Baseline and Projected Future Carbon Storage and Carbon Fluxes in Ecosystems of Hawai‘i
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Chapter 7. Baseline and Projected Future Aquatic Carbon Fluxes to Nearshore Waters in Hawai‘i

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7.1. Highlights

- Total carbon flux to nearshore waters from perennial streams and submarine groundwater discharge (SGD) from five of the seven main Hawaiian Islands was estimated to be 0.309 TgC/yr. This total was dominated by SGD inputs (74 percent or 0.228 TgC/yr), which were largely composed of dissolved inorganic carbon (DIC). Dominance by DIC in the total flux was partially the result of a lack of dissolved organic carbon (DOC) datasets and the general absence of particulate organic carbon (POC) from groundwater. SGD fluxes were greatest from Hawai‘i Island (0.146 TgC/yr), representing more than half of the total SGD DIC inputs, followed by Maui (0.032 TgC/yr), O‘ahu (0.024 TgC/yr), Kaua‘i (0.023 TgC/yr), and Moloka‘i (0.004 TgC/yr). Perennial stream fluxes were greatest from O‘ahu (0.023±0.008 TgC/yr), followed by Kaua‘i (0.020±0.005 TgC/yr), Hawai‘i (0.020±0.011 TgC/yr), Maui (0.014±0.008 TgC/yr), and Moloka‘i (0.004±0.003 TgC/yr).
- Total organic carbon (TOC), the combination of DOC and POC, represented 76.6 percent of carbon entering nearshore waters (0.062±0.028 TgC/yr) and ranged from 72.6 to 78.3 percent of total surface fluxes (0.003–0.016 TgC/yr) across the five of the seven main islands. DIC entering nearshore waters from perennial streams was estimated to be 0.019±0.006 TgC/yr. Lack of data precluded estimating carbon burial in stream systems of Hawai‘i. However, the “flashy” nature of these streams may limit carbon deposition, suggesting carbon burial is a small fraction in the overall aquatic carbon budget.
- Total carbon aquatic yields from perennial streams were greatest from O‘ahu (20.36±6.73 $gC/m^2/yr$), followed by Kaua‘i (16.63±4.45 $gC/m^2/yr$), Maui (16.41±9.75 $gC/m^2/yr$), Moloka‘i (10.04±7.16 $gC/m^2/yr$), and Hawai‘i Island (8.18±4.30 $gC/m^2/yr$). Again, TOC was the dominant form of carbon in carbon yields, representing 72.6–78.3 percent of aquatic carbon yields (10.26±4.6 $gC/m^2/yr$) across five of the main islands.
- Future increases in rainfall (0.3–39.5 percent) along wetter coasts of the Hawaiian Islands are expected to increase perennial stream TOC fluxes by nearly 10.6 percent and DIC fluxes by 8.1 percent. This would increase total surface aquatic fluxes to 0.089±0.036 TgC/yr. SGD DIC inputs will would increase by 22.3 percent, increasing SGD fluxes to 0.279 TgC/yr (from 0.228 TgC/yr).

7.2. Introduction

Pacific high islands of volcanic origin comprise watersheds with unique geomorphological, hydrological, and biological features compared to continental watersheds. Leeward and windward coasts are typically separated by high mountain ranges and consist of spatially compact, steeply sloped watersheds with relatively simple drainage networks and low-order streams (Resh and deSzalay, 1995). Because of their characteristics, stream systems on Pacific islands respond rapidly to short pulses of intense rain events that result from moisture laden airmasses moving off of the ocean and rising up along warm, high, volcanic island landmasses until they reach their dew point. Windward coasts are strongly influenced by trade winds and are characterized by perennial streams, whereas leeward coasts are isolated from trade winds by mountains and are characterized by intermittent streams. The spates or “freshettes” in windward perennial streams scour stream bottoms and deliver terrestrial-derived organic matter to nearshore waters.

The remote nature of Pacific islands has resulted in unique assemblages of endemic fauna as well as the absence of key species found in continental streams (Bright, 1982; Polhemus and others, 2000). Pacific-island streams generally lack native leaf-shredding organisms (such as stoneflies or caddisflies) (Larned,

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2000; Benstead and others, 2009; MacKenzie and others, 2013) and support lower levels of aquatic fungal biomass (MacKenzie and others, 2013) that are commonly found in continental streams and play an important role in leaf-litter breakdown and thus the carbon cycle (Vannote and others, 1980; Webster and Benfield, 1986). As a result, leaf-litter breakdown is much slower and is limited to fungal and microbial activity as well as physical abrasion (MacKenzie and others, 2013) resulting in a high export of coarse particulate organic carbon, especially during storm flows (Larned, 2000; Wiegner and others, 2009). Despite the lack of shredding insects, dissolved organic carbon (DOC) is still an important component of Pacific-island streams (Wiegner and others, 2009; Wiegner and Tubal, 2010) and nearshore waters (Atwood and others, 2012; Johnson and Wiegner, 2014). Modeled DOC fluxes from Pacific high islands in the Oceania region were equal to DOC fluxes to coastal zones in North America and Africa, with the per-area rate of DOC flux being greater in Oceania than anywhere in the world (Harrison and others, 2005).

Despite these modeled results, few studies have attempted to build carbon budgets from Pacific high islands; most studies have focused on POC and DOC fluxes from the Hawaiian Islands (Ringuet and MacKenzie, 2005; Mead and Wiegner, 2010; Wiegner and Tubal, 2010; Johnson and Wiegner, 2014). Baseline information on carbon budgets from high-island streams and groundwater and the factors that influence those budgets are paramount as human populations are expected to significantly increase in this area of the world over the next 25 years (Laws and Ferentinos, 2003) and climate and precipitation patterns are expected to change (Chu and Chen, 2005; Timm and others, 2011). Furthermore, flux of terrestrial-derived carbon to nearshore waters supports high levels of nearshore plankton and microbial production (Ringuet and MacKenzie, 2005; Wiegner and others, 2009; Mead and Wiegner, 2010; Johnson and Wiegner, 2014) that are fed on by many species of culturally and ecological important fin and shellfish (Atwood and others, 2012).

