# Island Wide Nutrient Modeling and Quantification of Coastal Freshwater Discharge for Tutuila, American Samoa

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**Executive Summary**

Excessive nutrient discharge to tropical island coastlines has the potential to cause effects such as algal blooms and eutrophication. To address these issues, environmental regulatory agencies often set water quality standards for discharging surface waters. However, these standards generally only consider surface water nutrient concentrations, which do not account for groundwater discharge, variability in flow, or dilution effects. The calculation of nutrient loads by multiplying concentrations of nutrients or other constituents in discharging waters by volumetric rates of water discharge, can provide better predictions of water quality conditions that influence nearshore biota. Nutrient loading can, therefore, be a more accurate indicator of terrestrial impact compared to discharging surface waters. The primary objective of this report is to document the development of an island-wide dissolved inorganic nitrogen (DIN) loading model for the island of Tutuila, in the Territory of American Samoa. The DIN loading model integrates results from an open-source water budget model, multi-month water sampling data, and publically available streamflow data.

The model development workflow involved calculating observed DIN loading rates from all hydrologic pathways in watersheds where sufficient sample data were available, then using these observations to calibrate individual N-release rates for different modeled nutrient source types on Tutuila. The model separately considered loading from three hydrologic pathways including (1) stream base flow from shallow aquifers, (2) surface runoff generated during rainfall events, and (3) submarine groundwater discharge (SGD) across the ocean-land interface into the ocean. The anthropogenic DIN sources included in the model were on-site wastewater disposal systems (OSDS), livestock pigs, and synthetic fertilizer inputs to agricultural lands. All DIN source data were collected as geospatial datasets from local agencies. Measurements of historical and contemporary stream flow were also assessed to (1) validate water-budget calculated surface runoff rates, and (2) separate base flow and SGD rates from water-budget calculated net-infiltration in ungauged watersheds.

Final island-wide DIN loading rates were estimated by applying an optimization routine designed to minimize error between observed and modeled DIN loads as predicted by the prevalence of each type of land use/source in each watershed. Once island-wide DIN flux estimates were constrained, a simple isotope mixing model was also set up to predict the hypothetical average $\delta^{15}N$ value for discharge from each watershed, based on assumed end-member $\delta^{15}N$ values from previous studies. Overall, model results indicated SGD is an important coastal delivery mechanism for terrigenous N, OSDS units are the predominant anthropogenic source of DIN to Tutuila's coastal waters, and the most likely hot-spots for coastal nutrient impacts are the Tafuna-Leone Plain, a number of watersheds in the Pago Harbor area, the Tula region, and areas down gradient from Aasu and Aoloau Villages.

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**Acronyms and definitions of commonly used phrases**

**SGD –** Submarine Groundwater Discharge

**N –** Nitrogen

**DIN** – Dissolved Inorganic Nitrogen

**$NO_3^-$** - Nitrate

**$NO_2^-$** - Nitrite

**N+N –** Nitrate plus Nitrite

**$NH_4^+$** - Ammonium

**MYA –** Million years ago

**CTDEM** - Composite Terrestrial Discharge End-Member

**ASPA** - American Samoa Power Authority

**UHWRRC** - University of Hawaii Water Resources Research Center

**USGS** - United States Geological Survey

**SWB2** - Soil Water Balance 2 water budget model

**"DIN release rates"** here refers to the quantity of DIN released to the land surface or subsurface from an individual land use activity (e.g. OSDS or pigs); units in kg-DIN/day.

**"DIN loading rates"** here refer to the quantity of DIN transferred from the land to coastal ocean waters; units in kg-DIN/day.

# 1. Introduction

On tropical islands, excessive nutrient discharge to naturally oligotrophic coastal waters can significantly disrupt the nearshore nutrient balance, potentially causing algal blooms or eutrophication (McCook, 1999; Morton et al, 2011). In these environments, excessive nitrogen (N) loading, and in particular, high dissolved inorganic nitrogen (DIN) concentrations have been shown to significantly affect phytoplankton, turf algae and macroalgae growth (e.g. Smith et al., 1981; Pendleton, 1995). Because of these issues, coastal managers often monitor water quality and define nutrient-based water quality standards for surface water discharge and coastal surface waters (AS-EPA, 2013; Hawaiʻi Administrative Rules, 2013; SWRCB, 2015). These types of regulatory standards typically focus on sampling streams and rivers to assess terrigenous inputs, thereby only considering surface water pathways of nutrient transport. However, this paradigm does not acknowledge the often more important effects of diffuse or point source groundwater seepage otherwise known as submarine groundwater discharge (SGD). In tropical island settings across the globe, SGD has been shown to deliver an equivalent or significantly higher nutrient load to coastal ecosystems than streams (e.g. D'elia et al, 1981; Moosdorf, et al. 2015; Bishop et al., 2017; Shuler et al., 2019). Additionally, water quality standards are usually set to address nutrient concentrations, which may or may not be representative of the true impact of freshwater discharge, due to the effects of in-stream or coastal water dilution. For example, a very small stream with high nutrient concentrations will be quickly diluted upon reaching the ocean; however, a larger river with lower nutrient levels, may ultimately affect coastal water column nutrient concentrations more. Therefore, nutrient loads which account for variability in flow, more accurately reflect water quality conditions that may be more predictive of impacts from terrestrial discharge on nearshore biota. Nutrient loads are generally calculated by multiplying concentrations of nutrients or other constituents by volumetric rates of water discharge (e.g. Delevaux et al., 2018). Although other factors such as wind, nearshore circulation, and wave driven currents affect the fate of dissolved nutrients upon reaching the ocean, assessment of terrestrial loading affords a better understanding of how land use affects the coastal zone and also provides a comparative dataset for contextualizing biological field results or parameterizing environmental models.

## 1.1 Objectives

The primary objectives of this report are to:

(1) Provide island-wide DIN loading estimates at the watershed scale, for the island of Tutuila, in the Territory of American Samoa.
(2) Develop an impact prioritization ranking for all Tutuila watersheds, based on DIN loads.
(3) Rank DIN loading impacts of different hydrologic pathways, i.e. baseflow, SGD, etc…
(4) Rank impacts from different nutrient sources, i.e. wastewater, piggeries, etc…

These objectives were accomplished by implementing a spatially distributed DIN loading model, which was developed by integrating an island-wide water budget model, 12-month water sampling data from multiple watersheds, and publically available streamflow data collected over the last half-century by the United States Geological Survey (USGS) and local agencies.

Development of the DIN loading model supports work initiated through an American Samoa EPA monitoring and assessment project, *Improving Watershed and Island-Scale Resilience Through a Quantitative Priority-Setting Management Framework.* This project funded by the US EPA Wetland Program Development Grant, sets to integrate a diverse array of biological and physical datasets into a decision making framework that supports management of stressors threatening coral reef resilience in the territory. Results from the DIN loading model will be integrated into the framework to constrain the spatial distribution of nutrient stress on costal systems thereby providing natural resource managers with insight into which locations or land use activities may be high nutrient-management priorities.

## 1.2 Study Location

The island of Tutuila is the largest and most populous island in the Territory of American Samoa (Fig. 1). Tutuila is located in the South Pacific Ocean near the coordinates of 14° 20' S and 170° 40' W, has a land area of 142 $km^2$, and has a population of 56,000 (AS-DOC, 2013). Tutuila's climate is warm and humid, and due to its position within the South Pacific Convergence Zone, the island receives significant rainfall, between 1,800 to 5,000 mm/yr. depending on location (Daly et al., 2006). Geologically, Tutuila can be divided into two primary lithologic terrains (1) an older (1.5 MYA) series of highly eroded Pleistocene age shield volcanoes and (2) a geologically young (Holocene age) lava delta on the island's southwestern flank that is referred to as the Tafuna-Leone Plain (Stearns, 1944). The majority of Tutuila's development is located on the Tafuna-Leone Plain, with development off the plain concentrated on narrow strips of coastal land and in steep sided valleys wherever alluvial and marine deposition has created enough flat land to build. Three primary anthropogenic land use types (i.e. nutrient sources) have been previously identified on Tutuila by Shuler et al. (2017); these include (1) On-Site wastewater Disposal Systems (OSDS), (2) small-scale pig farms, and (3) agricultural fertilizers. Additionally, natural sources of nitrogen were found by Shuler et al. to produce fairly consistent background levels of dissolved nitrogen in environmental waters.

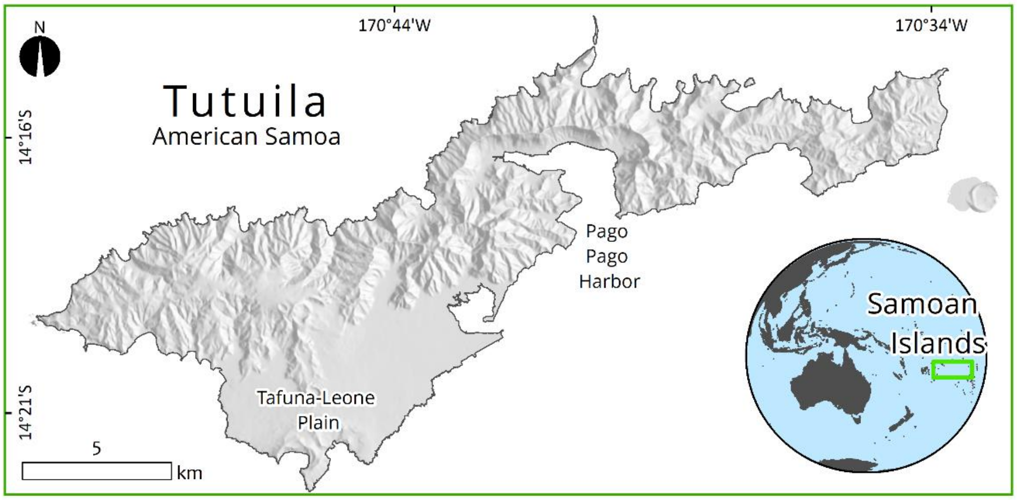


Figure 1: Study location map of Tutuila Island showing hill-shaded topography.

# 2. Methods and Results

## 2.1 Methodological Summary

The DIN loading model was developed by calculating observed DIN loading rates in watersheds where sufficient sample data were available, and then using these observations to calibrate individual DIN-release rates for each type of modeled anthropogenic nutrient source. Observed DIN loading rates were calculated by: (1) constraining coastal water discharge rates from all hydrologic pathways in each sampled watershed (2) multiplying hydrologic discharge rates by respective end member DIN concentrations thereby yielding DIN loading rates in kg per day, and (3) summing DIN loading rates from all three pathways to obtain total DIN flux to the coast for each watershed. High-resolution geospatial data used to determine the locations of modeled nutrient sources were primarily obtained from local agencies, which allowed for estimation of DIN loading rates across the whole island based on the prevalence of each type of source in each watershed. (Fig. 2). The hydrologic pathways considered in this model included (1) stream baseflow, which consists of groundwater derived streamflow originating from shallow aquifers, (2) surface runoff, which consists of overland storm-flow generated during rainfall events and (3) SGD, which is commonly defined as, *"direct groundwater outflow across the ocean-land interface into the ocean*" (Church, 1996).

Because streamflow and SGD observation data only exist for a limited set of watersheds (Figs. 3 and 4) measured flows were not used to directly calculate DIN loading. Instead, the measured streamflow observations were used to (1) validate water-budget surface runoff results, and (2) separate base flow and SGD rates from water-budget calculated net-infiltration in ungauged watersheds, thereby allowing the use of water discharge rates calculated by a previously developed SWB2 water budget model to be used for production of observed DIN loading rates. Water sample data was also only available for a limited number of the island's watersheds (Figs. 3 and 4). Therefore, the calibrated model was used to develop empirical relationships between land use and calculated DIN loads in sampled watersheds through regression analysis. Land use parameters included numbers of OSDS units, numbers of pigs in piggeries (small backyard-scale livestock rearing operations), and synthetic fertilizer inputs to agricultural lands. Once island wide DIN flux estimates were constrained, a simple isotope mixing model was also set up to predict the hypothetical average $\delta^{15}N$ value for discharge in each watershed, based on assumed end-member $\delta^{15}N$ values from previous studies. The details of these relationships and calculations are presented below.

