Management Summary of

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

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Prepared for:
American Samoa
Environmental Protection Agency
P.O. Box PPA
Pago Pago, AS 96799

Prepared by:
Chris K. Shuler
Shuler Hydrologic LLC
796 Isenberg St
Honolulu, HI 96826

Executive Summary

Excessive nutrient discharge to tropical island coastlines can cause algal blooms and eutrophication. To address these issues, environmental regulatory agencies often set water quality standards for discharging surface waters. However, such standards typically only consider surface water nutrient concentrations, which do not account for groundwater discharge, variability in flow, or dilution effects. 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, and may be a more accurate indicator of terrestrial impact. This report documents the development and application 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 island-wide water quality information from extensive water sampling data with water flux estimates derived from an open-source water budget model and publically available streamflow data. The model workflow used observed DIN loading rates from all hydrologic pathways in watersheds where sufficient samples were available as model calibration data. The three hydrologic pathways considered were (1) stream baseflow from shallow aquifers, (2) surface runoff generated during rainfall events, and (3) submarine groundwater discharge (SGD). The anthropogenic DIN sources included in the model were on-site wastewater disposal systems (OSDS), livestock pigs, and synthetic fertilizer inputs to agricultural lands. Measurements of historical and contemporary stream flow were also assessed to (1) validate water-budget calculated surface runoff rates, and (2) separate baseflow and SGD rates from water-budget calculated net-infiltration in ungauged watersheds.

Final island-wide DIN loading rates were optimized by calibrating individual N-release rates for different modeled nutrient source types on Tutuila with the observed DIN loading rates in each fully sampled watershed. Overall, model results indicated SGD is an important coastal delivery mechanism for terrigenous N, that OSDS units are the predominant anthropogenic source of DIN to Tutuila’s coastal waters, and that the Tafuna-Leone Plain, various watersheds in the Pago Harbor area, the Tula region, and areas down gradient from Aasu and Aoloau Villages are likely hot-spots for coastal nutrient impacts.

Shuler Hydrologic LLC
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Background

On tropical islands, excessive nutrient discharge to 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). Existing water quality standards in American Samoa are focused on assessing concentrations of nutrients in surface water discharge and coastal surface waters (AS-EPA, 2013) However, submarine groundwater discharge (SGD) has been shown to deliver an equivalent or significantly higher nutrient load to coastal ecosystems when compared with streams (e.g. D'elia et al, 1981; Moosdorf, et al. 2015; Bishop et al., 2017; Shuler et al., 2019). Therefore, total nutrient loads which include loading from all hydrologic pathways and also account for variability in flow, can more accurately reflect water quality conditions that influence 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).

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 based on DIN loads for all of Tutuila's watersheds.
(3) Rank the impact of different hydrologic pathways, i.e. baseflow, SGD, etc... in nutrient transport.
(4) Rank impacts from different nutrient sources, i.e. wastewater, piggeries, etc...

These objectives were accomplished by implementing a spatially distributed DIN loading model for the island of Tutuila, which is the largest and most populous island in the Territory of American Samoa (Fig. 1). The model 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.

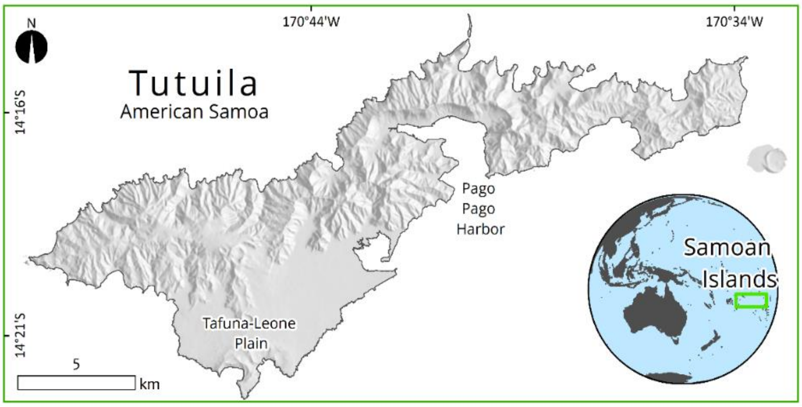

Figure 1: Study location map of Tutuila Island showing hill-shaded topography.