This chapter reports results from a first attempt to estimate carbon fluxes and yields from surface- and groundwater sources to nearshore waters around the seven main Hawaiian Islands: Hawai‘i, Moloka‘i, Lāna‘i, Kaho‘olawe, Maui, O‘ahu, and Kaua‘i. The steeply sloped and “flashy” nature of these and other Pacific-island stream systems has resulted in the development of few lakes and ponds. Furthermore, carbon and streamflow data from surface water were largely restricted to perennial streams and rivers. Therefore, our surface water model only focuses on carbon fluxes from perennial streams. Lentic systems could potentially play an important role in the overall carbon cycle of Pacific islands (Stackpoole and others, 2012) and additional information is needed from these ecosystems. However, when combined with reservoirs, lentic systems represent less than 0.03 percent of the landmass in Hawai‘i. Additional information on flow and carbon dynamics of intermittent streams is also needed as these ecosystems are often overlooked and can contribute significantly to overall stream function (Datry and others, 2014; Strauch and others, 2014). Finally, river CO_2 emissions were also not included in this assessment. Additional data are needed to quantify this important component of the aquatic carbon cycle in Hawai‘i. The objectives of this chapter are to (1) estimate coastal export of dissolved inorganic and total organic carbon from perennial streams and submarine groundwater discharge (SGD), (2) compare carbon export values across the seven main Hawaiian Islands and evaluate inter-island variability, and (3) provide a preliminary examination of how the onset of climate change would impact carbon export to coastal waters.

7.3. Input Data and Methods

7.3.1. Surface Water Carbon Inputs to Nearshore Ecosystems

Carbon fluxes to nearshore areas were limited to watersheds with perennial streams on five of the seven main Hawaiian Islands; neither Lāna‘i nor Kaho‘olawe have any perennial streams. Carbon fluxes were first modeled from 16 perennial streams that had long-term discharge and carbon datasets from the U.S. Geological Survey (USGS) National Water Information Service (NWIS) (USGS, 2012). Dissolved inorganic carbon (DIC) concentrations (in micromoles) were estimated from USGS NWIS measurements of pH, temperature, and either filtered or unfiltered alkalinity (Stets and Striegl, 2012). Total organic carbon (TOC) concentrations (in milligrams per liter) were either direct measurements or the sum of dissolved and particulate organic carbon. Daily DIC and TOC fluxes were then determined for those 16 streams using the USGS Load Estimator Model (LOADEST) (Runkel and others, 2004). LOADEST is a multiple-regression Adjusted Maximum Likelihood Estimation (AMLE) model which uses measured DIC or TOC concentration values to calibrate a regression among constituent load, streamflow, season, and time by the following equation:

$$\ln LOAD = a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin(2\pi \text{ dtime}) + a_4 \cos(2\pi \text{ dtime}) + a_5 \text{ dtime} + a_6 \text{ dtime}^2 + \varepsilon \quad (1)$$

where

- $\ln LOAD$ is the natural log of the DIC or TOC constituent load (mol/d or kg/d, respectively),
- Q is the discharge,
- dtime is time in decimal years,
- $a_0, a_1 \ldots a_n$ are regression coefficients, and
- ε is an independent and normally distributed error.

Model calibration required at least 12 paired water-quality (for example, DIC, TOC) and daily streamflow measurements over at least a 3-year period from 1972 to 2013. We chose 1972 as the starting time point because a long-term streamflow analysis revealed no significant change in streamflow since that time (Bassiouni and Oki, 2012). Once the model was calibrated for each of the 16 streams, LOADEST was then used to estimate daily carbon flux for those streams using continuous flow data during the time range of carbon measurements. Input data were log-transformed to avoid bias and centered to avoid multicollinearity. The models used to estimate loads for individual USGS stations varied in terms of coefficients and estimates of log load (equation 1). LOADEST output complications, including retransformation bias, data censoring, and non-normality were reduced using (AMLE) and the highest value for Schwarz Posterior Probability Criterion (SPCC). The estimated loads and their standard errors were used to develop 95-percent confidence intervals for various periods. The model's performance was examined by reviewing its output, such as the partial load factor (PLF), Nash-Sutcliffe Efficiency (NSE) coefficient (Stenback and others, 2011), and AMLE's coefficient of determination (R^2) values and residuals (model error). PLF ranges from -1 to 1; model values below zero were rejected owing to over prediction. NSE ranges from $-\infty$ to 1 with values above zero indicating model predictions more accurate than the mean of the observed data. Mean daily DIC and TOC loads were then estimated for each of the 16 streams using the best of nine models based on Akaike's Information Criterion (Runkel and others, 2004). Daily values were then summed up for each year and averaged across years.

Average annual TOC and DIC fluxes for each of these 16 watersheds were then correlated to various characteristics of watersheds above each USGS streamgage in Sigma Plot. Independent variables included drainage area (in square miles), mean basin slope (in percent), area-weighted mean soil permeability (top 12 inches; in inches per hour), percent barren land, percent evergreen forest, percent cultivated crop, percent impervious area, percent urban land cover, mean annual precipitation (in inches), and Q_{50} (in cubic feet per second). All but Q_{50} were obtained from STREAMSTATS program using geospatial data made available by the USGS (Rea and Skinner, 2012). Q_{50} was the median streamflow in each stream and was averaged across the water years from which DIC and TOC measurements were obtained. We looked at all possible linear combinations among log TOC and log DIC and all possible combinations of 1, 2, and 3 of the 9 predictors listed above. We took this approach because the sample size (n = 16) was too small to warrant more than three predictors in a single model. We then chose the model with the lowest Akaike Information Criterion (AIC) score and highest AIC weight to estimate TOC and DIC loads (fig. 7.1) from the remaining 401 ungaged and short-term gaged perennial streams. Q_{50} estimates for these 401 perennial streams were estimated using the formula developed by Fontaine and others (1992):

$$Q_{50} = 4.49 \times DA^{\,0.808} \times CE^{\,-0.641} \times P^{\,0.985} \qquad (2)$$

where DA is drainage area,
CE is mean channel elevation from 10 and 85 percent of channel length, and
P is mean annual precipitation.

Individual watershed annual TOC and DIC fluxes were then converted to teragrams of carbon per year and summed by island. Yields (in grams of carbon per square meter per year) were estimated by dividing fluxes by the sum of the watershed area for each island. Total carbon fluxes were then calculated as the sum of TOC and DIC fluxes across five of the main Hawaiian Islands; total carbon yields were the sum of the carbon fluxes divided by the watershed area for each catchment. Standard errors were determined for TOC and DIC fluxes and yields from each watershed using the applied delta method and variances and covariance from the coefficients in figure 7.1 (Bishop and others, 1975). The square root of the sum of these errors squared was then used to determine the standard errors for each island and across Hawaiʻi.

Tropical island streams differ from temperate continental streams in several ways (see Resh and deSzalay, 1995) and models developed for temperate watersheds (for example, the Universal Soil Loss Equation) do not always function similarly in tropical ones (Millward and Mersey, 1999; Prasannakumar and others, 2012). Therefore, to determine the accuracy of LOADEST predicted carbon loads from Hawaiian streams, we compared LOADEST model output of particulate carbon (PC) to actual continuous measurements of PC from three watersheds along the north Hilo coast of Hawaiʻi Island. Sub-daily (15-minute-interval) measurements of turbidity (Strauch and others, 2014) and streamflow (Strauch and others, 2015) were used to estimate total suspended sediment (TSS) fluxes for the 2013 calendar year. TSS fluxes were then converted to PC by using grab samples collected across a range of streamflows, analyzed for PC, and then calibrated to the TSS values. PC was then estimated by summing values (in milligrams of carbon per second) for each watershed for the whole year. PC measurements were also used to calibrate the LOADEST Fortran model. Actual observed PC fluxes were then compared to LOADEST estimates.