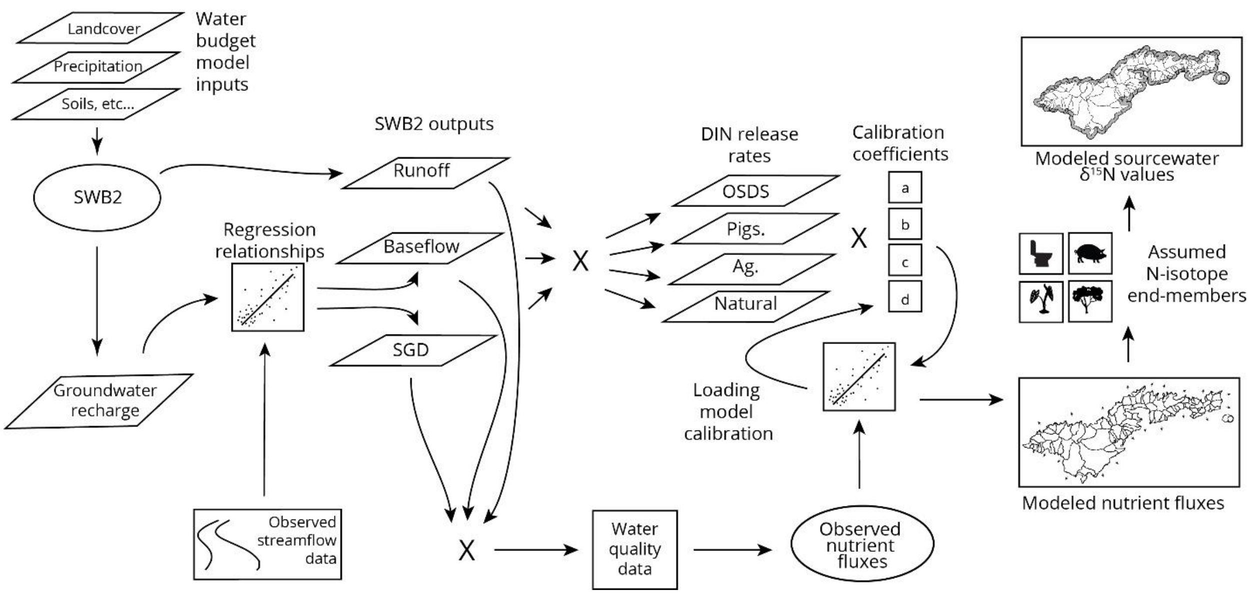


Figure 2: Schematic of DIN loading model and N-isotope mixing model workflow. The SWB2 component represents the water budget model used to determine water discharge rates and observed streamflow and nutrient fluxes from field data used to calibrate and validate the model. The DIN release rates were initially parameterized with values from Shuler et al. (2017) and final rates were determined through loading model calibration. The isotope-mixing model was used to develop uncalibrated estimates of $\delta^{15}N$ in DIN from all terrestrial discharging waters combined. Steps marked with Xs indicate multiplication of values used to calculate derived components.

## 2.2 Water Sampling and Nutrient Concentrations

Water sample data used for this work was procured from two main sources: (1) streamflow and coastal spring sampling data from the AS-EPA Phase 1 Ridge to Reef Project as documented by Comeros-Raynal et al. (2018) and coastal spring data, curated from sources including Shuler et al. (2017), Shuler et al. (2019), and Shuler (2019). The Ridge to Reef data was collected through monthly resolution water sampling at thirty-eight individual stream sites, over a one-year period between September 2016 to September 2017 (Fig. 3). All stream samples were collected at low tide and were taken at stream outlets to ensure samples were as representative as possible of actual coastal surface water discharge. Additionally, at each stream sample site, a staff gauge was installed in order to document the relative water height (stage) during each sampling event. While it is not possible to derive streamflow rates with stream height alone, stage measurements allowed the flow during each sampling event to be classified into a flow regime of either baseflow or surface runoff. This allowed calculation of separate nutrient fluxes from each flow regime (i.e. hydrologic pathway), which is important as the hydrologic processes that generate each of these types of flow are different. To distinguish between baseflow samples and surface runoff samples, the average flow for each site was calculated and used as a threshold value to classify each sampling event. Any sample taken when the stream height exceeded the mean was considered to be surface runoff, and any sample taken when the stage was lower than the threshold was classified as baseflow.

The Ridge to Reef dataset also included coastal spring samples taken at twenty-six locations throughout the island (Fig. 3). For most of these sites, the temporal spring sampling resolution was approximately every 3 months. Note that flow was not measured as the flow rates of individual coastal springs are not predictive of total SGD rates. To supplement this limited but important groundwater end-member dataset, additional coastal spring data taken at thirty-one locations between 2013 and 2018 as documented in Shuler et al. (2017) and Shuler (2019) were also grouped in with the Ridge to Reef coastal spring dataset (Fig. 3). All stream and coastal spring samples were analyzed for nitrate ($NO_3^-$), nitrite ($NO_2^-$) and ammonium ($NH_4^+$) concentrations, which when summed, represent the DIN concentration. See Shuler (2019) and Comeros-Raynal et al. (2018) for sampling and nutrient analysis methodologies.

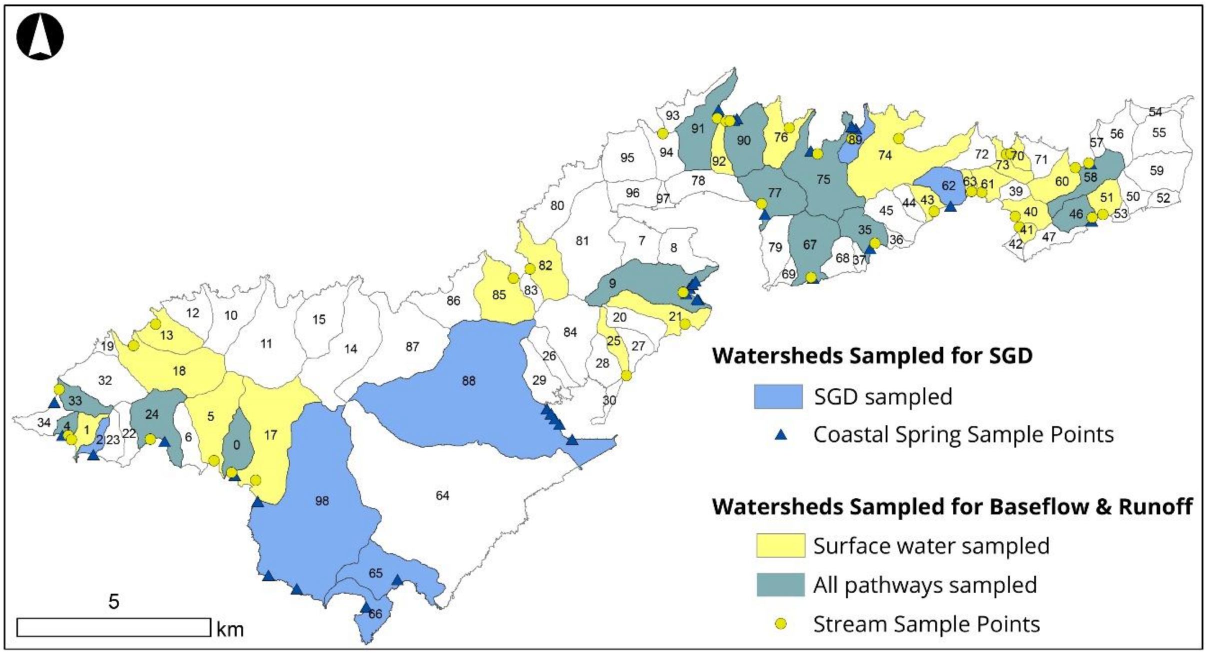


Figure 3: Locations of stream and coastal spring sample sites shown as circles and triangles, respectively, with shaded model watersheds draining to each site. Model designated watershed ID numbers are also shown.

## 2.3 Water Fluxes

### 2.3.1 Observed Streamflow Data

All available long-term streamflow measurement data for the island of Tutuila was consolidated and integrated for use in this study. A variety of continuous-record and partial record stream gauging stations have been set up and operated on Tutuila for different periods of record over the last half-decade. Starting in the 1950's, the USGS installed at least 11 continuous record streamflow measurement stations and operated them over various years extending until 2008 when all USGS operations in the territory ended. In 2016, the American Samoa Power Authority (ASPA) and the University of Hawaii Water Resources Research Center (UHWRRC) installed and began operating new streamflow stations as a collaborative effort. Some of the ASPA-UHWRRC stations are located at the same sites as old USGS stations and some are at new sites (Fig. 4, Table 1). Two main documents detailing methodology and summarizing the USGS flow data are Wong (1996), which provides data up to 1995, and Perreault (2010), which provides continuous-record USGS data for the time period up to 2008. All USGS data is also available from the USGS water data portal. (https://waterdata.usgs.gov/nwis). Streamflow data collection with the ASPA-UHWRRC network began in April 2016 and is ongoing as of this writing. Raw data is collected in the field on a quarterly basis and processed through an open-source code, which is available online at (https://github.com/cshuler/ASPA-UH_Integrated_Modeling_Framework).

Data from Wong (1996) were presented as a summarized mean and median flow for each station, whereas data from Perreault (2010) were given as transient streamflows, which were then separated into baseflow and runoff components using the turning point baseflow separation program (Wahl and Wahl, 1995). Streamflow data from the ASPA-UHWRRC network is also automatically separated into baseflow and surface runoff components using the same turning point method. The locations, periods of record, and measured flows from all of the continuous-record sites is presented in Table 1. Measured streamflow data were applied in this modeling effort to (1) validate modeled runoff values from the Soil Water Balance 2 (SWB2) model, and (2) provide justification for partitioning the hydrologic components of baseflow and SGD from the modeled net-infiltration total, as detailed in section 2.4.1.1.

Table 1: List of continuous record streamflow data stations, annualized total flows, and fractions of annual average baseflow and annual average surface runoff for each station. Data from Wong (1996), Perreault (2010), and Shuler and El-Kadi (2018a). Water flows from stations with data from both USGS and ASPA-UHWRRC efforts are presented with USGS average discharges listed first and ASPA-UHWRRC discharges listed second.

| USGS Site # | Watershed Name | Data Source | Longitude | Latitude | Record Start Date | Record Length | Average Flow ($m^3$/day) | Average Baseflow ($m^3$/day) | Average Surface Runoff ($m^3$/day) |
|---|---|---|---|---|---|---|---|---|---|
| 9205 | Aasu | USGS only | -170.759537 | -14.292619 | 12/1/1958 | 43.9 | 15,976 | 6,997 | 8,979 |
| 9310 | Afao | USGS only | -170.801802 | -14.330928 | 12/1/1958 | 38.2 | 3,841 | 1,248 | 2,593 |
| 9315 | Asili | USGS only | -170.795079 | -14.321321 | 11/1/1977 | 8.8 | 6,165 | 2,471 | 3,719 |
| 9600 | Alega | USGS only | -170.640106 | -14.278009 | 4/1/1958 | 18.4 | 2,936 | 1,615 | 1,321 |
| 9060 | Aoa | USGS only | -170.593170 | -14.267217 | 5/1/1958 | 13.6 | 1,028 | 367 | 661 |
| 9639 | Auasi | USGS only | -170.575363 | -14.269214 | 3/1/1972 | 14.5 | 758 | 220 | 538 |
| 9480 | Matuu | USGS only | -170.686646 | -14.297050 | 5/1/1958 | 38.8 | 3,621 | 636 | 2,862 |
| 9442 | Nuuuli | USGS and ASPA-UHWRRC | -170.710526 | -14.308333 | 7/1/1966 | 13.3 | 9,786 – 15,413 | 1,468 – 5,382 | 8,318 – 10,276 |
| 9120 | Afono | USGS and ASPA-UHWRRC | -170.651764 | -14.262611 | 11/1/1958 | 47.0 | 8,318 – 7,829 | 2,691 – 1,468 | 5,627 – 6,361 |
| 9175 | Fagasa | USGS and ASPA-UHWRRC | -170.720612 | -14.286192 | 7/1/1966 | 13.2 | 3,670 – 10,276 | 1,223 – 4,648 | 2,691 – 5,382 |
| 9335 | Leone | USGS and ASPA-UHWRRC | -170.781691 | -14.320453 | 12/1/1977 | 11.8 | 11,010 – 19,328 | 4,159 – 7,340 | 7,095 – 11,988 |
| 9495 | Fagaalu | ASPA-UHWRRC | -170.685150 | -14.291450 | 4/1/2016 | 3.0 | 20,135 | 7,888 | 12,247 |
| 9999 | Fagaitua | ASPA-UHWRRC | -170.617812 | -14.268472 | 3/1/2017 | 2.0 | 2,087 | 857 | 1,231 |
| 9250 | Maloata | ASPA-UHWRRC | -170.812130 | -14.306905 | 4/1/2016 | 3.0 | 18,711 | 12,013 | 6,698 |
| 9510 | Vaipito | ASPA-UHWRRC | -170.705075 | -14.276759 | 4/1/2016 | 3.0 | 13,040 | 4,232 | 8,807 |