Approaches and Methods

The DIN loading model was built by first finding relationships between land use and observed DIN loads in sampled watersheds through regression analysis. The model was calibrated with observed DIN loading rates, which were calculated in watersheds where sufficient water sample data were available (Fig 2). 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. Hydrologic pathways 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). Water sample nutrient concentrations were multiplied by water discharge from all hydrologic pathways to calculate observed nutrient loads to sampled watersheds.

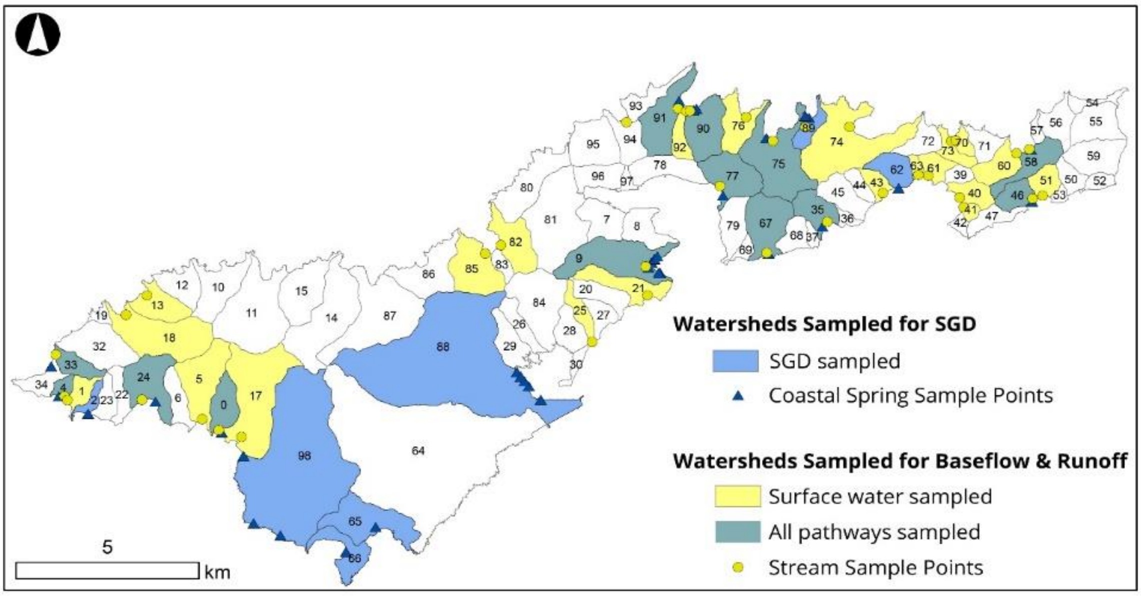

Figure 2: Locations of stream and coastal spring sample sites shown as circles and triangles, respectively, with shaded model watersheds draining to each site. Model designated watershed ID numbers are also shown.

The observed nutrient loads were then used as calibration data to calibrate individual DIN-release rates for each of the modeled anthropogenic nutrient sources in the DIN loading model. Anthropogenic nutrient sources in the model included On-Site wastewater Disposal System (OSDS) units, livestock pigs, and agricultural lands. To determine the locations of modeled nutrient sources high-resolution geospatial data were obtained from local agencies (Fig. 3). The Tutuila DIN loading model was developed using the following workflow steps: (1) island-wide water discharge rates from all three hydrologic pathways were calculated for every watershed by using a 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 across Tutuila.

