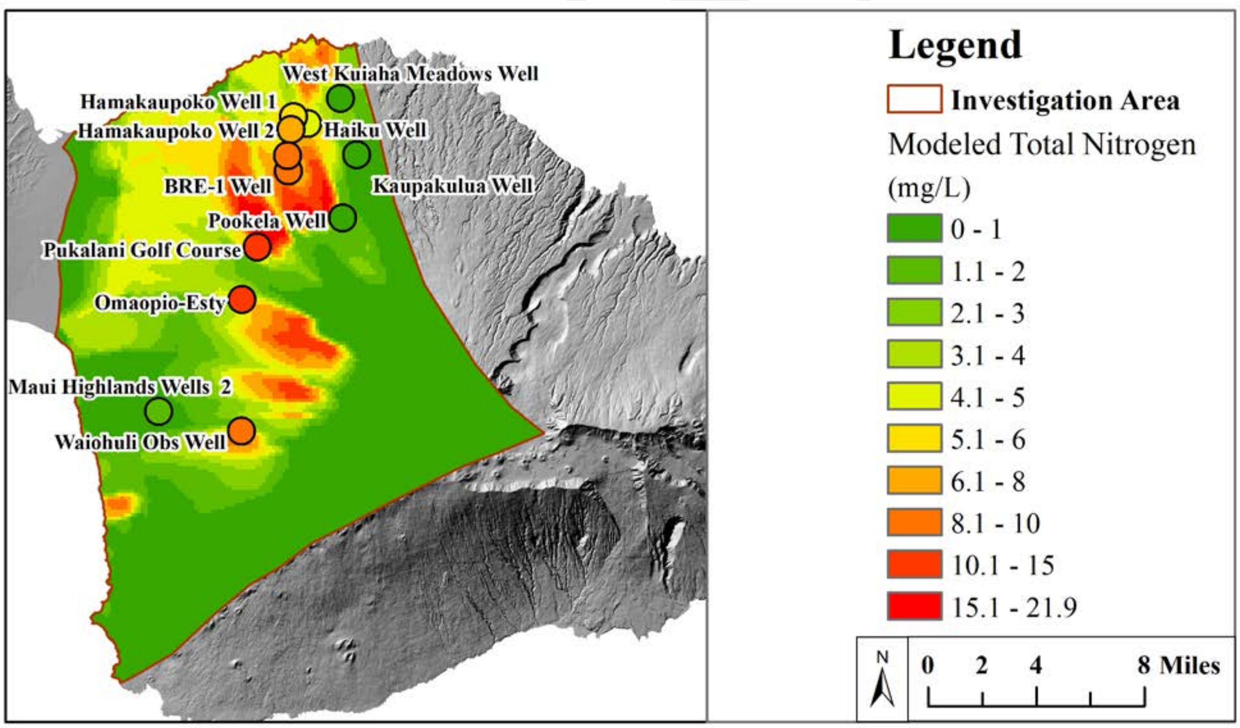

Figure 3-4. The modeled and measured distribution of groundwater nitrogen

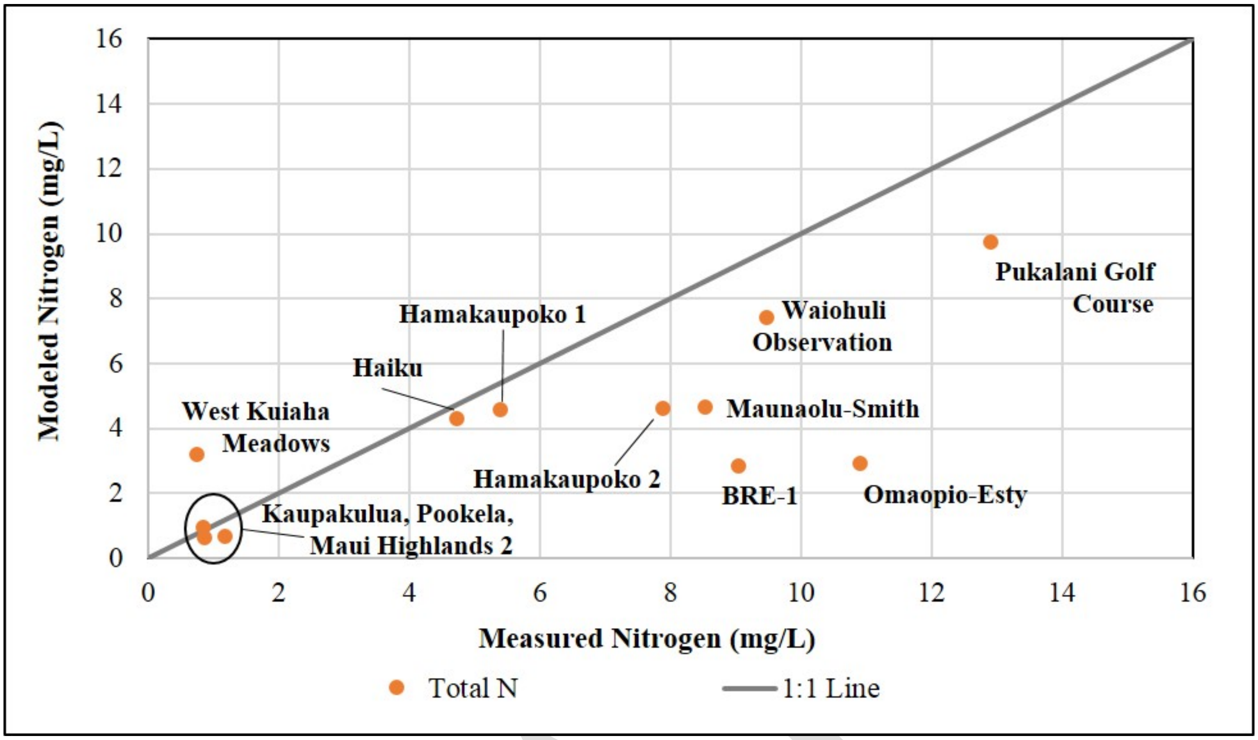

Figure 3-5. A graph of the measured groundwater