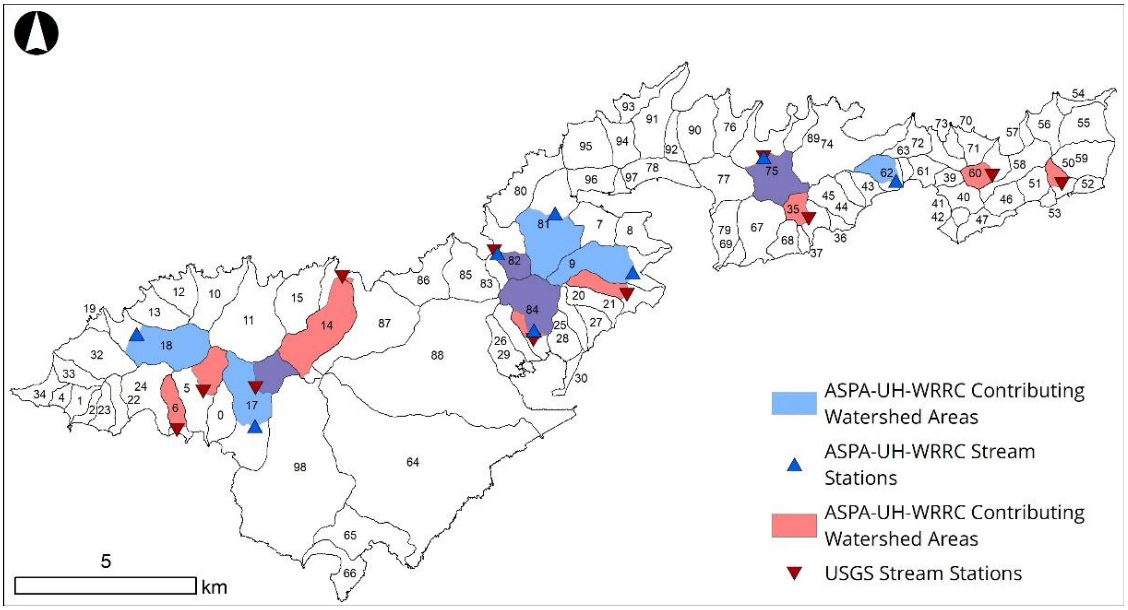

Figure 4: Map of continuous record streamflow stations and watershed areas representing the area measured by each gauge for ASPA-UHWRRC and USGS gauges. Note purple colored watershed areas represent locations of overlap between USGS and ASPA-UHWRRC datasets. Model designated watershed ID numbers are also shown.

### 2.3.2 SWB2 Water Budget Model Background

A recently completed groundwater recharge assessment by Shuler and El-Kadi (2018b) provides island-wide estimates of water budget components for Tutuila. While the Shuler and El-Kadi model was focused on calculation of groundwater recharge, the model code was made open-source and publically available, and therefore could be downloaded and modified to develop customized estimates of discharge from hydrologic pathways that are consolidated by user-set geographic boundaries. Shuler and El-Kadi applied the SWB2 water budget code, which was originally developed by the USGS, to develop the Tutuila Water Budget Model. The SWB2 code allows the user to create spatially distributed estimates of water balance components including precipitation, evapotranspiration, runoff, streamflow infiltration, and groundwater recharge. The water balance approach is based on the soil-water balance formulation originally developed by Thornthwaite-Mather (1955).

For this project, the Tutuila SWB2 model code, data, and results were obtained from an open source repository (https://github.com/UH-WRRC-SWB-model) and the gridded spatially distributed output was modified to calculate totalized water fluxes within the geographic watershed boundaries used in this study. The Tutuila SWB2 model input data included precipitation data, land use data, soil type data, direct infiltration layers, runoff-to-rainfall ratios, potential evapotranspiration data, maximum and minimum temperature data and mountain front recharge information. Information regarding sources and calculation of all inputs is detailed in Shuler and El-Kadi (2018b), which is also publically available for download at the above GitHub link. The SWB2 model produces spatially and temporally-distributed NetCDF datasets for each output parameter, including net-infiltration, runoff, interception, actual evapotranspiration, and others. Because the DIN loading model detailed in this work is focused on assessing delivery of DIN through all hydrologic pathways to the coastal zone, surface runoff and net infiltration were the primary SWB2 model outputs used in this study. Additionally, the SWB2 model was only designed to estimate water budget components above the soil zone, thus, the SWB2 model does not explicitly calculate baseflow or SGD. Baseflow originates from groundwater aquifers, thus the process of baseflow generation is dependent on subsurface processes, which are not included in the SWB2 model. To address this issue and to apply the model outputs for this study, the empirical relationship between baseflow, runoff, and SGD was determined with regression analysis between SWB2 modeled water budget components and observed streamflow counterparts from field data. This method relied on the assumptions that the island's water budget is in a steady state, and that all net-infiltration not extracted by wells, exits the island through streams as baseflow or through the coastline/nearshore benthos as SGD.

## 2.4 Dissolved Inorganic Nitrogen Loading Model

The Tutuila DIN loading model was developed using the following workflow steps: (1) island-wide discharge rates from all three hydrologic pathways were calculated for every watershed by using the SWB2 water budget model, (2) observed DIN fluxes were calculated in sampled watersheds by multiplying measured DIN concentrations from each hydrologic pathway by SWB2 calculated water fluxes, (3) The prevalence of anthropogenic and natural DIN sources in every watershed was determined by geospatial additions of the total numbers of OSDS units, pigs, and agricultural lands within each watershed, and (4) modeled DIN fluxes were calculated by using measured fluxes as calibration for an optimization routine that parameterized DIN release rates from the sources described in step 3, in order to obtain coastal DIN loading estimates for all watersheds. Each of these steps is described in greater detail below.

### 2.4.1 Model Workflow Step (1): Island-Wide Water Budget Modeled Discharge

#### 2.4.1.1 Modeled Baseflow and SGD

The SWB2 water budget model directly produces estimates of surface runoff and net-infiltration. However, baseflow and SGD estimates needed to be indirectly calculated from the net-infiltration output by assuming that net-infiltration (minus groundwater extraction) only leaves the island as SGD or baseflow. Under this assumption, modeled SGD and baseflow rates can be calculated by determining the fraction of net-infiltration that is partitioned to each component through analysis of observed baseflow rates. To accomplish this, the water lost to groundwater pumping in each watershed was first calculated from groundwater extraction rates as provided by ASPA. These watershed-totalized pumping rates were subtracted from SWB2 net-infiltration estimates in watersheds with continuous streamflow data. Observed baseflow rates were subtracted from the difference, which left the remaining water as the best available estimate of SGD for each observed watershed. The ratios of SGD and baseflow to net-infiltration in each measured watershed were averaged and these ratios were extrapolated to ungauged watersheds to estimate SGD and baseflow rates island wide. For measured watersheds using the Perreault (2010) and ASPA-UHWRRC streamflow observation datasets, average baseflow to net-infiltration ratios were 38% ± 24%, and 29% ± 13%, respectively, with the SGD fraction equaling 1 – the baseflow fraction. Performing a weighted average yielded a baseflow to net-infiltration ratio of 33% ± 17%, which was the value used to partition all SWB2-calculated net-infiltration into baseflow in ungauged watersheds. Note that the ± values given above represent 1σ standard deviations, and that the uncertainty on SGD estimates specifically was determined to be 48% based on a more direct comparison to measured SGD as described in the section below.

The mean baseflow to net-infiltration ratio was used to calculate island-wide modeled SGD and baseflow rates for all of Tutuila's watersheds except for those located on the Tafuna-Leone Plain. On the plain, very high aquifer permeabilities promote rapid infiltration, and no perennial streams flow in this region. Geologically, this is a result of extremely high hydraulic conductivities in young and fractured lava flows that make up the area (Bentley, 1975; Izuka et al., 2007). On the plain, stream channels are poorly developed or non-existent, and any baseflow that reaches the plain from the mountains above is rapidly lost to the subsurface through the process of mountain front recharge (Perreault, 2010). Therefore, for this work, all SWB2 calculated net-infiltration was classified as SGD in the plain area.

#### 2.4.1.2 SWB2 Validation and Uncertainty

The use of SWB2 to provide discharge rates for each of the desired streamflow components relied upon the assumption that the SWB2 model accurately estimated the total water discharging from the island, and was able to accurately partition incoming precipitation into surface runoff and net-infiltration. This assumption was tested by directly comparing measured surface runoff fractions from all continuous record streamflow observations to SWB2 calculated surface runoff totals for the watershed areas above each stream gauge. These comparisons as least-squares regressions (Fig. 5) had correlation coefficients ($r^2$) of 0.81, and 0.35 for the Perreault (2010), and ASPA-UHWRRC datasets, respectively, which suggests that the SWB2 model did a reasonable job of estimating surface runoff island-wide. Furthermore, the Mean Absolute Percentage Error (MAPE) of each regression provided an indication of the uncertainty implicit in the SWB2 model results. This error was 16% and 35% for the Perreault (2010), and ASPA-UHWRRC datasets, respectively, yielding a weighted average of 24%. This value was used to represent the uncertainty on the SWB2 discharge estimates, which could then be propagated through the DIN loading model to assess the final nutrient flux uncertainty bounds.

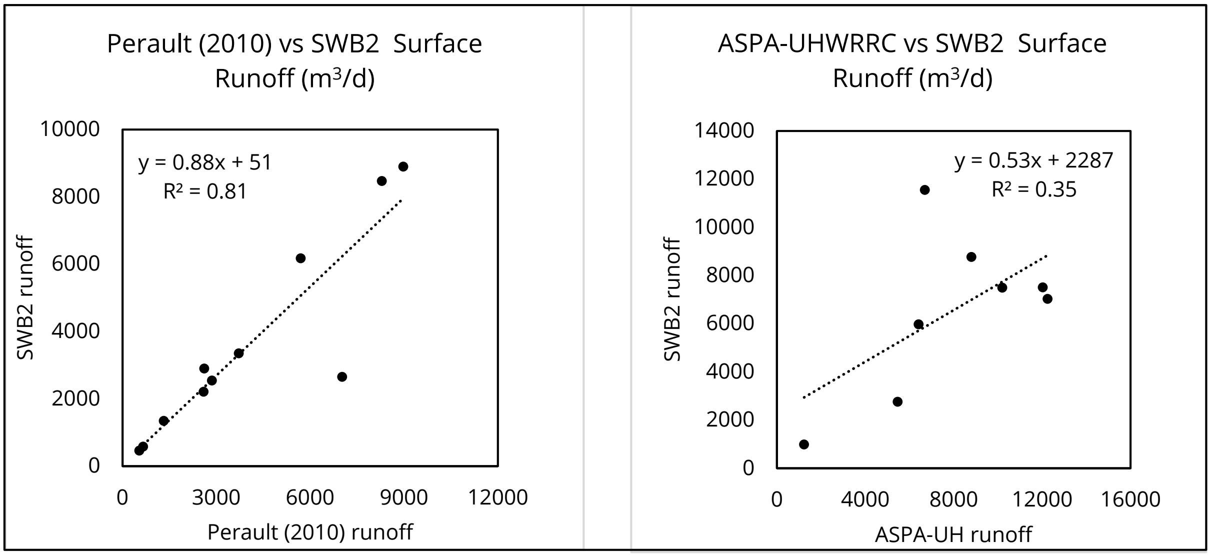


Figure 5: Comparison between SWB2 calculated and a) Perreault (2010), and b) ASPA-UHWRRC measured annual average surface runoff.