The Tutuila SWB2 water budget model was used to estimate water fluxes from each hydrologic pathway on an island wide basis. The SWB2 code was originally developed by the USGS (Westenbroek et al., 2018) and a Tutuila based application of the model by Shuler and El-Kadi (2018) is available as an open source model (https://github.com/UH-WRRC-SWB-model). The water budget model directly produces estimates of surface runoff and net-infiltration, which was then used to indirectly calculate baseflow and SGD rates for each watershed. Observed streamflow data were obtained from historical USGS

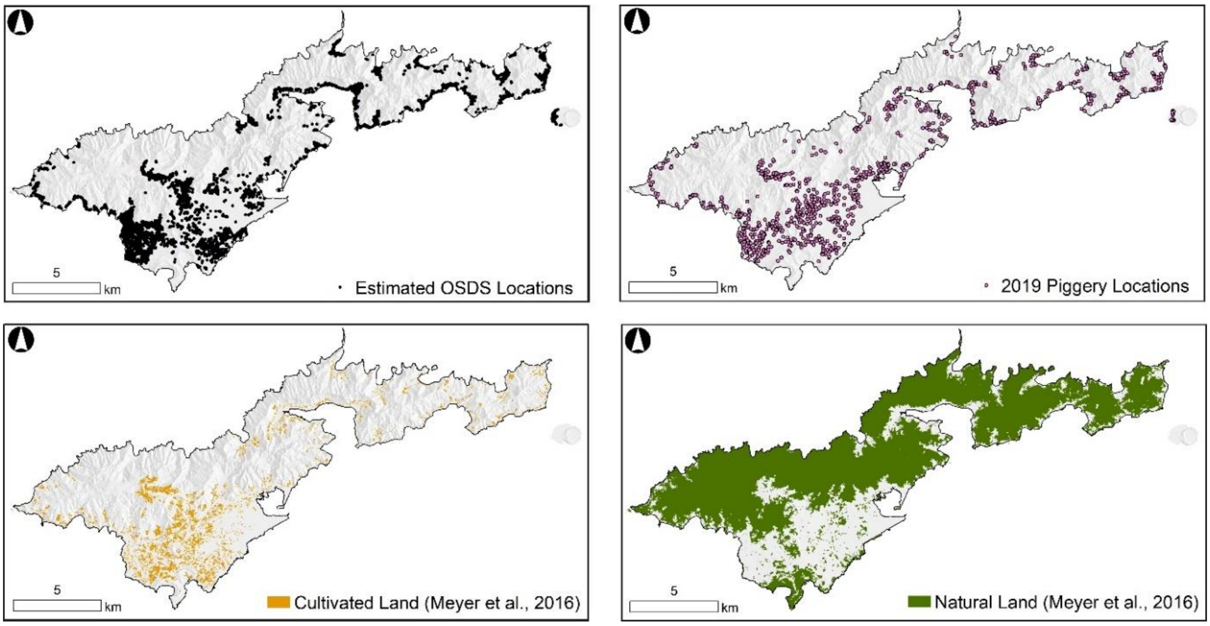

Figure 3: Locations of DIN sources used as model input. Initial DIN release rates from Shuler et al. (2017) were 0.021 kg-DIN/day per OSDS unit, 0.0381 kg-DIN/day per pig, 0.77 kg-DIN/day per km2 of agricultural land, and 0.36 kg-DIN/day per km2 of natural land.

sources (Wong 1996; Perreault, 2010), and the existing ASPA-UHWRRC streamflow network (https://github.com/cshuler/ASPA-UH_Integrated_Modeling_Framework). These were used to refine and validate the water flux estimates calculated with the water budget model, and to separate the net-infiltration component into a baseflow and a SGD component. The model was calibrated with a Python-based optimization function (scipy.optimize.minimize) and sensitivity testing was performed on each model parameter to assess the impact each calibrated loading rate had on the final total DIN load in each watershed.