nitrogen versus the results of the transport model

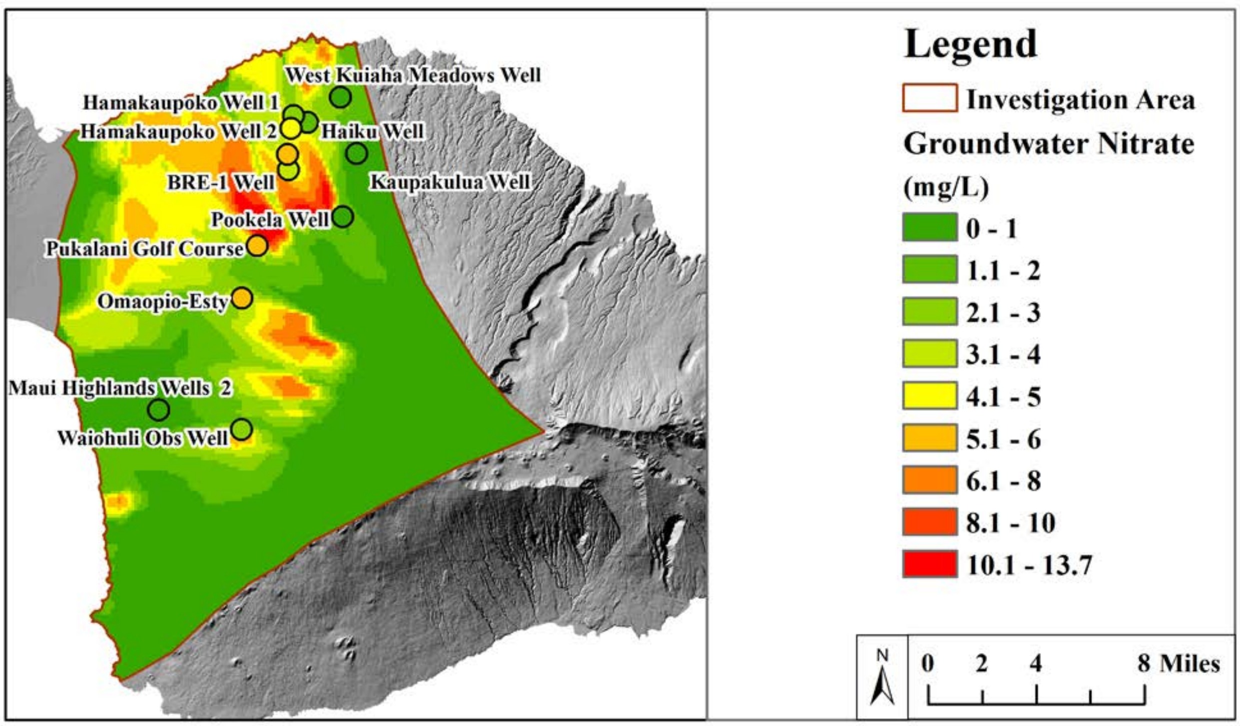

Figure 3-6. The distribution of calculated groundwater nitrate and the measured nitrate concentrations