To check the reliability of the SWB2 calculated SGD estimates and to determine an appropriate uncertainty estimate for SGD calculations, one-time, snapshot resolution SGD measurements taken by Shuler et al. (2019) were compared to the water budget model results in four bays on Tutuila (Table 2). These measurements represent the only published SGD calculations from Tutuila Island as of this writing. While the error on both modeled and measured estimates is on the same order of magnitude as the estimates themselves, they nonetheless compare reasonably well (Table 2). Notably the SWB2 modeled SGD in Fagaalu and in Vatia Bays is somewhat larger than the measured values, but this may be partially due to the fact that the measurement areas from Shuler et al. (2019) were somewhat smaller than the areas for which the SWB2 calculation was made (see Shuler et al. (2019) for the exact areas of SGD measurements). Overall, this comparison suggests that the SWB2 estimated SGD fluxes are reasonable, and by using the relative percent difference (RPD) method between measured and modeled SGD rates, an average RPD value of 48% was determined and applied as the uncertainty on the SWB2 calculated SGD rates.

Table 2: Comparison of SWB2 estimated SGD rates to snapshot SGD measurements published in Shuler et al. (2019). Values in parentheses are 1σ standard deviations.

| Location | SWB2 indirect SGD (1σ std.) [$m^3/d$] | Shuler et al. (2019) measured fresh SGD (1σ std.) [$m^3/d$] |
|---|---|---|
| Pala Lagoon | 61,821 (44,290) | 68,482 (74,126) |
| Fagaalu Bay | 11,925 (8,543) | 7,270 (4,455) |
| Vatia Bay | 15,848 (11,354) | 4,428 (2,027) |
| Oa Bay | 1,787 (1,280) | 2,258 (1,891) |

### 2.4.2 Model Workflow Step (2): Observed DIN Loading Rates

Observed watershed scale DIN loads were calculated by multiplying measured DIN concentrations with water discharge rates, and were ultimately used to calibrate the nutrient loading model. Because most water sampling sites were sampled repeatedly, DIN concentrations at each site were grouped by hydrologic pathway (surface runoff, baseflow, or SGD) and average DIN concentrations for each were individually calculated. Multiplying the average DIN concentration in each pathway by pathway-specific SWB2 modeled water fluxes for the sampled watersheds yielded individual DIN loading rates for each pathway in every sampled watershed. Of the ninety-three watersheds delineated for this project, thirty-four watersheds were sampled for surface water nutrients, and coastal springs were sampled in twenty-two watersheds. However, of these, only thirteen were sampled for both surface waters and coastal springs (Fig. 3), partially due to the fact that hydrogeolgic regions with more SGD (i.e. more prevalent coastal springs) often have fewer surface water features. Therefore, total observed coastal DIN fluxes (summed from all three pathways) could only be calculated in these thirteen watersheds. All observed watershed scale DIN fluxes for each hydrologic pathway are presented in Table 3. Uncertainties on total DIN loading were calculated by propagating error from the SWB2 fluxes (as described in section 2.4.1.2) and the 1σ standard deviation of DIN concentrations in sample waters.

Table 3: Watershed scale DIN loading rates calculated with observed nutrient concentrations and SWB2 calculated water fluxes. Values in parentheses represent propagated uncertainties. Watershed ID numbers reference those shown on Figure 3.

| Watershed ID #, Watershed Name | Baseflow DIN Load [kg/d] | Runoff DIN Load [kg/d] | SGD DIN Load [kg/d] | Total DIN Load [kg/d] |
|---|---|---|---|---|
| #0, Leone | 0.21 (0.13) | 0.21 (0.19) | 1.71 (1.05) | 2.13 (1.08) |
| #1, Amanave | 0.03 (0.02) | 0.11 (0.08) | - | - |
| #2, Nua - Seetaga | - | - | 0.19 (0.19) | - |
| #4, Amanave | 0.06 (0.04) | 0.14 (0.12) | 0.27 (0.20) | 0.48 (0.24) |
| #5, Afao - Asili | 0.30 (0.17) | 0.30 (0.11) | - | - |
| #9, Fagaalu | 0.92 (0.72) | 0.43 (0.39) | 3.62 (2.39) | 4.97 (2.53) |
| #13, Fagamalo | 0.10 (0.07) | 0.30 (0.11) | - | - |
| #17, Malaeloa | 1.69 (1.29) | 2.02 (1.15) | 69.88 (96.29) | - |
| #18, Maloata | 0.50 (0.51) | 0.87 (0.45) | - | - |
| #21, Matuu - Faganeanea | 0.28 (0.23) | 0.22 (0.10) | - | - |
| #24, Nua - Seetaga | 0.17 (0.09) | 0.56 (0.79) | 0.94 (0.52) | 1.67 (0.95) |
| #25, Nuuuli Pala | 0.14 (0.10) | 0.22 (0.04) | - | - |
| #31, Nuuuli Pala | - | - | 7.15 (3.87) | - |
| #33, Poloa | 0.17 (0.15) | 0.26 (0.12) | 0.37 (0.25) | 0.80 (0.32) |
| #35, Alega | 0.37 (0.24) | 0.37 (0.24) | 1.01 (0.95) | 1.76 (1.01) |
| #40, Fagaitua | 0.16 (0.09) | 0.12 (0.06) | - | - |
| #41, Fagaitua | 0.13 (0.11) | 0.06 (0.05) | - | - |
| #43, Fagaitua | 0.07 (0.05) | 0.02 (0.00) | - | - |
| #46, Amouli | 0.22 (0.34) | 0.04 (0.02) | 0.35 (0.2) | 0.61 (0.40) |
| #51, Amouli | 0.06 (0.05) | 0.04 (0.01) | - | - |
| #58, Aoa | 0.30 (0.21) | 0.18 (0.12) | 0.74 (0.57) | 1.22 (0.62) |
| #60, Aoa | 0.25 (0.23) | 0.16 (0.04) | - | - |
| #61, Fagaitua | 0.23 (0.28) | 0.04 (0.01) | - | - |
| #62, Fagaitua | - | - | 0.82 (0.43) | - |
| #63, Fagaitua | 0.06 (0.05) | 0.06 (0.05) | - | - |
| #65, Fagatele - Larsen | - | - | 18.96 (18.9) | |
| #66, Fagatele - Larsen | 0.08 (0.05) | - | 0.08 (0.08) | - |
| #67, Laulii - Aumi | 0.37 (0.27) | 0.38 (0.14) | 4.48 (3.22) | 5.22 (3.24) |
| #70, Masausi | 0.04 (0.02) | 0.03 (0.01) | - | - |
| #73, Masausi | 0.04 (0.03) | 0.05 (0.02) | - | - |
| #74, Masefau | 0.70 (0.47) | 0.53 (0.48) | - | - |
| #75, Afono | 0.60 (0.50) | 1.13 (0.80) | 2.98 (1.22) | 4.71 (1.54) |
| #76, Vatia | 0.15 (0.09) | 0.17 (0.07) | - | - |
| #77, Pago Pago Harbor | 1.28 (1.11) | 2.77 (2.29) | 4.19 (2.53) | 8.25 (3.59) |
| #82, Fagasa | 0.34 (0.24) | 0.53 (0.18) | - | - |
| #85, Fagasa | 1.00 (0.80) | 0.72 (0.30) | - | - |
| #89, Afono | 0.09 (0.07) | - | 0.36 (0.15) | |
| #90, Vatia | 0.19 (0.16) | 0.28 (0.10) | 0.71 (0.43) | 1.17 (0.47) |
| #91, Vatia | 0.74 (0.66) | 1.21 (1.51) | 2.08 (1.35) | 4.03 (2.13) |
| #92, Vatia | 0.09 (0.06) | 0.12 (0.05) | - | - |
| #98, Leone | - | - | 31.78 (15.97) | - |

### 2.4.3 Model Workflow Step (3): Spatial Distribution of DIN Sources

Consistent with the assumptions and findings of Shuler et al. (2017), three specific anthropogenic activities were identified as the primary non-natural DIN sources on Tutuila. Anthropogenic DIN sources included OSDS units, piggeries, and agricultural fertilizer inputs. To acknowledge the effects of naturally occurring biogeochemical nutrient cycling and transport processes, a fourth source herein referred to as 'naturally sourced DIN' was used to represent the natural load of DIN delivered to the coast from each watershed. This value was intended to approximate the natural N-loading rate determined by Shuler et al. (2017) and here was set at a release rate of 0.36 kg-DIN/day per $km^2$ of unimpacted watershed area as delineated in a high-resolution land use map completed by Meyer et al. (2016).

To resolve the spatial distribution of anthropogenic DIN sources to a watershed scale, locations of every OSDS unit, every pig, and all known agricultural land were geospatially intersected by watershed boundaries. The locations of OSDS units were determined with the same methods used by Shuler et al. (2017). This involved identifying all buildings located more than 50 m from a sewer main or service line and under 120 $m^2$ in size. These buildings were assumed to rely on an OSDS unit for wastewater disposal. Small buildings were excluded since sheds or outbuildings typically do not contain facilities requiring an OSDS unit. Building locations were obtained from the American Samoa Department of Commerce (AS-DOC, 2009) and sewer line locations were obtained from ASPA. Locations of piggeries and the number of pigs in each was obtained directly from AS-EPA. While there exists no direct data regarding fertilizer application in American Samoa, agricultural areas as designated by the Meyer et al., (2016) land use map were considered to be the most likely locations for fertilizer applications (Fig. 6). Ultimately, DIN release rates from each source were determined through model calibration. However, the initial values for parameterization were set to equal the rates used by Shuler et al. (2017), for the equivalent source-activities on Tutuila. These rates were 0.021 kg-DIN/day per OSDS unit, 0.0381 kg-DIN/day per pig, and 0.77 kg-DIN/day per $km^2$ of agricultural land.