7.3.2. Groundwater Inputs to Nearshore Ecosystems

Aquifers in Hawaiʻi have been delineated into a series of "hydrologic units" based on surface geology, such as topographic divides, and subsurface geology, such as rift zones (Mink and Lau, 1990, 1992, 1993). Each hydrologic unit typically includes several watersheds within a similar geologic and climatic setting. Within each hydrologic unit, the groundwater flux of TOC and DIC to the ocean was calculated as follows:

$$GWflux = Q \times C \qquad (3)$$

where Q is the submarine groundwater discharge (SGD) and
C is the concentration of TOC or DIC in groundwater.

The TOC and DIC fluxes from groundwater were computed using available data from the USGS (http://nwis.waterdata.usgs.gov/usanwis/qwdata). The methods for compiling data and data sources are further described below.

7.3.2.1. Submarine Groundwater Discharge Data

Hydrologic budgets have been used widely to estimate groundwater recharge of each hydrologic unit on the seven largest islands in Hawaiʻi (Shade, 1995, 1997, 1999; Shade and Nichols, 1996; Engott and Vana, 2007; Engott, 2011). Ultimately, this groundwater recharge flows back to the ocean, and can be used as an estimate of fresh submarine groundwater discharge. Because most of these models do not account for baseflow groundwater discharge to rivers and streams, this estimate of recharge is an upper limit. For hydrologic units not in direct contact with the sea, the recharge was treated as an underflow and added to an adjacent aquifer unit. For Kahoʻolawe, groundwater recharge was estimated based on the average rainfall and the recharge to rainfall ratio of 21 percent calculated for hydrologic units on the leeward side of east Maui (Shade, 1999).

7.3.2.2. Chemical Data

Well data for pH and alkalinity were summarized from the USGS (2014). To maximize the available data for this analysis, alkalinity data measured using both fixed endpoint and inflection point titration data of filtered and unfiltered samples, measured either in the field or the lab, were used (399 alkalinity measurements from 269 wells). Of these wells, 17 were not used because they had a specific conductivity greater than 5 microsiemens per centimeter (mS/cm) and were likely impacted by high alkalinity seawater or a temperature greater than 35 °C and geothermally altered. Of the remaining measurements, 94 percent were from less than 7 km in from the shoreline, providing a reasonable estimate of the alkalinity for basal groundwater flowing into the ocean. Measurements more than 7 km from the shoreline were only made on Oʻahu and Hawaiʻi Island. Alkalinity reported in milligrams of $CaCO_3$ per liter was converted to milliequivalents per liter (meq/L) by multiplying by 0.01998 (Rounds, 2006) before calculating total CO_2 (TCO_2) or DIC. For pH, only field measurements of unfiltered water were used (481 pH measurements from 283 wells), because repeated measurements in the lab were 0.42±0.41 pH units greater than field measurements, suggesting CO_2 degassing during transport (n = 301). For each well, the average alkalinity, pH, and temperature were computed. For wells with alkalinity data but no pH data, pH data from nearby wells within the same hydrologic system were used (n = 35). Of these, half of the pH measurements were from wells within 5 km of the corresponding alkalinity measurements. DIC for the 234 wells was calculated using the USGS CO_2Calc software, using K1 and K2 from Millero (1979), the pH NBS scale, an average SiO_2 of 790 μM, and a water density of 0.998 g/cm^3 (Robbins and others, 2010).

For each hydrologic system, the mean (±1 SD) concentration was computed. For systems lacking measurements, the average DIC concentration of adjacent hydrologic units was applied. No data were available for Kahoʻolawe and Lānaʻi, so the average DIC for Maui and the average DIC for West Maui and Molokaʻi were applied, respectively. Uncertainty could not be estimated for DIC SGD estimates, either by island or across Hawaiʻi, owing to lack of data.

All DOC data were from the USGS (n = 58) (USGS, 2014), and were filtered water samples except three unfiltered samples from well 3–1851–22 on Ala Moana Boulevard in Honolulu, Oʻahu. For samples below the detection limit (n = 39), a nominal concentration of one-half of the detection limit was applied.

7.3.3. Total Carbon Fluxes and Yields

Total carbon fluxes (in teragrams of carbon per year) were then estimated by adding the stream total carbon fluxes (TOC and DIC) and the DIC SGD fluxes. Total carbon yields (in grams of carbon per square meter per year) were estimated by dividing the total carbon fluxes by the total area of five of the main Hawaiian Islands (Hawaiʻi, Kauaʻi, Molokaʻi, Maui, and Oʻahu). Uncertainty could not be estimated for total carbon fluxes because of the lack of uncertainty from SGD estimates.

7.3.4. Future Impacts on Carbon Inputs to Nearshore waters

Impacts of climate change on perennial stream and SGD carbon fluxes were examined by calculating the projected change in mean annual precipitation (MAP) for each respective watershed. Changes in MAP between current (annual average of 1990–2010) and end-of-century (annual average of 2080–2100) scenarios were calculated from the Hawaiian Regional Climate Model (HRCM) with 3-km spatial resolution (Zhang and others, 2012).

The HRCM is based on the Weather Research and Forecasting model ver. 3.3. It considers future climate forcing based on the SRES A1B emission scenario and the mean of multiple CMIP3 global circulation models. The HRCM simulations replicate the regional and island climate mechanisms that largely dictate local climate such as extreme orographic-based precipitation gradients and trade wind inversions (Zhang and others, 2012). As such, the computing requirements to run the HRCM simulations limit our analyses to a single future climate scenario. However, preliminary results showed that interpolated global circulation model (GCM) projections, such as those commonly used in continental species distribution model analyses, are of very limited value for a small, hyper-diverse climatic region such as Hawaiʻi.

Changes in mean annual rainfall from each hydrologic unit described above were used to estimate changes in SGD based on the mean annual rainfall-to-recharge ratio of the hydrologic unit. The mean annual rainfall-to-recharge ratio also changes with variations in precipitation. To estimate the changes in the mean annual rainfall to recharge ratio, the modeling results for changes in recharge in different rainfall conditions on Hawaiʻi Island were examined (Engott, 2011). Based on these modeled scenarios, a linear relationship between the fractional change in precipitation and the change in recharge to mean annual rainfall ratio was identified and applied to all islands:

$$Fppt = (Pcurrent - Pfuture) / Pcurrent \quad (4)$$

$$\Delta R = Rcurrent - Rfuture \quad (5)$$

where

Fppt	is fractional change in precipitation,
Pcurrent	is current precipitation,
Pfuture	is precipitation at the end of the century (2100),
ΔR	is change in recharge,
Rcurrent	is current recharge, and
Rfuture	is recharge at the end of the century (2100).