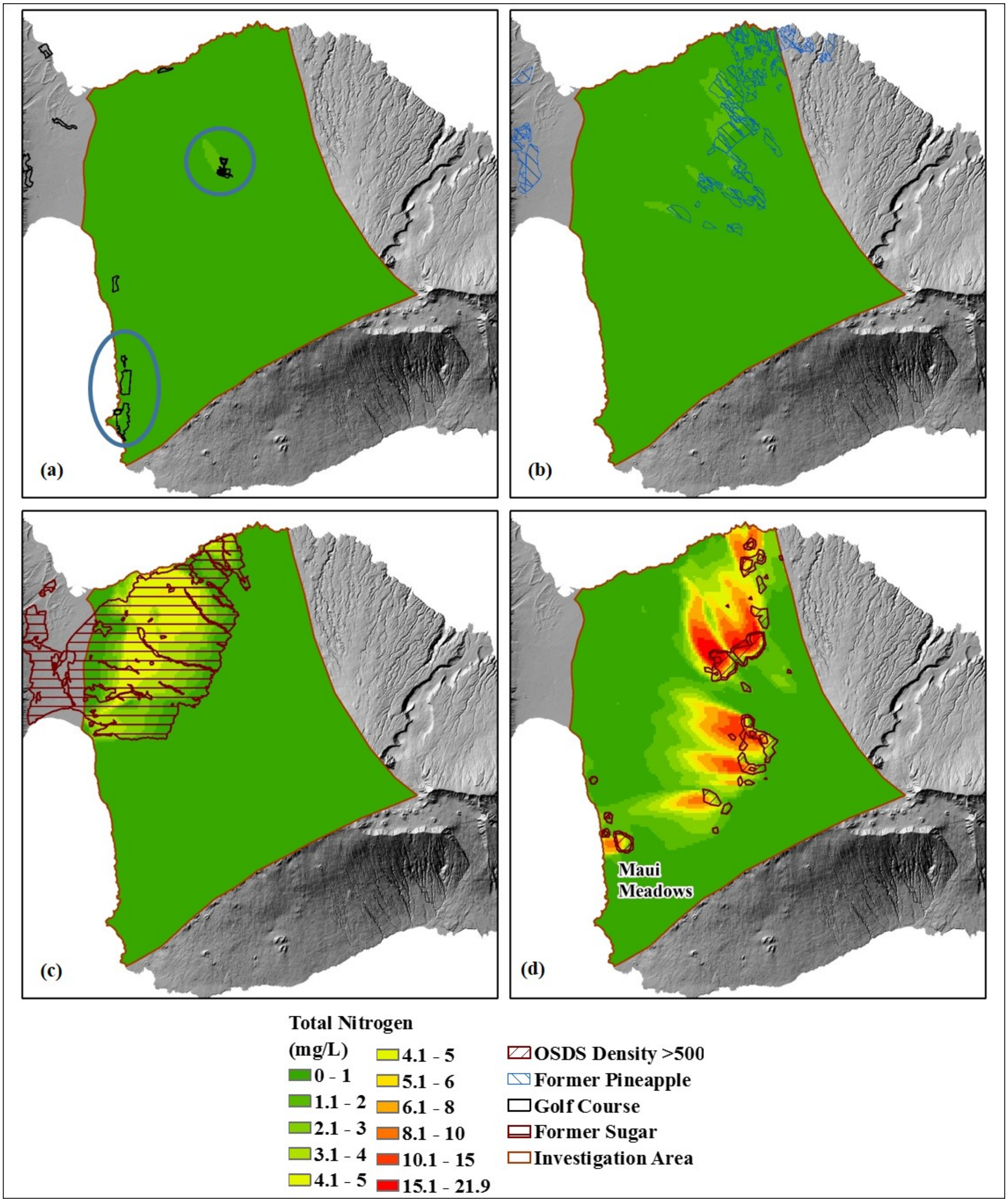

Figure 3-7. The modeled groundwater nitrogen from the primary sources

SECTION 4 FINAL SUMMARY AND CONCLUSIONS

4.1 SUMMARY

This report details the methods and data used during the construction and running of a groundwater model to simulate the distribution of dissolved nitrogen in the groundwater of Upcountry Maui. The groundwater processes used in this modeling effort included groundwater recharge, groundwater flow in the aquifer, pumping, the limited groundwater exchange between east and west Maui, and the discharge of groundwater to the coast. The transport processes simulated included the flux of nitrogen into groundwater by way of groundwater recharge, and the distribution of nitrogen by groundwater flow due to the hydraulic gradient and the plume spread due to hydrodynamic dispersion.