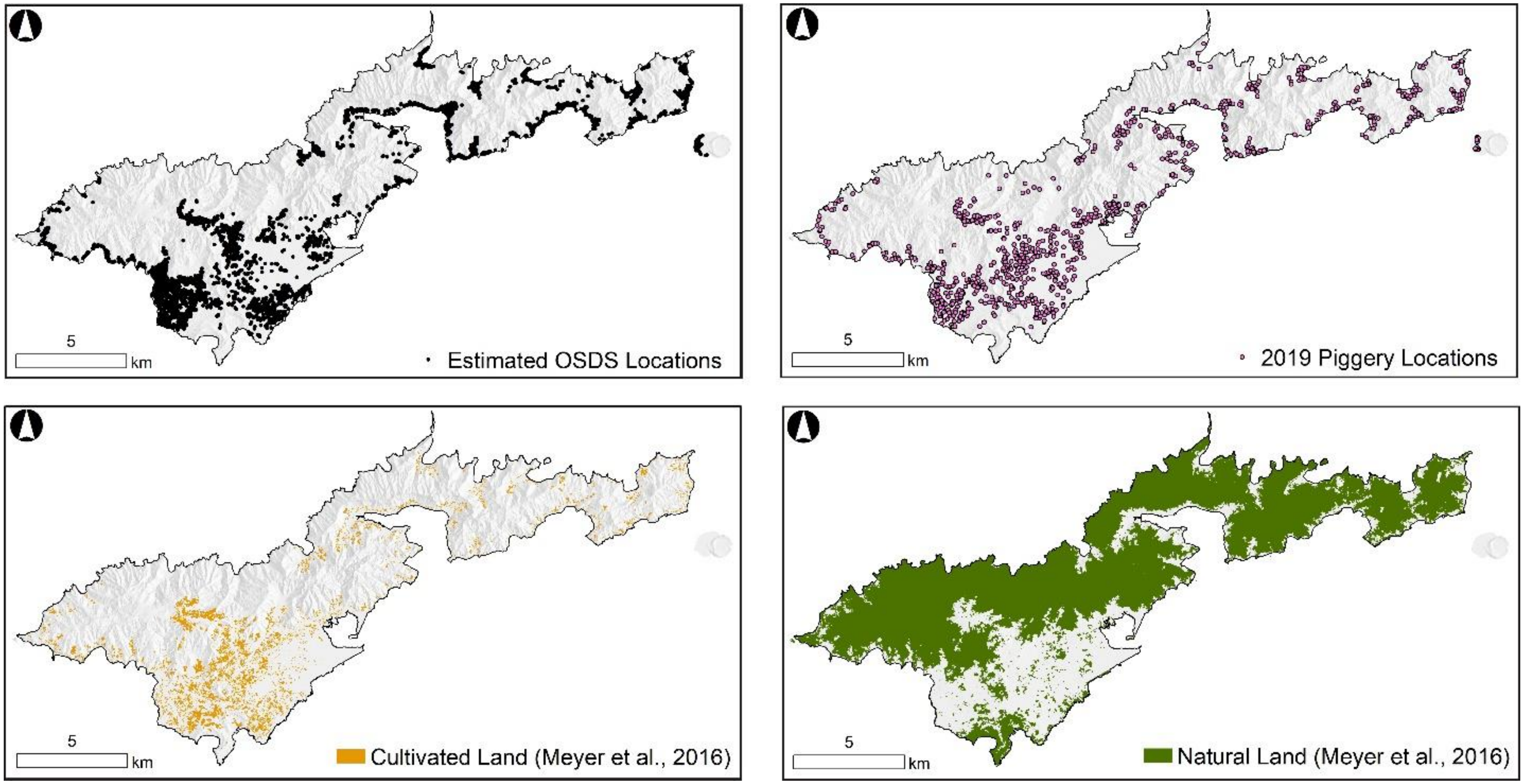


Figure 6: Locations of DIN sources used as model input. Initial DIN release rates from Shuler et al. (2017) were 0.021 kg-DIN/day per OSDS unit, 0.0381 kg-DIN/day per pig, 0.77 kg-DIN/day per km$^2$ of agricultural land, and 0.36 kg-DIN/day per km$^2$ of natural land.

### 2.4.4 Model Workflow Step (4): Nutrient Model Calibration

The nutrient loading model was calibrated with an optimization routine formulated to minimize error between observed and modeled DIN loading rates based on the prevalence of anthropogenic nutrient sources in each watershed. Calibration was set up by parameterizing an individual DIN release rate for each of the anthropogenic sources, and parameter optimization was performed using the Nelder-Mead unconstrained minimization method (Nelder and Mead, 1965). The optimization was implemented in Python using the scipy.optimize.minimize function. (https://docs.scipy.org/doc/scipy-0.14.0/reference/generated/scipy.optimize.minimize.html). The selected objective function was a linear regression between calculated and modeled nutrient loads, with the slope of the regression fixed at 1, so the optimization would be forced to minimize error without biasing the model towards over or under prediction, which could occur with an unconstrained least-squares regression. When error was minimized by the optimization routine, the model's calibrated error was ± 0.18 kg-DIN/day and the $r^2$ of the regression was 0.74 (Fig. 7). It should be noted that this optimization step acts as a "black-box" to conceptually represent all attenuation and N-transformation processes between sources and sinks, by using a single lumped parameter for each DIN release rate. In reality, these processes are complex, non-linear, interdependent, and spatially distributed, which makes it extremely difficult to accurately model them explicitly.

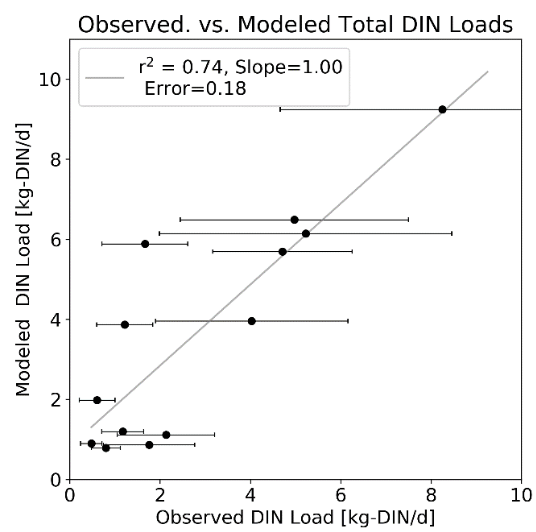


Figure 7: Scatterplot of final calibrated observed vs. modeled total DIN loads, with error bars representing propagated error on observed loads. Grey line is the 1:1 line and represents a fixed model slope of 1.

The calibration resulted in final DIN release rates of 0.037 kg-DIN/day per OSDS unit, 0.010 kg-DIN/day per pig, and 0.579 kg-DIN/day per $km^2$ of agricultural land. Multiplication of these release rates by the prevalence of anthropogenic DIN sources in each watershed yielded absolute loading rates ranging from 0.1 kg-DIN/day for some of the smallest watersheds, to 88.2 kg-DIN/day for the largest watershed on the Tafuna-Leone Plain (Fig. 8). For interpretation, these coastal DIN loading rates were scaled by both watershed area (Fig. 9a), and by length of watershed coastline (Fig. 9b). These approaches remove the watershed-size dependence of the absolute loads and may be more representative of the relative impact of DIN sources within each watershed on the terrestrial landscape or in the coastal zone.

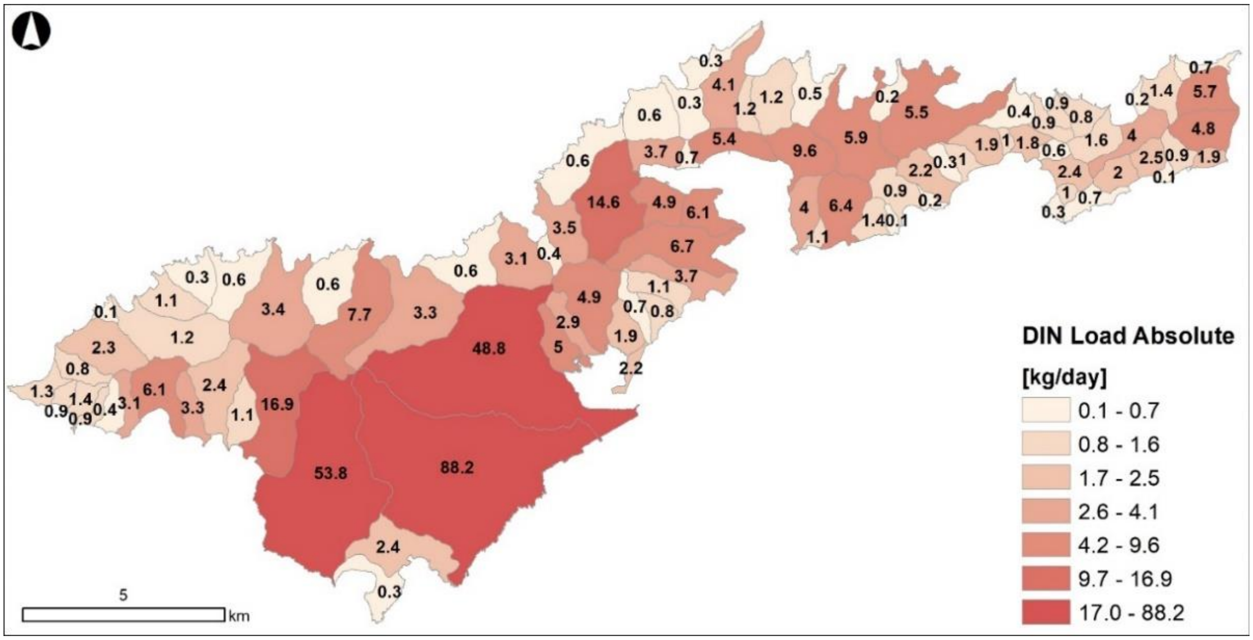


Figure 8: Final model calculated DIN loading rates for each watershed. Note that lower uncertainty boundary should be expected to be at least 50%, and additional uncertainty from the parameter optimization may be assessed through sensitivity testing, as shown in section 2.4.5. Labels inside watersheds indicate absolute magnitude of DIN loading in kg-DIN/day.

Additionally, the DIN loading model allows the estimation of the fraction of total DIN loading originating from each of the individual sources. This is shown graphically in Figure 10, where the total modeled DIN load from each watershed is shown in the upper left panel, and the other three panels (clockwise from upper right) show the proportion of DIN loaded to each watershed from OSDS units, pigs, and agriculture, respectively. If the island-wide DIN loads from each source are totaled, the model predicts that of a total island-wide daily load of approximately 410 kg-DIN/day, about 260 originates from OSDS units, about 110 comes from pigs, 35 comes from natural sources, and only 6 kg-DIN/day is sourced from agriculture. The average %-uncertainty (Table 3) for observed loading rates in the thirteen watersheds used for calibration was almost exactly 50%. While uncertainties were not propagated through the optimization routine, the observed loading uncertainty of 50% can be considered to be the lower uncertainty bound for the modeled loading rate. However, the upper uncertainty bound of the final model output would include this uncertainty as well as the uncertainty in each of the optimized model parameters. Due to the non-linearity of the model setup, this is most appropriately expressed through sensitivity testing as described in section 2.4.5