Results

The calibrated model produced DIN loading rates ranging from 0.1 kg-DIN/day for some of Tutuila's smallest watersheds, to 88.2 kg-DIN/day for the largest watershed on the Tafuna-Leone Plain (Fig. 4). The relative impact of each modeled source can be seen graphically in Fig. 10. Total modeled DIN loads in each watershed are shown in the upper left map, and the other three maps (clockwise from upper right) show the proportion of DIN loaded to each watershed from OSDS units, pigs, and agriculture, respectively. When summed, island-wide, the total model-predicted DIN load from all sources equaled approximately 410 kg-DIN/day. Of this, the model predicted about 260 (63%) was from OSDS units, about 110 (27%) was from pigs, 35 (9%) was from natural sources, and only 6 (1%) kg-DIN/day originated from agriculture.

To account for bias caused by different sized watersheds, absolute loading rates were also scaled by watershed area, and by length of watershed coastline. In reality, each of these three metrics provides a different and unique presentation of impacts, while at the same time being limited by unique biases. To simplify the model results and aid interpretation for coastal management, a single watershed prioritization scheme that incorporates each of the three scaling methods was developed by calculating each watershed's rank with the three methods described above, and summing the departure from the mean for each. This total was summed and watersheds were then ranked from 1 to 93 with the highest DIN impact being assigned the lowest rank. Results of the prioritization ranking system are shown in Fig. 5, and in general, 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 areas throughout the island.

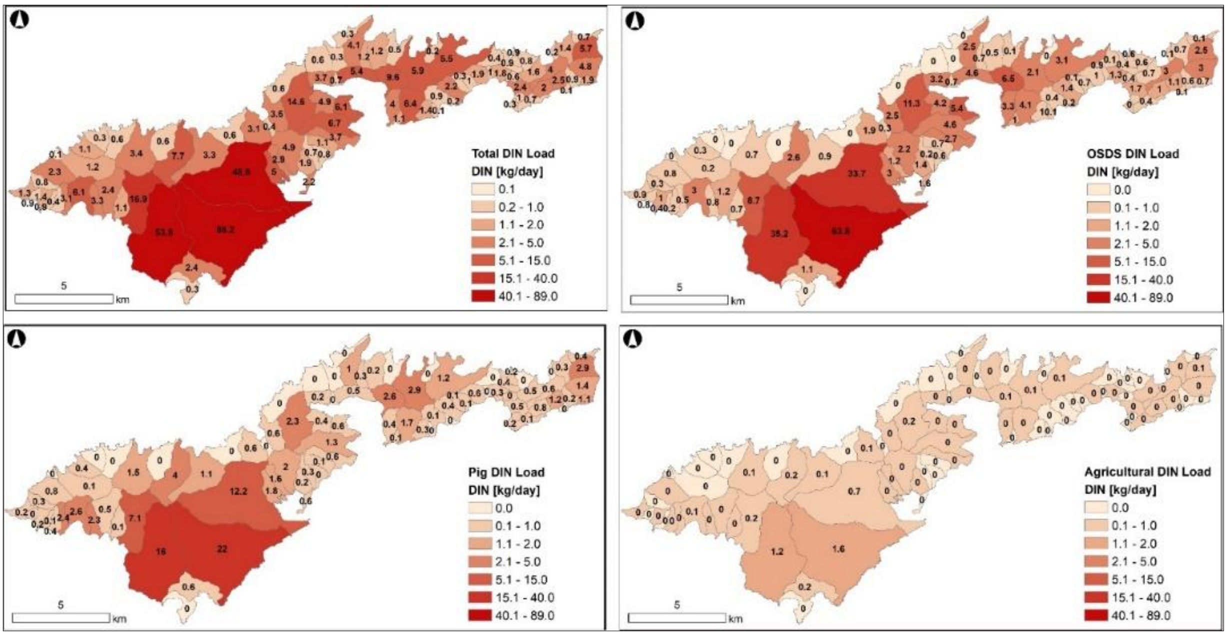

Figure 4:Comparisons between modeled DIN loading rates as separated by each nutrient source. Upper left panel shows total modeled DIN loads from all sources, and the other three panels (clockwise from upper right) show the absolute magnitude of DIN loaded to each watershed from OSDS units, pigs, and agriculture, respectively.