Data utilized in this model were drawn from CWRM well and pumping records, previous SWAP and OSDS model of east Maui (Whittier et al., 2004; and Whittier and El-Kadi, 2014), the USGS groundwater flow model of central and west Maui (Gingerich, 2008) and various GIS coverages from the State GIS website (http://planning.hawaii.gov/gis/download-gis-data/). The groundwater nitrogen concentrations used for the transport model evaluation targets were those values measured by the Upcountry Maui Groundwater Nitrate Investigation. The modelled distribution of nitrate, the contaminant of concern, was estimated based on the measured relationship between the total groundwater nitrogen concentrations and the nitrate concentrations.

4.2 MODEL LIMITATIONS

The numerical model developed for this study simulates groundwater flow and groundwater nitrogen distribution at a regional scale and may not accurately replicate localized conditions. The result of this limitation is that there is an element of uncertainty at specific points in the model; however, on the larger regional scale the model results reflect actual conditions. The groundwater flow model only simulated freshwater flow in the aquifer by assuming the mid-point of the freshwater/saltwater transition zone constituted a no-flow boundary. In actuality, the groundwater flow system has both fresh and saltwater components with mixing between the two. This is not a serious limitation since it is the upper part of the aquifer and inland from the coast that is of interest. The groundwater flow in the upper part of the aquifer is predominantly freshwater water with nearly uniform density. This condition was verified since all of the wells sampled had chloride concentrations that correlated to salinities of less than one (1) part per thousand.

The most significant limitations were:

- There was insufficient groundwater elevation data to validate the water table elevations simulated by the flow model;
- The assumption that infiltration path is strictly vertical; and
- Uncertainties about the transformations that dissolved nitrogen undergoes between the time water containing the nitrogen enters the shallow subsurface and is captured by wells.

Inaccuracies in the simulated water table elevation will lead to inaccuracies in the simulated groundwater flow paths and thus the simulated groundwater nitrogen distribution. However, the simulated water levels did provide good agreement with the water level data that were available and the simulated flow paths are consistent with current conceptual models for this area as inferred by the USGS groundwater modeling study (Gingerich, 2008).

The model assumed that the infiltrating water takes a strictly vertical path from the ground surface to the water table. In reality, due to the extensive unsaturated zone and the dip of the lava flows, the actual infiltration path is sub-vertical due being diverted somewhat downslope by dip of the lava bedding. The infiltrating water will tend to flow in a stepwise pattern downward from the ground surface. The net effect is likely that the actual groundwater nitrogen plume is offset downslope from the simulated plume. If this is true, it improves the agreement between the simulated and measure groundwater nitrogen concentrations.

There is significant uncertainty about the transformations that the dissolved nitrogen undergoes after it is released to the environment. This includes any processes that may reduce the nitrogen load to the groundwater by transformation to nitrogen gas. The groundwater data indicate that normally assumed transformation to nitrate is not complete since in many wells the total groundwater nitrogen concentration is significantly greater than the nitrate concentration. Also, the model tends to under predict the groundwater nitrate concentration. This may be due to assumption of strictly vertical infiltration not being accurate and also that the model layers at the well location are thicker than the screened interval of the wells sampled. The effect of the thicker layers would be to dilute the simulated groundwater nitrogen over a greater vertical interval that the well draws water from.

4.3 CONCLUSIONS

As with all groundwater flow and transport models there are significant limitations. In spite of the limitations described above, the model did adequately represent the distribution of groundwater nitrogen in the east-central Maui aquifer with sufficient accuracy to draw conclusions about the sources and relative magnitudes of nitrogen from the various sources. The model allowed this study to estimate the distribution of groundwater nitrogen between the points of measured data collected by the Upcountry Maui groundwater sampling. The groundwater sampling done during the field portion of this study provides a sufficient correlation between total dissolved nitrogen and nitrate to estimate the distribution of the regulated contaminant nitrate. The nitrate concentrations based on simulated groundwater nitrogen concentrations lead this study to conclude that the nitrate concentration in the groundwater downgradient from the areas with the highest OSDS density very like exceeds the drinking water Maximum Contaminant Level of 10 mg/L. The fundamental conclusion is that while there are multiple sources of nitrogen and nitrate to the groundwater, the source that elevates the concentrations to problematic concentrations is the high density of OSDS. The OSDS type that dominates Upcountry Maui and discharges the highest nitrogen load is cesspools.

4.4 ACKNOWLEDGEMENTS

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- Maui Department of Water Supply,
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- Pukalani Golf Course,
- Hawaii Department of Hawaiian Homelands,
- U.S. Geological Survey, and
- BRE-1 Well owners, Lot 3, LLC.

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