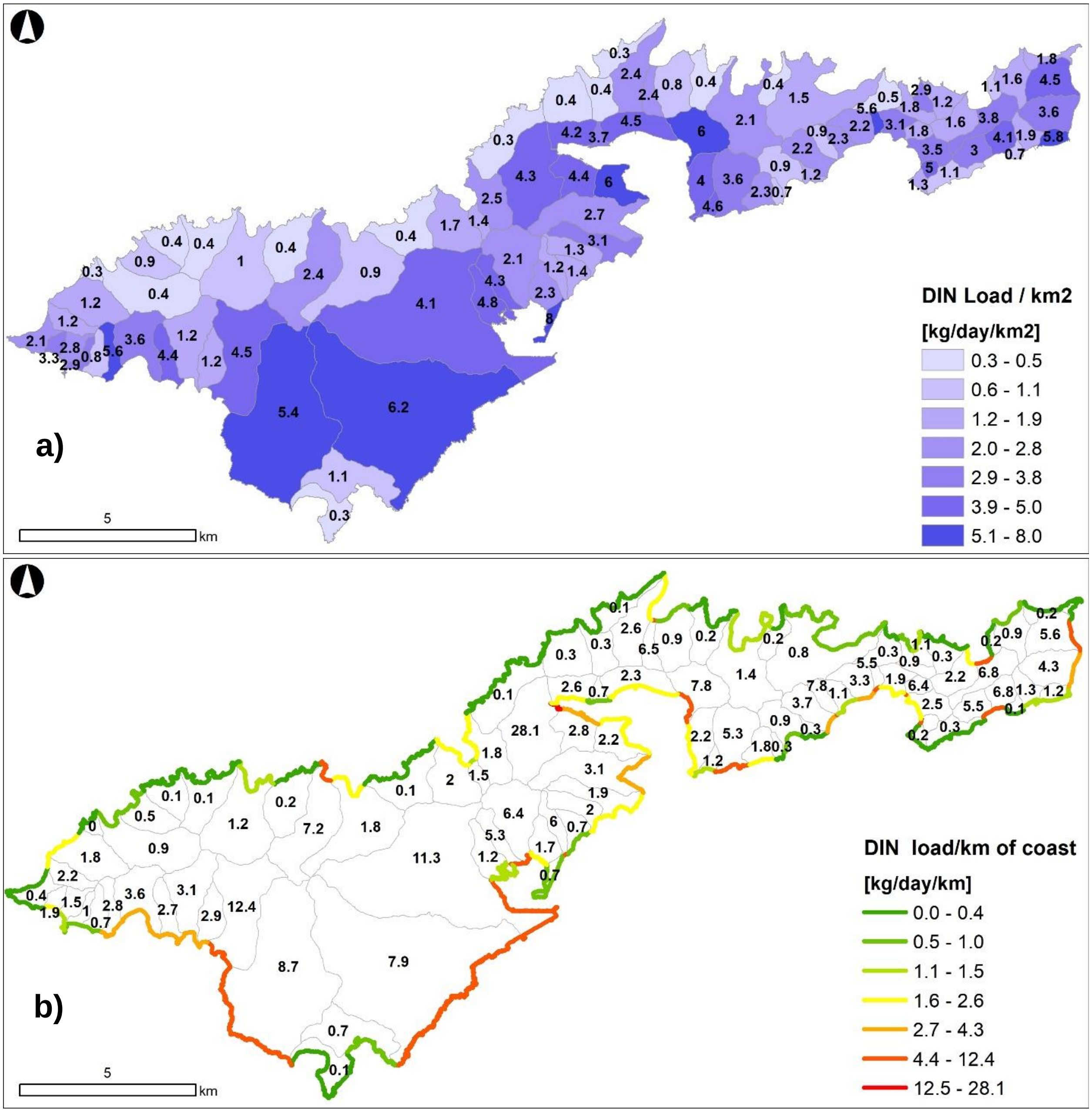


Figure 9: Relative model calculated DIN loading rates for each watershed, a) scaled by sub watershed area, in kg-DIN/day per km$^2$ of land and b) scaled by length of watershed shoreline in kg-DIN/day per km of coastline. Numbers within watersheds show each of the DIN loads in kg/day/km$^2$ and kg/day/km, respectively.

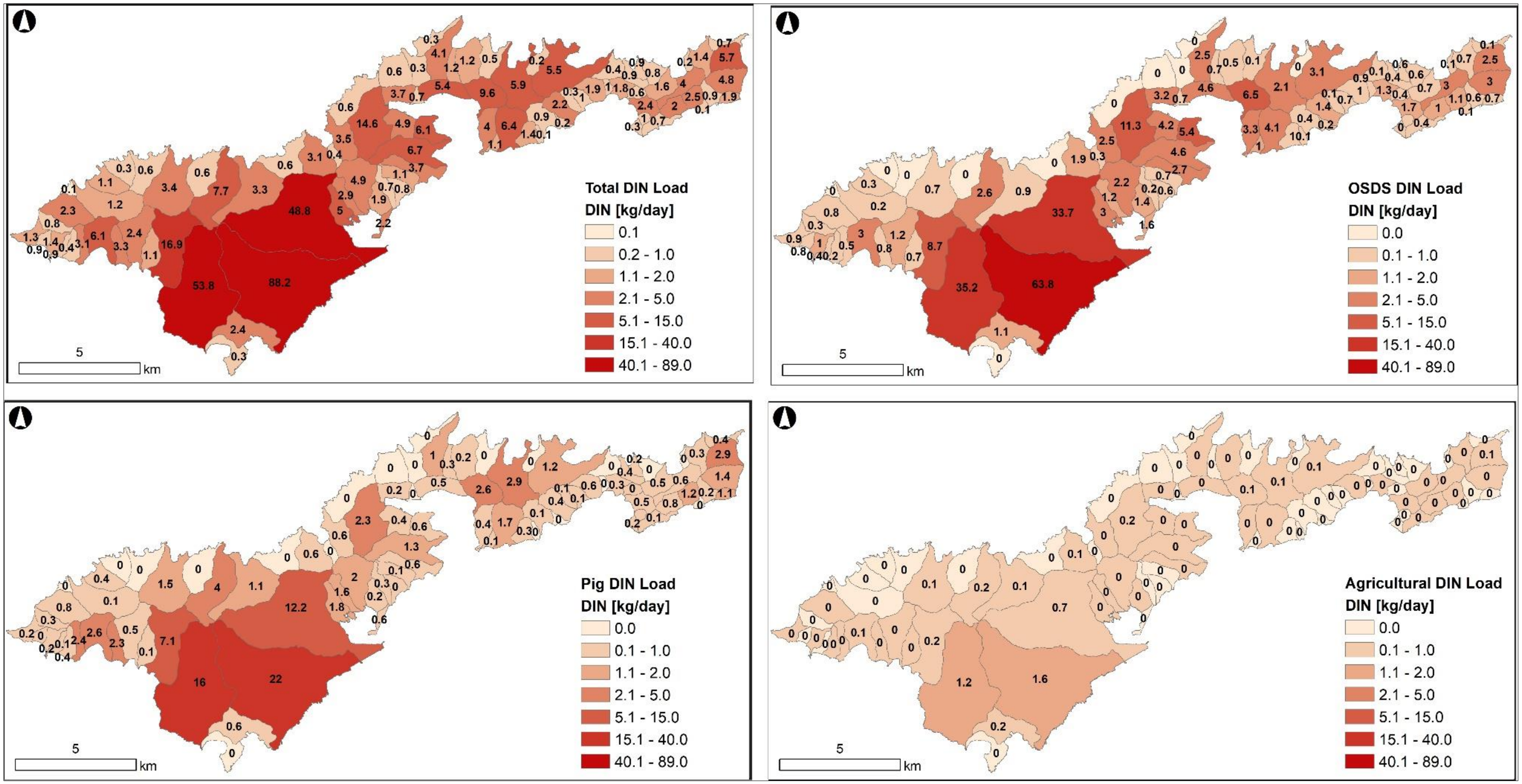


Figure 10: Comparisons between modeled DIN loading rates as separated by each nutrient source. Upper left panel shows total modeled DIN loads from all sources, and the other three panels (clockwise from upper right) show the absolute magnitude of DIN loaded to each watershed from OSDS units, pigs, and agriculture, respectively.

### 2.4.5 Sensitivity Testing

To examine how sensitive the model was to the DIN release rates associated with each anthropogenic DIN source, modeled island-wide DIN loading was calculated with a variety of 'scenarios' representing a %-shift in individual release rates. Each of the loading rates for OSDS, pigs, and agricultural loads, were modified independently by -50%, -25%, -10%, +10%, +25%, and +50%, and a fourth set of scenarios were run where all three anthropogenic release rates were modified by the aforementioned %-change values at the same time. Sensitivity test results were compared to the base case model by computing the %-difference between the scenario and the base-case for island-wide DIN loading. Results indicated that the model is most sensitive to OSDS loading rates and least sensitive to agricultural loading rates (Table 4).

Table 4: Sensitivity test results for assessment of DIN release rates. Rates from each of the individual anthropogenic sources were varied independently and together for a total of six different values of relative changes, ranging from -50% to +50%.

| | **Sensitivity Test Change in Modeled Input Loading Rates** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Percent change in modeled loading** | **-50%** | **-25%** | **-10%** | **0%** | **+10%** | **+25%** | **+50%** |
| | **Resulting Change in Modeled Output Island-Wide DIN Loading Rate** | | | | | | |
| **All parameters changed** | 54% | 77% | 91% | 100% | 109% | 123% | 146% |
| **Only OSDS loading changed** | 69% | 84% | 94% | 100% | 106% | 116% | 131% |
| **Only piggery loading changed** | 87% | 94% | 97% | 100% | 103% | 106% | 113% |
| **Only Ag. loading changed** | 99% | 99% | 100% | 100% | 100% | 101% | 101% |

### 2.4.6 Exploration of Correlation Relationships

Although the model could only be calibrated using the thirteen watersheds for which measurements of both surface water and groundwater were collected, two-variable linear regressions were also produced to explore how variability in modeled loading related to variability in observed loads for individual DIN sources and individual hydrologic pathways. Figure 11 provides a comparison matrix showing least-squares regressions between observed DIN loads and modeled loads. Observed loads can be separated by hydrologic pathway as is shown in the top row of the matrix, and while modeled loads cannot be separated by pathway, they ca be separated into the amount of DIN originating from each source, as is shown in the bottom row.

These plots show how much variability in model output is controlled by the input variables (observed loading from each hydrologic pathway), as well as showing how each of the individual DIN sources contributes to the variability in the total modeled load.  Slopes of the regressions on the top row indicates the proportion of DIN transported through each pathway, and slopes on the bottom row indicate the proportion of DIN modeled to be coming from each source. Similarly, $r^2$ coefficients show how strongly DIN loading from each pathway controls the variability in the total modeled loading or how strongly the total observed loading affected the modeled load from each source. Higher $r^2$ coefficients in the bottom row suggest that the specific modeled nutrient source involved in the regression is more important to the total nutrient load and thus may be important for management.

Specific conclusions that can be drawn from these relationships are: (1) the high slope and $r^2$ value in the regression including OSDS loading suggests that OSDS acts as a primary control on DIN loads in baseflow and SGD, (2) the low slope in the regression with agricultural sources suggest these are the least important of the anthropogenic sources, (3) relatively large magnitudes of observed DIN loading through SGD suggest that SGD is an important nutrient delivery pathway and deserving of additional management attention, (4) lower $r^2$ coefficients for regressions with surface runoff loading suggest that runoff stage nutrient fluxes are not as well predicted by this model as baseflow stage fluxes, which is expected, considering the larger variability in surface runoff nutrient concentrations, and (5) high $r^2$ (0.74) and a nearly perfect slope (1.01) for the total modeled vs. total observed loading plot indicates that the DIN release rates used in the model are able to reproduce the spatial distribution and the absolute magnitude of DIN loading in the sampled watersheds relatively well.

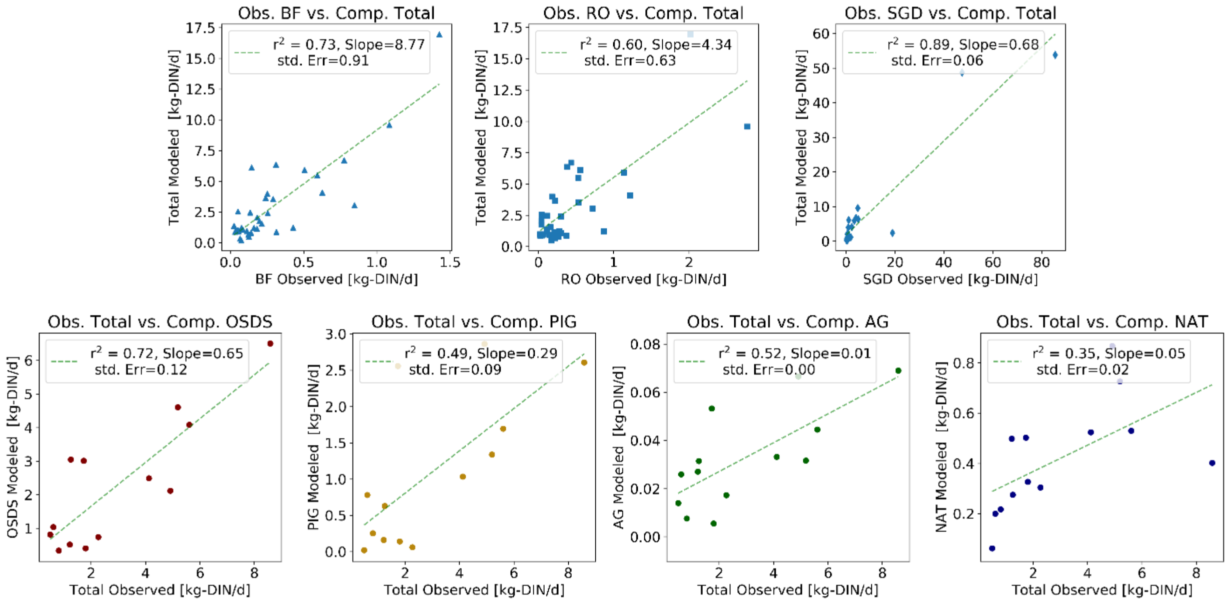

Figure 11: Scatterplot matrices of total observed and modeled DIN loading rates, separated by DIN sources, and hydrologic pathways, respectively. All values are in kg-DIN/day. Abbreviation key: Obs. = Observed loading rates, Comp. = Computed loading rates, OSDS = on-site disposal systems, AG = Agriculture, NAT = Natural, BF = Baseflow, RO = Surface runoff.