The relationship for increasing mean annual rainfall ($\Delta R = 0.256 \times Fppt$; $R2 = 0.93$) differed from the decreasing mean annual rainfall relationship ($\Delta R = 0.34Fppt$; $R2 = 0.78$) owing to different hydrologic processes occurring (for example, transpiration, vadose zone transport). For perennial streams, changes in mean annual rainfall to each perennial watershed were determined by multiplying the current mean annual rainfall by the predicted percent change. Future mean rainfall values were then used to model Q_{50} for each perennial stream following the equation in Fontaine (1992), which was then used to predict TOC and DIC using the methods described above.

7.4. Results

7.4.1. LOADEST Model Calibration

Of the 16 stream datasets used to calibrate LOADEST, 10 included the years 1975–1981. Six stream datasets had calibration and flow data from the 2000s and 2 were calibrated exclusively after 1999. Thus the range years of all included data in the model runs was from 1972 to 2012. Although three stations had less than 5 years of data that met our guidelines, the mean number of years used was 10.8. When LOADEST output was correlated to the various watershed parameters, only Q_{50} proved to be a significant predictor of carbon load (fig. 7.1).

7.4.2. Lateral Carbon Transport in Riverine Systems

Based on the Division of Aquatic Resources (DAR) Hawaiian watershed atlas, there were a total of 417 perennial streams on the five main Hawaiian Islands (fig. 7.2; table 7.1). Hawai‘i Island had the greatest number of perennial streams (fig. 7.2; table 7.1), with 30 percent more perennial streams

Table 7.1. Summary of available surface water data for the State of Hawai‘i.

[Area of watersheds includes only those watersheds where estimates could be made. TOC, total organic carbon; DIC, dissolved inorganic carbon]

Island	Area (km²)	Number of perennial Streams	Area of perennial watersheds (km²)	Number of USGS gage sites used	Number of distinctly gaged watersheds	Number of TOC/ DIC sites
Hawai‘i	10,432	126	2,457	6	5	3
Kaua‘i	1,430	77	1,215	11	8	1
Moloka‘i	637	58	431	1	1	1
Maui	1,884	92	824	9	9	1
O‘ahu	1,545	64	1,121	22	17	10
Total	15,928	417	6,048	49	40	16

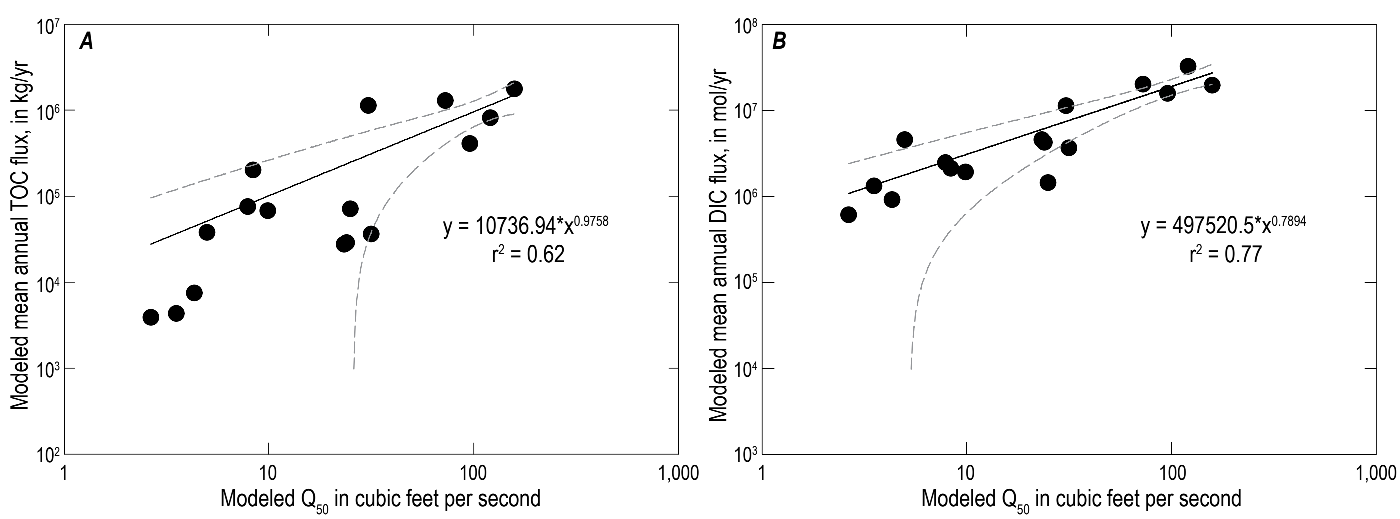
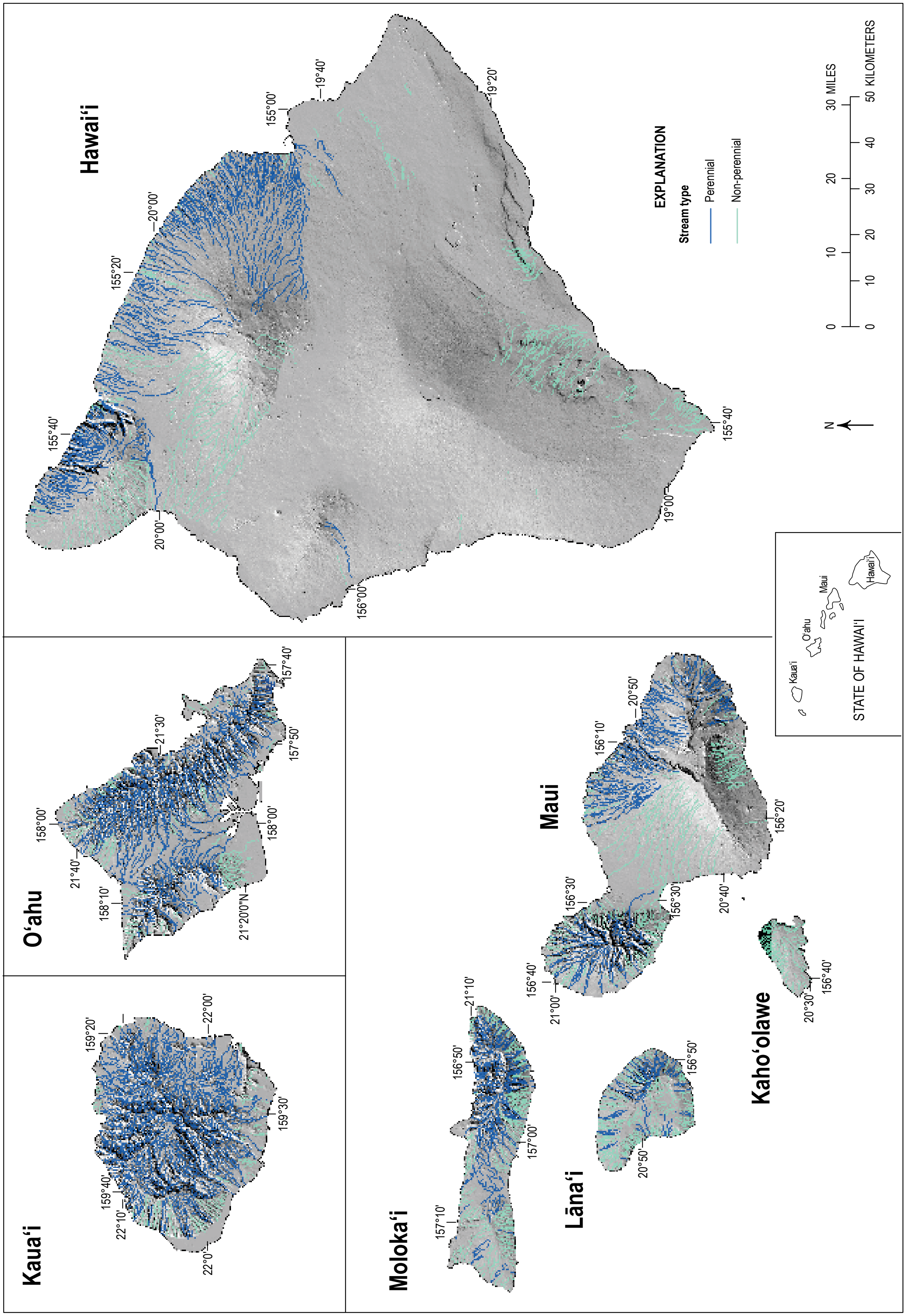