Discussion and Conclusions

Observed DIN loads were calculated for all hydrologic pathways including baseflow, surface runoff, and SGD. Results suggest that SGD is likely to be the most important of these nutrient delivery mechanisms to Tutuila's coastal waters. The model also allowed partitioning between distinct land use sources including OSDS units, pigs, agriculture, and natural background DIN loading. Considering DIN loading on an island-wide scale, model results suggest OSDS units are Tutuila's primary source of DIN to coastal waters, producing about 260 kg-DIN/day. In comparison, pigs produced 110 kg-DIN/day, natural sources released 35 kg-DIN/day, and agriculture produced 6 kg-DIN/day.

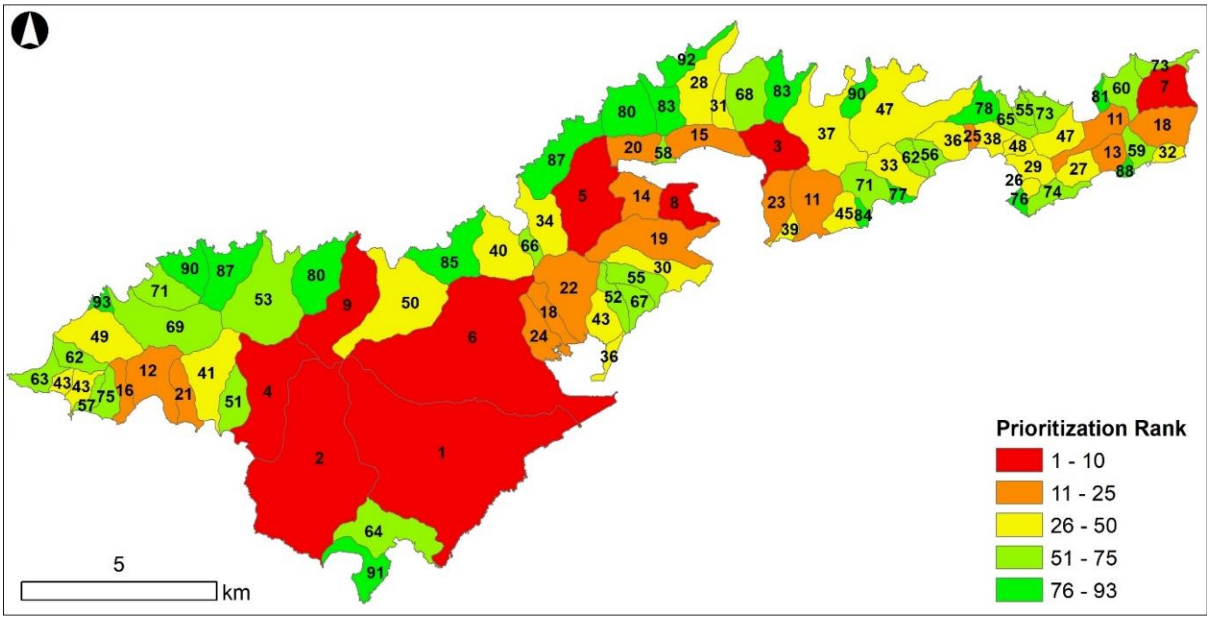

Figure 5: Relative impact prioritization through equal-weight ranking of absolute, area-scaled, and coastline length-scaled DIN fluxes from each watershed to the nearshore. Both colors and numeric labels in watersheds indicate the DIN impact prioritization ranking in each watershed with 1 being the most impacted and 93 the least. Note that if two watersheds had the same final score they were assigned the same rank number; thus some numbers are repeated.

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, additional surface runoff and coastal spring discharge in water sampling programs, would significantly improve this model and future nutrient loading analyses. To promote the continued use of this model and 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 (https://github.com/cshuler/R2R_DIN_Loading_Model). By archiving the model components in this way, the model can become dynamic, allowing for refinement in the future as new management questions come up. The open-source archive also allows for transparent reproducibility of the results, which supports good scientific practices and the missions of land and coastal resource managers working towards the betterment of American Samoa's terrestrial and marine environments.

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