## 2.5 Impact Prioritization Ranking

While the absolute amount of DIN loading (Fig. 8) provides the most straightforward comparison between different watersheds, this measurement may not be the most compelling. Absolute DIN loads are fundamentally biased towards the watershed size, as larger watersheds hold more nutrient sources and thus produce more DIN. To control for this 'area bias', DIN loads can be scaled by watershed area or coastline length (Fig. 9). While area scaled loads essentially assess the density of sources, which is more representative of human effects in terrestrial areas, this metric does not provide representation of the effects of DIN dilution upon discharge. Thus, the effects of coastal DIN loading are better represented by scaling absolute DIN loads by the coastline lengths of each watershed. However, this metric itself is biased by the selection of watershed boundaries, whereas watersheds fronted by more convex parts of the island coastline will have longer coastlines, and watersheds fronted by more concave coastlines will have much smaller coastlines, in some cases significantly increasing the length-scaled DIN release rates. In reality, each of these metrics provides different and unique understanding of human impacts, while at the same time being limited by different biases. Thus, to simplify results and to aid management priorities, a single watershed prioritization scheme was developed. This scheme incorporates each of these three metrics, and weights them equally in the output. This watershed prioritization raking was performed by calculating the island wide mean of all of the absolute watershed scale DIN loads, the area scaled DIN loads, and the coastline length scaled loads, so that each watershed's anomaly from the mean of each metric could be computed. For each individual metric, anomalies from the mean were ranked from 1 to 93 with the highest absolute anomaly (i.e. highest DIN impact) from each metric being assigned the lowest rank. The ranks were then summed to incorporate the importance of each metric into a single ranking to produce the prioritization ranks of each watershed; again with the lowest ranked watersheds being the ones with the highest degree of impact as indicated by each of the three metrics. Results of the prioritization ranking system are shown in Figure 12. Ranks are labeled as numbers in or adjacent to each watershed and colors also indicate rank on the figure. This system indicated that Tutuila's most heavily DIN-impacted areas are on the Tafuna-Leone Plain, with the villages of Utulei, Aua, Vaipito (Pago Pago), Aasu, and Tula also being more heavily impacted than other watersheds throughout the island.

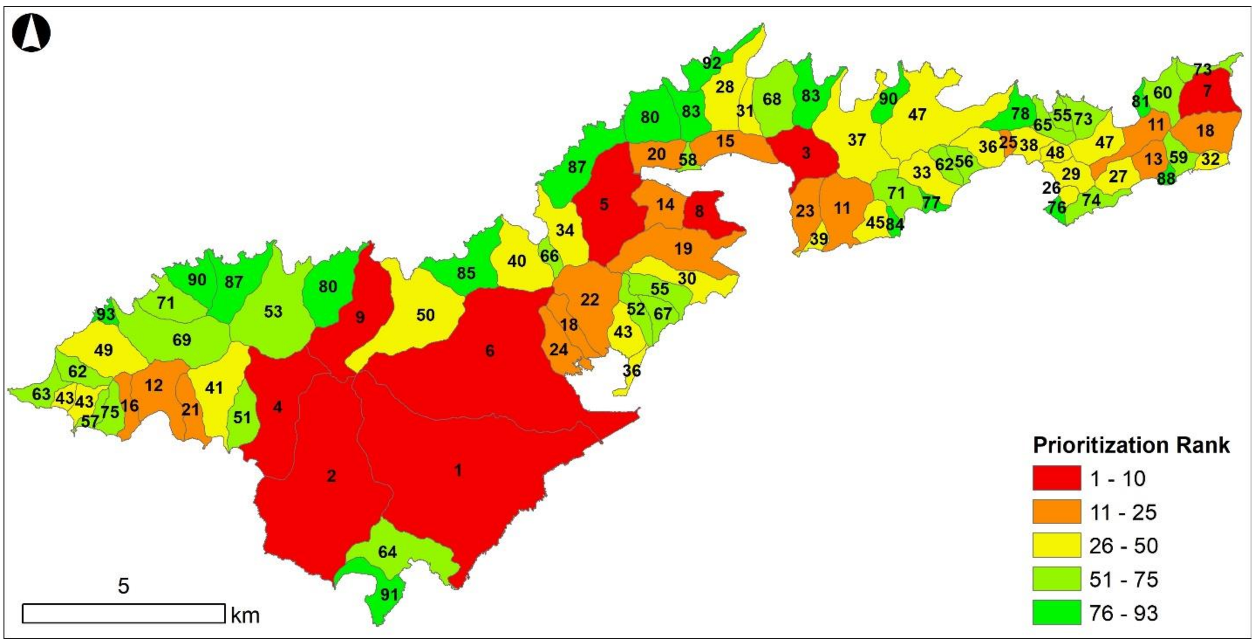


Figure 12: Relative impact prioritization through equal-weight ranking of absolute, area-scaled, and coastline length-scaled DIN fluxes from each watershed to the nearshore. Both colors and numeric labels in watersheds indicate the prioritization ranking of impact in each watershed with 1 being the most impacted and 93 the least. Note that if two watersheds had the same final ranking they were assigned the same rank number; thus some numbers are repeated.

## 2.6 Nitrogen Isotope Mixing Model

To provide future opportunities for validating the modeled source-specific DIN release rates, an isotope mixing model was developed to predict N-isotopic composition ($\delta^{15}N$) of nitrate plus nitrite expected in the 'composite terrestrial discharge end-member' (CTDEM) from each watershed. The CTDEM represents a hypothetical water sample end-member consisting of a volume-weighted mixture of all the baseflow, surface runoff, and SGD from each watershed to the coastal zone. While this end-member cannot be directly sampled, its isotopic signature would theoretically be expressed, after consideration of any biological processes driving further isotopic fractionation, in the tissues of benthic organisms that metabolize N from the water column and experience the cumulative impact of nutrient delivery from all sources and hydrologic pathways over their lifetimes. Therefore, if nearshore organisms, such as macroalgae (e.g. Dailer et al., 2010; Osawa et al., 2010) or corals, (e.g. Risk et al., 2001; Hoegh-Guldberg et al., 2004) are sampled in the future, their tissue-N isotopic compositions can be compared to these modeled CTDEM $\delta^{15}$N values to potentially validate or re-calibrate this model thereby potentially providing the opportunity to obtain more accurate results.

Isotope mixing models are widely used across disciplines to partition mixtures of substances derived from multiple isotopically unique sources (Phillips and Gregg, 2001; Hobson et al., 2007). Using $\delta^{15}$N values as source-dependent tracers relies on the idea that different nutrient sources release nitrate plus nitrite that contains N with distinct and reasonably predictable ranges of $\delta^{15}$N values. Numerous studies have applied $\delta^{15}$N analysis to partition the impact between N sources globally (e.g. Kendall and Aravena, 2000; Cole et al., 2006), in tropical island settings (e.g. Wiegner, et al., 2016; Bishop et al., 2017), and specifically in American Samoa (e.g. Garrison et al., 2007; Shuler et al., 2017; Shuler at al., 2019). Kendall and Aravena (2000) report $\delta^{15}$N values originating from natural sources are typically around +2 to +6‰, whereas $\delta^{15}$N values originating from agriculture are lower, ranging between -5 to +5‰, and often near 0‰. Studies in tropical environments similar to Tutuila, have reported wastewater $\delta^{15}$N values ranging between +5 to 23‰ (e.g. Hunt and Rosa, 2010; Amato et al., 2016; Bishop et al., 2017). Manure from pigs would be expected to fall into the same range as wastewater, though some evidence suggests that due to its release mechanism, manure may discharge N with slightly higher $\delta^{15}$N values (Fenech et al., 2012; Shuler et al., 2017). While some overlap in end-member $\delta^{15}$N values found in water influenced by different anthropogenic sources somewhat complicates interpretation of results, the benefits of this method have made it very widely used and accepted as a tool for detecting source-dependent human impacts on environmental waters (Fenech et al., 2012).

Previously, a nitrogen-isotope mixing model was developed for Tutuila by Shuler et al. (2017) to assess groundwater impacts from anthropogenic nutrient sources. For this study, the selection of N-sources and the end-member $\delta^{15}$N values used in the Shuler et al. (2017) study were considered to be the most directly applicable to this work. By applying the design of the Shuler et al. (2017) mixing model, predicted, volume-weighted $\delta^{15}$N values in CTDEM from each watershed were calculated according to the following relationship:

$$F_p \times \delta^{15}N_p + F_c \times \delta^{15}N_c + F_a \times \delta^{15}N_a + F_n \times \delta^{15}N_n = \delta^{15}N_{modeled-CTDEM}$$

Where:
p = pig
c = OSDS
a = agriculture
n = natural
F = fraction of total DIN from each source

The assumed $\delta^{15}N$ end-member values were equivalent to those used in Shuler et al. (2017):

$\delta^{15}Np$ = +13‰

$\delta^{15}Nc$ = +9‰

$\delta^{15}Na$ = 0‰

$\delta^{15}Ns$ = +4‰

Results of this mixing model for each watershed on Tutuila are presented in Figure 13. Although field data for $\delta^{15}N$ values in water or from biologic indicators are not available at present, collection of these data by other researchers is as of this writing, underway. Through comparison to this $\delta^{15}N$ mixing model, observation values may eventually be useful for validation or calibration of the Tutuila DIN-loading model.

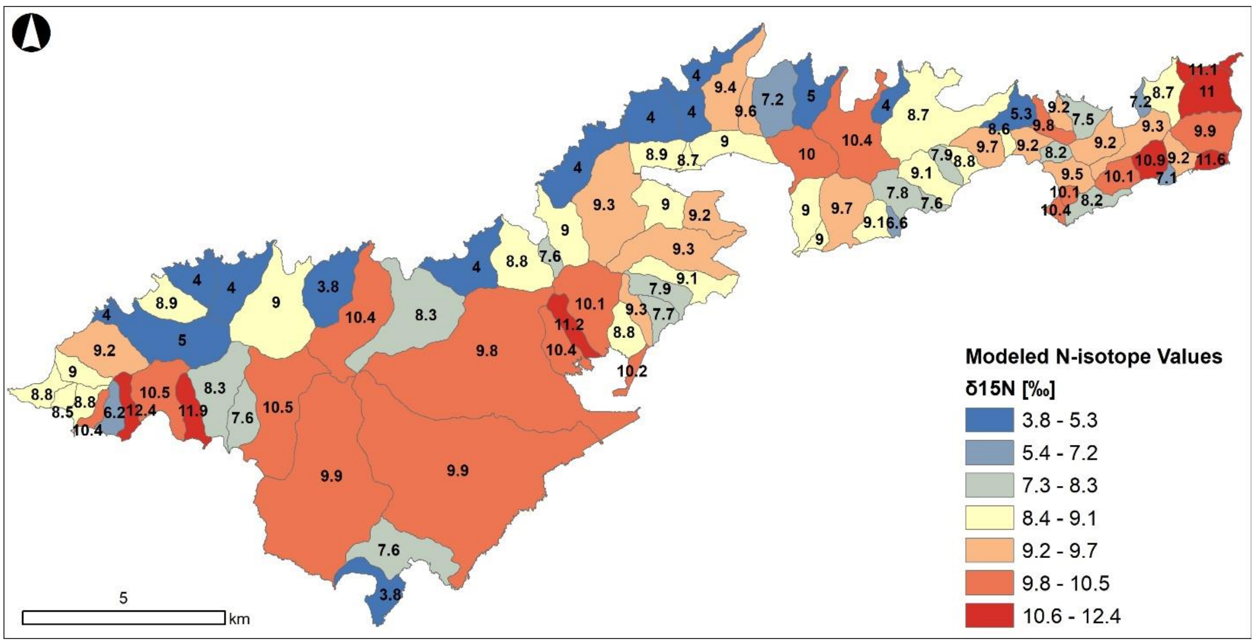


Figure 13: Results of the $\delta^{15}N$ mixing model, showing the predicted $\delta^{15}N$ value of the composite terrestrial discharge end-member, which represents the integrated N-isotopic signal of all waters discharging to the coastal zone.