Figure 7.1. Plots of relationship between modeled median streamflow (Q_{50}) and modeled mean annual total organic carbon (TOC) (*A*) and dissolved inorganic carbon (DIC) (*B*) for watersheds across the State of Hawai‘i. kg/yr, kilograms per year; mol/yr, moles per year.



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 7.2. Maps showing Hawai‘i State Division of Aquatic Resources designated perennial and non-perennial streams for each major island of Hawai‘i.

than the other Hawaiian Islands in this assessment. Only 38 percent of the area of the five main islands was represented by watersheds with perennial streams, owing to vast leeward areas of the largest two islands (Hawai‘i [76 percent] and Maui [56 percent]) lacking any perennial streams. By contrast, 85 percent of Kaua‘i, 73 percent of O‘ahu, and 68 percent of Moloka‘i were represented by perennial-stream watersheds.

LOADEST-modeled TOC and DIC values were highly variable among streams in Hawai‘i. Kaua‘i Island has the highest average (±1 SE) modeled TOC fluxes (1,298,000±466,000 kg/yr), followed by Hawai‘i (1,247,000±222,000 kg/yr), Moloka‘i (203,000±26,000 kg/yr), O‘ahu (70,000±13,000 kg/yr), and Maui (68,000±11,000 kg/yr). Hawai‘i Island had the highest average (±1 SE) LOADEST-modeled DIC fluxes (252,000±32,000 kg/yr), followed by Kaua‘i (240,000±52,000 kg/yr), O‘ahu (47,000±3,000 kg/yr), Moloka‘i (25,000±2,000 kg/yr), and Maui (23,000±2,000 kg/yr).

The total carbon flux from perennial Hawaiian streams was estimated to be 0.080±0.033 TgC/yr (table 7.2). The amount of carbon exported to Hawai‘i’s nearshore waters was greatest from O‘ahu (0.023±0.008 TgC/yr), followed by Kaua‘i (0.020±0.005 TgC/yr), Hawai‘i (0.020±0.011 TgC/yr), Maui (0.014±0.008 TgC/yr), and Moloka‘i (0.004±0.003 TgC/yr). TOC fluxes were higher than DIC fluxes from streams on all five islands, with TOC fluxes representing nearly 76.6 percent of the total stream carbon entering Hawaiian nearshore waters. DIC fluxes were nearly half that of TOC fluxes and were greatest from Hawai‘i Island (0.005 TgC/yr) and O‘ahu (0.005±0.001 TgC/yr), followed by Kaua‘i (0.004±0.001 TgC/yr), Maui (0.003±0.001 TgC/yr), and Moloka‘i (0.001±0.001 TgC/yr).

When area of watersheds was used to normalize stream carbon fluxes, contributions from the different islands were somewhat similar. Total carbon aquatic yields from perennial streams were greatest from O‘ahu (20.36±6.73 gC/m^2/yr), followed by Kaua‘i (16.63±4.45 gC/m^2/yr), Maui (16.41±9.75 gC/m^2/yr), and Moloka‘i (10.04±7.16 gC/m^2/yr). Streams from Hawai‘i Island, the largest of the five islands, had the lowest carbon yield (8.18±4.30 gC/m^2/yr) owing to the larger area of perennial watersheds. Total modeled stream carbon yield from all islands was 13.39±5.68 gC/m^2/yr, with TOC yields being slightly greater than DIC yields and making up 72.6–78.3 percent of total carbon yields.

Comparison of LOADEST-modeled PC flux to observed fluxes revealed that LOADEST underestimated PC fluxes. LOADEST estimates ranged from 37,902 to 726,322 kgC/yr, whereas observed values ranged from 155,391 to 1,225,825 kgC/yr (table 7.4). LOADEST values were 40.7–75.6 percent lower than observed values, with the level inaccuracy increasing with decreased mean annual rainfall, watershed area, and mean streamflow (Q_{50}).

7.4.3. Carbon Fluxes from Submarine Groundwater Discharge

DIC was calculated at 250 wells across Hawai‘i, ranging from 3.3 to 81.5 mgC/L (fig. 7.3). Most samples fell within a relatively narrow range of 20.3±11.6 mgC/L. DIC varied considerably on each island, with the highest values in areas likely with geothermal activity (Hawaii Institute of Geophysics, 1983). The median DIC in groundwater varied significantly among islands according to a Kruskal-Wallis nonparametric test (H = 35, p <0.001). Although the highest mean DIC was on Kaua‘i, there was no obvious trend in DIC as a function of island age (table 7.5).

Table 7.2. Estimated baseline total organic carbon and dissolved inorganic carbon fluxes and yields (±1 SE) based on the Q_{50} regression model.

[Total surface flux and yield from perennial riverine systems for each island and the entire State of Hawai‘i are also presented. Q_{50} values (annual median streamflow over the sampling period) for each river were estimated using the equation from Fontaine and others (1992) and the mean annual precipitation, drainage areas, and mean channel elevations. Fluxes were normalized to entire or total island areas. TOC, total organic carbon; DIC, dissolved inorganic carbon; m^3/s, cubic meters per second; TgC/yr, teragrams of carbon per year; gC/m^2/yr, grams of carbon per square meter per year]

Island	Number of sites	Mean annual precipitation (mm/yr)	Mean Q_{50} (m^3/s)	Estimated TOC flux (TgC/yr)	Estimated TOC yield (gC/m^2/yr)	Estimated DIC flux (TgC/yr)	Estimated DIC yield (gC/m^2/yr)	Estimated total surface flux (TgC/yr)	Estimated total surface yield (gC/m^2/yr)
Hawai‘i	123	3,130	0.34	0.015 (0.008)	6.17 (3.52)	0.005 (0.002)	2.01 (0.78)	0.020 (0.010)	8.18 (4.30)
Kaua‘i	75	2,030	0.75	0.016 (0.004)	13.02 (3.47)	0.004 (0.001)	3.61 (0.98)	0.020 (0.005)	16.63 (4.45)
Moloka‘i	58	1,428	0.15	0.003 (0.003)	7.28 (5.83)	0.001 (0.001)	2.75 (1.33)	0.004 (0.004)	10.03 (7.16)
Maui	92	3,356	0.31	0.010 (0.007)	12.23 (8.03)	0.003 (0.001)	4.18 (1.72)	0.013 (0.008)	16.41 (9.75)
O‘ahu	64	1,960	0.81	0.018 (0.006)	15.93 (5.46)	0.005 (0.001)	4.43 (1.26)	0.023 (0.007)	20.36 (6.73)
Total	413			0.062 (0.028)	10.26 (4.60)	0.019 (0.006)	3.13 (1.07)	0.080 (0.033)	13.39 (5.68)

Table 7.3. Projected future total organic carbon and dissolved inorganic carbon fluxes and yields (±1 SE) based on the Q_{50} regression model.

[Total surface flux and yield from perennial riverine systems for each island and the entire State of Hawai‘i are also presented. Q_{50} (annual median streamflow over the sampling period) values for each river were estimated using the equation from Fontaine and others (1992) and the predicted changes in mean annual precipitation, drainage areas, and mean channel elevation. Fluxes were normalized to entire or total island areas. TOC, total organic carbon; DIC, dissolved inorganic carbon; TgC/yr, teragrams of carbon per year; gC/m²/yr, grams of carbon per square meter per year]

Island	Projected TOC flux (TgC/yr)	Projected TOC yield (gC/m²/yr)	Projected DIC flux (TgC/yr)	Projected DIC yield (gC/m²/yr)	Projected total surface flux (TgC/yr)	Projected total surface yield (gC/m²/yr)
Hawai‘i	0.018 (0.009)	7.37 (3.75)	0.005 (0.002)	2.31 (0.84)	0.023 (0.011)	9.68 (4.59)
Kaua‘i	0.017 (0.004)	13.99 (3.62)	0.005 (0.001)	3.71 (0.99)	0.022 (0.005)	17.71 (4.61)
Moloka‘i	0.003 (0.003)	7.43 (5.91)	0.001 (0.001)	2.80 (1.34)	0.004 (0.004)	10.23 (7.26)
Maui	0.012 (0.007)	15.01 (9.04)	0.004 (0.002)	4.94 (1.92)	0.016 (0.009)	19.95 (10.96)
O‘ahu	0.018 (0.006)	16.00 (5.47)	0.005 (0.001)	4.45 (1.26)	0.023 (0.007)	20.45 (6.73)
Total	0.069 (0.029)	11.35 (4.87)	0.020 (0.007)	3.38 (1.13)	0.089 (0.036)	14.72 (6.00)

Table 7.4. Comparison between total particulate carbon flux and yield estimates for three watersheds on the north Hilo coast of Hawai‘i Island during the calendar year 2013.

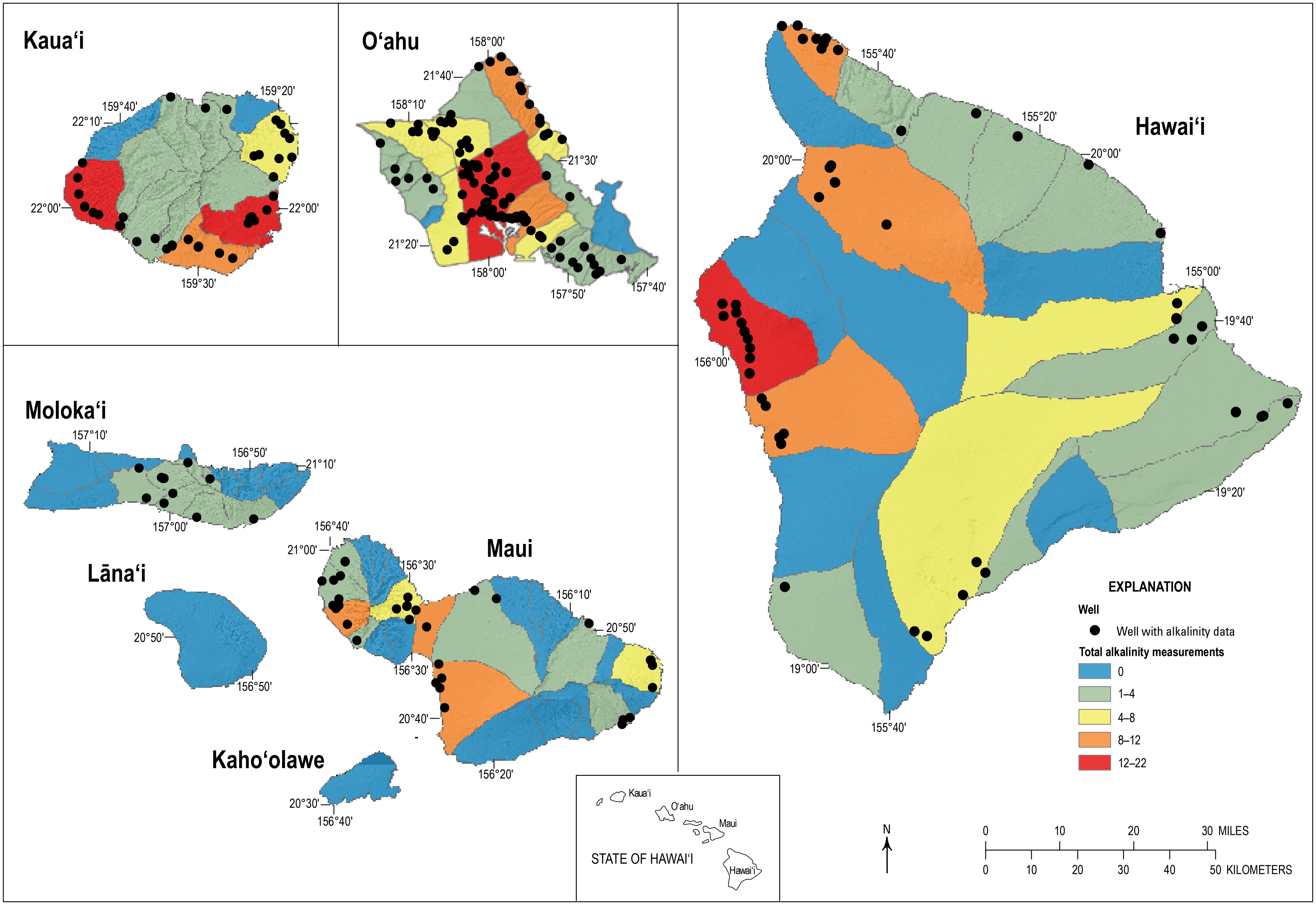
[Total particulate carbon flux and yield estimates using sub-daily flow with sub-daily total particulate carbon measurements and LOADEST Fortran model. Mean annual rainfall from Giambelluca and others (2013) except rainfall above 1,800 m, which is from Strauch and others (2015). Q_{50} is the annual median streamflow that occurred during the sampling period (Strauch and others, 2015). TPC, total particulate carbon; mm/yr, millimeters per year; kgC/yr, kilograms of carbon per year; gC/m²/yr, grams of carbon per square meter per year]