## 2.7 Assumptions and Limitations of the DIN Loading Model

It is highly likely that surface water nutrient concentrations and thus DIN loads are as variable as stream discharge itself. However, the incredible cost and time that is required to sample at a resolution appropriate to fully characterize this variability is prohibitive. Thus in this study, natural variability of stream flows and DIN concentrations were statistically characterized by averaging often low numbers of samples. This results in the necessity of drawing conclusions despite relatively high uncertainties. This problem is not unique to this study; ever present data limitation faced by geochemists due to high sample analysis costs, and hydrogeologists due to conceptual-model uncertainty, typically limits the statistical significance of results in similar studies. Therefore, it should be recognized that the results and conclusions presented herein are estimates with wide uncertainty bounds, as the calculations used rely on input from many sources with high uncertainties themselves. Despite the high uncertainties with the models used, the utility of this study lies in highlighting trends and showing the locations or 'hotspots' where prioritizing additional management actions may be warranted. The specific assumptions and limitations that could not be directly constrained, but allowed this work to develop include:

(1) Partitioning of baseflow and SGD in gauged watersheds relied on the assumption that all net infiltration was either extracted by wells or lost as baseflow or SGD.

(2) Extrapolation of SGD:net-infiltration ratios from gauged to ungauged watersheds relied on the assumption that these ratios were similar for all watersheds.

(3) The model assumes that the three modeled anthropogenic DIN sources, OSDS, pigs, and agriculture, are the island's only significant anthropogenic sources of N, and that all other natural sources release DIN evenly throughout the landscape.

(4) While the locations of DIN sources were reasonably well known, the loading rates, and the actual fraction of released DIN that escapes attenuation processes such as sorption, volatilization, denitrification, and uptake was, in this study, empirically derived and all of these processes were represented with a single lumped parameter.

(5) The $\delta^{15}N$ mixing model ignores differences in fractionation effects between $NO_3^-$, $NO_2^-$ and $NH_4^+$ and simplifies the selection of end-member values by assuming that fractions of $NO_3^-$, $NO_2^-$ and $NH_4^+$ released from each source are consistent across each watershed and each anthropogenic DIN source.

## 2.8 Model Archiving and Data Storage

Owing to recent advancements in cloud-computing technologies, it is now common to post computational projects online in an open-source setting. This significantly increases methodological transparency and makes the study entirely reproducible or modifiable as the user's discretion. To provide free public access to this work, all raw data files, the model code, and descriptive information has been archived on GitHub at: (https://github.com/cshuler/R2R_DIN_Loading_Model). Note that sensitive information, or datasets that are not intended to be publically available, are not posted in raw forms. The model code is licensed under the GNU General Public License v3.0 which is an open-access license designed to explicitly affirm any user's unlimited permission to run, copy, and use the unmodified code from this repository. Please note that some raw datasets used in this work are not owned by the authors and may be subject to other licenses or conditions. The model code and data will be archived at the aforementioned location for as long as is reasonably feasible, for a time not shorter than one year after the date of this report's creation (June, 2019).

# 3. Management Recommendations

While numerous terrigenous stresses including sediments, nutrients, acidification, and toxic compounds conspire to drive coastal ecosystem health, DIN loading has been found to be an important consideration for coastal resource management. The DIN loading model developed for this report integrates information regarding OSDS sources, piggery locations, agriculture areas, stream water nutrient concentrations, and coastal spring nutrient concentrations to develop a whole-island, watershed-scale, human-impact ranking in order to meet four specific objectives, these being:

(1) Provide island-wide DIN loading estimates at the watershed scale, for the island of Tutuila, in the Territory of American Samoa.
(2) Develop an impact prioritization ranking for all Tutuila watersheds, based on DIN loads.
(3) Rank DIN loading impacts of different hydrologic pathways, i.e. baseflow, SGD, etc…
(4) Rank impacts from different nutrient sources, i.e. wastewater, piggeries, etc…

The implications for natural resources management are discussed for objectives (1) and (2) in section 3.1 below, and objectives (3) and (4) are discussed in sections 3.2 and 3.3, respectively. The following discussions are intended to highlight the utility of model results in context of providing actionable information to coastal resource managers interested in reducing human impacts on fragile nearshore ecosystems.

### 3.1.1 Utility of DIN loading rates and identification of hotspots

Absolute DIN loading rates for individual watersheds closely tracked watershed size, as larger watersheds typically have higher populations. However, even when scaled by watershed area or by watershed coastline length, the model still predicted the large watersheds of the Tafuna-Leone Plain to have the highest impact, which is likely due to the much greater proportion of flat, developable land, and thus higher population densities in these areas. It should come as no surprise that the Tafuna-Leone and Pago Pago /Fagaalu areas are likely to be human-impact hotspots considering the results of past studies (e.g. Whitall and Holst 2015; Polidoro et al., 2017; Shuler et al., 2017; Shuler et al., 2019). However, little attention has been focused in Eastern Tutuila, near Tula Village or in the Seetaga area of Western Tutuila. Figure 12 shows the prioritization ranking resulting from the DIN loading model in map form. The results of this assessment indicate that these areas may be subject to DIN loading impacts that are higher than other parts of the island, and may warrant additional management attention.

### 3.1.2 Prioritization of Loading through Different Hydrologic Pathways

The American Samoa EPA has been progressive in implementing environmental water quality standards for coastal waters and for territorial surface waters. However, this and other recent assessments (Whitall and Holst 2015; Shuler et al. 2019) suggest that groundwater is likely to be a significant nutrient transport mechanism to coastal areas. Only limited management attention has so far been placed on understanding the effect of groundwater discharge on Tutuila's coastal zones. Nonetheless, the results of this study suggest that groundwater (SGD) quality monitoring and its inclusion in regulatory standards could improve the effectiveness of land use management. The work performed for this report may be useful as a coastal groundwater quality baseline as it consolidates some of the first known, and most comprehensive measurements of coastal spring water quality. This baseline is an important start to building the database of information required to effectively understand and set standards for managing land use in a way that does not negatively affect reef health. While it is rare for jurisdictions to define environmental groundwater quality standards, and those that do are typically focused on maintaining drinking water quality (Kimsey, 2005; N.J.A.C, 2018). However, because American Samoa has a significant motivation to protect reef health, and is of a size where island-wide projects are feasible, the territory may be a good place to conduct a pilot coastal groundwater monitoring program.

Another aspect that should be considered in development of sampling protocols is the poorly studied, but clearly important mechanism of coastal groundwater discharge that occurs within the boundaries of stream mouths and in estuaries. In nearshore portions of streams,nutrient concentrations can be significantly elevated relative to the higher reaches of the stream due to baseflow discharge originating from nearshore basal-lens aquifers, which are subject to subsurface contamination in villages (Shuler, 2019). Work done by Shuler (2019) identified and quantified the magnitude of this phenomenon in Fagaalu Stream. However, other locations remain essentially understudied in this regard. Apart from directly quantifying nutrient impacts from different baseflow fractions at all sampling sites, this effect can be controlled for by always sampling streams at consistent locations, ideally at the highest point in the stream mouth where saltwater influence is not evident, during low tide, as was done with the streamflow samples taken for this study. Another option would be to always sample at locations above potential groundwater – stream water influence. However, this would likely have to be at points above villages, and would only represent the composition of surface waters prior to them becoming impacted by human activities, and would not represent the actual magnitude of surface water impacts on the coastal ecosystem.

### 3.1.3 Management of Land Use and Nutrient Sources

Over the last decade in American Samoa, management of pig waste originating from widespread traditional piggeries has been a top priority for water resources management. Coordinated scientific, educational, and regulatory efforts have significantly reduced the number of pigs and the management of pig waste in American Samoa (AS-EPA, 2005; AS-EPA 2014). Because pigs are no longer the management priority they once were, it is clear that other land use activities, specifically discharge of household wastewater to the subsurface though cesspools also require management attention. While piggeries have been hypothesized to disproportionately affect surface water quality, due to how the waste is managed, cesspools prove to be a much more insidious threat (Shuler et al., 2017). When modeled DIN loading rates from this study are partitioned between land-use sources, results support this hypothesis, as DIN loading from OSDS sources is generally around 2x to 4x higher than DIN loading from pigs. Cesspool effluent is discharged unseen underground, often below Tutuila's thin soil layers, to be contributed directly and without treatment to the aquifer below. Since most development in American Samoa is concentrated on coastal plains, OSDS effluent discharged as SGD likely has the most prominent effects on coastal ecosystems.

# 4. Conclusions

This report documents the development of an island wide DIN loading model for the island of Tutuila, in the Territory of American Samoa. The model incorporates historical and contemporary streamflow data, water discharge rates from an open-source SWB2 water budget model, and water quality data from long-term water sampling efforts as input data. The loading model was optimized with observed DIN loads, and when these were compared with modeled DIN loads, the model achieved a reasonable linear-regression fit, with an $r^2$ of 0.74 and a standard error of 0.18 kg-DIN/day. To aid interpretation, absolute DIN loading rates were scaled in multiple ways, (1) by watershed area, and (2) by coastline length. Each interpretation is subject to different biases, but provides unique information that may be relevant to different stakeholder groups. Maps showing the distribution of DIN loading were produced for each of these interpretations and are presented in Figures 8 and 9. A single prioritization ranking scheme was also developed to incorporate all information from scaled and absolute DIN loading calculations into a single easy-to understand metric (Fig. 12). According to this scheme, modeled impacts of DIN loading were predicted to be highest in the watersheds of the Tafuna-Leone Plain, the Pago Pago Harbor area, the Tula area, and in watersheds down gradient from Aasu and Aoloau Villages.

Calculation of observed nutrient loading was performed for all coastal hydrologic pathways, these being baseflow, surface runoff, and SGD. Model results suggest that SGD is likely to be the most important nutrient delivery mechanism to Tutuila's coastal waters. While the model was not set up to directly calculate pathway specific loading, it did allow for the partitioning of different nutrient loads from distinct land use sources including OSDS units, pigs, agriculture, and natural background DIN loading. When total modeled DIN loading is considered on an island-wide scale, results suggest that OSDS units are the primary source of DIN, producing about 260 kg-DIN/day. In order of impact, the other sources produced 110, 35, and 6 kg-DIN/day, for pigs, natural sources, and agriculture, respectively.

While this work was based upon a fairly extensive set of calibration data, including all known available streamflow data collected on Tutuila Island, and a water quality dataset consisting of over 500 individual samples, model accuracy can always be improved by including additional data. In particular, samples of surface runoff and coastal spring discharge are not as well represented in existing water quality datasets as baseflow samples, and additional long-term monitoring of these hydrologic pathways would make this model, and future nutrient loading analyses more robust. To promote the continued use of this model or to support the development of other analyses as additional data is collected in the future, all model input, model code, and model output data has been archived in an open-source, publically-available repository located at: https://github.com/cshuler/R2R_DIN_Loading_Model. By archiving the model components in this way we hope to allow this model to be refined in the future, to promote the dynamic use of the model as new management questions come up, and to easily and transparently share the results of this work with land use and coastal resource managers working towards the betterment of American Samoa's terrestrial and marine environments.

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