Watershed	Watershed Area (km²)	Mean annual rainfall (mm/yr)	Q_{50}	Observed TPC flux (kgC/yr)	Estimated TPC flux (kgC/yr)	Observed TPC yield (gC/m²/yr)	Estimated TPC yield (gC/m²/yr)
Umauma	74.332	5,582	0.331	1,225,825	726,322	16.491	9.771
Pahale	10.143	4,968	<0.001	730,122	227,757	71.982	22.454
Manowaiopae	3.836	4,689	0.004	155,391	37,902	40.509	9.881

Table 7.5. Mean groundwater dissolved inorganic carbon concentration, total submarine groundwater discharge, and total groundwater dissolved inorganic carbon flux for each island.

[Carbon flux (C flux) was calculated as the sum of the carbon fluxes of each hydrologic unit, and therefore differs slightly from the product of the dissolved inorganic carbon (DIC) concentration and submarine groundwater discharge (SGD). mgC/L, milligrams of carbon per liter; km³/yr, cubic kilometers per year; TgC/yr, teragrams of carbon per year]

Island	Mean DIC (mgC/L)	SGD (km³/yr)	C flux (TgC/yr)	Projected future SGD (km³/yr)	Projected future C flux (TgC/yr)
Kaua‘i	24.2±6.6	0.90	0.023	0.97	0.025
O‘ahu	21.2±7.7	1.18	0.024	1.19	0.024
Moloka‘i	15.7±4.4	0.26	0.004	0.27	0.004
Lāna‘i	21.0	0.09	0.002	0.08	0.002
Maui	22.2±9.9	1.56	0.032	2.14	0.042
Kaho‘olawe	23.9	0.01	0.0002	0.01	0.0002
Hawai‘i	16.9±10.1	9.12	0.146	11.54	0.184
Total	20.0±8.7	13.11	0.230	16.20	0.281



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 7.3. Map of wells where alkalinity data were collected in Hawai'i. Each hydraulic sector is colored based on the number of alkalinity samples made in the sector.

SGD differed widely among hydrologic units (from 0.01×10^6 to 3.96×10^6 m^3/d), largely depending on rainfall and surface area (fig. 7.5). The largest SGD estimates were on the windward slopes of Hawai‘i Island and Maui, whereas lower discharges are predicted for leeward parts of the islands. The flux of DIC from each aquifer sector was calculated as the product of the SGD and DIC concentrations. In general, the largest DIC fluxes were from hydrologic units with the largest SGD, such as on the windward coasts of Hawai‘i Island, Maui, and Moloka‘i (fig. 7.5). The greatest flux was on Hawai‘i Island, accounting for 71 percent of the total (table 7.5). Although the DIC concentration was greatest on Kaua‘i, the flux was not as large as other islands owing to the smaller SGD.

DOC was measured in 56 unique wells, concentrated on O‘ahu (mean: 0.44±1.01 mg DOC/L) and in the Kamaole system in central Maui (mean: 0.80±0.66 mg DOC/L). Given the paucity of data available, a mean concentration of all samples (0.50±0.96 mg DOC/L) was used to calculate a statewide average groundwater flux to the ocean of 0.007 TgC/yr.

7.4.4. Future Changes to Carbon Inputs to Nearshore Waters

The HRCM-based climate projections show general precipitation shifts that include a 17.1–39.5 percent increase in precipitation on wet windward areas of Hawai‘i and Maui, a 0.3–2.7 percent increase on the remaining islands, and a general slight drying trend across the drier areas of the islands. Increased rainfall is expected to increase stream and SGD carbon fluxes to Hawaiian nearshore waters. This is expected to increase stream carbon fluxes by nearly 10 percent, from 0.081±0.034 to 0.089±0.036 TgC/yr, with greatest increases expected from Maui (21.6 percent) and Hawai‘i (18.3 percent) (table 7.3). Stream TOC fluxes will increase by nearly 10 percent and DIC will increase by 8 percent (table 7.3). SGD DIC fluxes will have a greater response, increasing by 24 percent and raising SGD fluxes from 0.228 to 0.279 TgC/yr (table 7.5 and fig. 7.6). Again, the statewide increase is dominated by the large SGD of Hawai‘i Island. Assuming the DIC concentration of groundwater remains constant, the statewide DIC flux will also increase by 22 percent. The only projected decreases in DIC flux were for the islands with the least data, Kaho‘olawe and Lāna‘i.

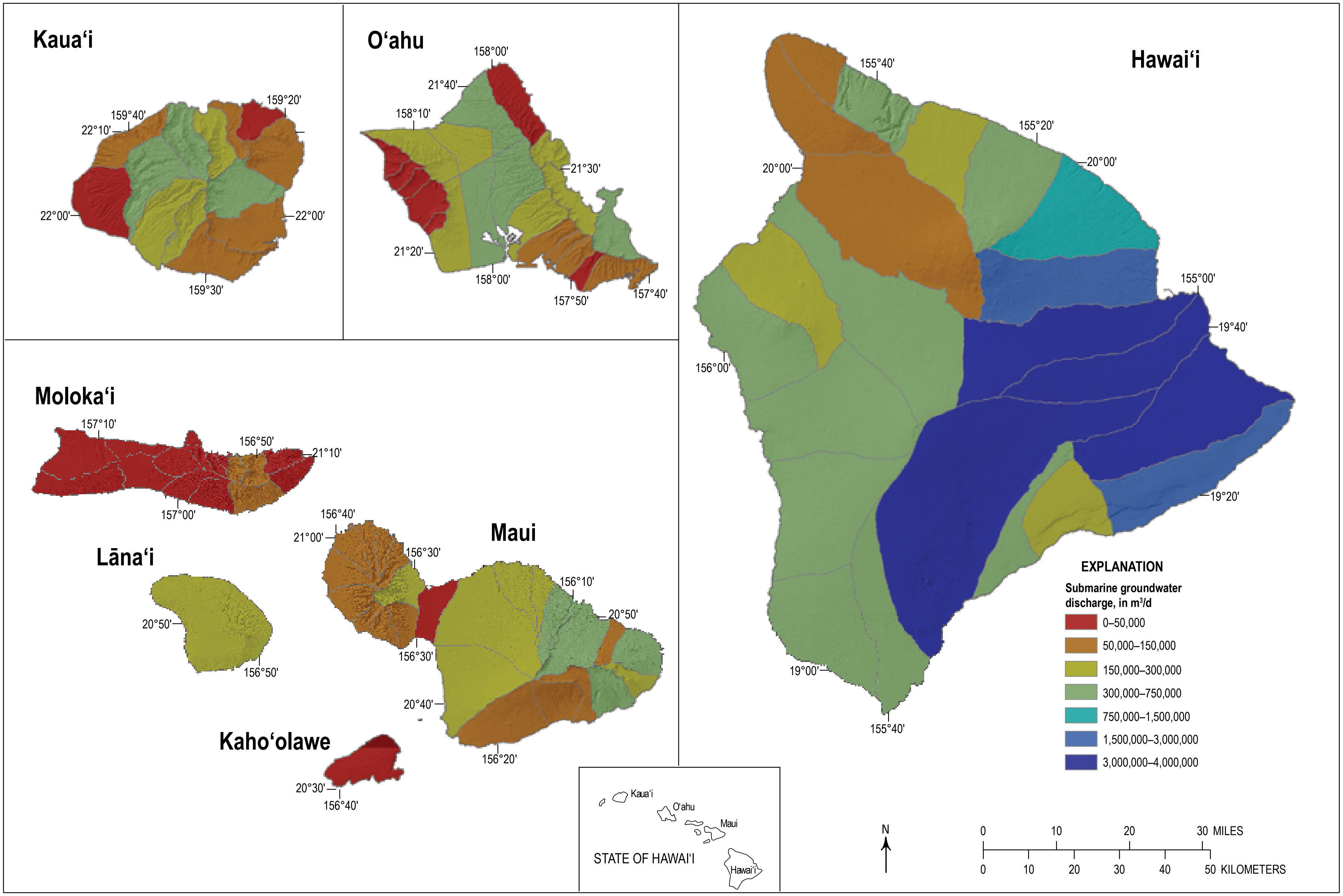
7.5. Discussion

Streams, rivers, and groundwater provide an important mechanism for processing and delivering particulate and dissolved forms of carbon to nearshore waters (Datry and others, 2014). Once thought to be simple conduits of carbon, streams and rivers process nearly half of the terrestrial carbon inputs before they are delivered to the ocean. The rest is buried within the system or lost to the atmosphere through various physical, biogeochemical, and ecological processes (Cole and others, 2007). Streams and groundwater likely play similar roles in Pacific Island carbon cycles, yet few studies have attempted to construct entire carbon budgets for this region. This is particularly important in the tropics because carbon fluxes to nearshore waters from perennial streams and submarine groundwater discharge are a valuable energy source that supports sustainable levels of coastal primary productivity (Hoover and others, 2006; Mead and Wiegner, 2010; Johnson and Wiegner, 2014) and secondary productivity (Atwood and others, 2012). Our results provide an initial assessment of surface and groundwater carbon inputs to Hawaiian nearshore waters. Inputs were dominated by DIC fluxes from SGD, whereas total organic carbon fluxes were largely due to surface water inputs and both of these fluxes are expected to increase under future climate scenarios. Higher inputs of DIC from SGD sources are likely due to the fact that estimates from SGD encompassed entire island areas, whereas surface water inputs were only calculated for perennial streams and were limited to perennial watershed scales. Higher total organic carbon values were likely due to the fact that SGD flowing through aquifers lacks the particulate carbon sources that dominate surface water carbon loading (Johnson and Wiegner, 2014). Comparisons across islands revealed that DIC in SGD decreased with decreasing island area; Hawai‘i Island had the most SGD DIC, whereas Moloka‘i had the least. Stream carbon fluxes were much more variable. A general lack of data limited our ability to estimate accurate stream and groundwater inputs or examine what factors (for example, land use, rainfall, streamflow) have the greatest influence on carbon loading to nearshore waters.

7.5.1. Stream Carbon Inputs

The initial correlation analysis revealed that carbon loading was best predicted by median streamflow; none of the other land-use categories—such as forest cover, percent agriculture, or impervious services—that are known to influence surface runoff, and thus carbon loading, proved to be effective predictors of carbon loading (Booth and others, 2002; Bruland and MacKenzie, 2010). This is likely due to the fact that only 16 values were used in the initial analysis. Additional data points will increase our ability to correlate carbon fluxes to other land uses and increase the robustness of our model.

Stream carbon inputs for the State of Hawai‘i are likely to be underestimates for several reasons. First, as identified above, carbon outputs for 401 streams were modeled from LOADEST output from only 16 streams. Additional streamgages coupled with water quality and quantity monitoring would alleviate this data gap and increase the robustness of this effort. Second, surface water estimates only included perennial streams and ignored intermittent or ephemeral streams. Intermittent rivers, which are rarely monitored because of their limited economic importance, are a potentially important source of carbon across the Hawaiian Islands because of their extent along the leeward sides of the islands and because of the carbon dynamics that occur within them. Leaf litter and other forms of particulate organic carbon can accumulate in drying or dried streambeds (Acuña and Tockner, 2010; Corti and others, 2011). Lower flow in drying streams can also result in increased leaf-litter breakdown, likely through increased water temperatures and increased bacterial activity (MacKenzie and others, 2013; Roberts and others, 2016). Breakdown in dried-out



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 7.4. Map showing submarine groundwater discharge of each hydrologic sector of Hawai‘i. m^3/d, cubic meters per day.

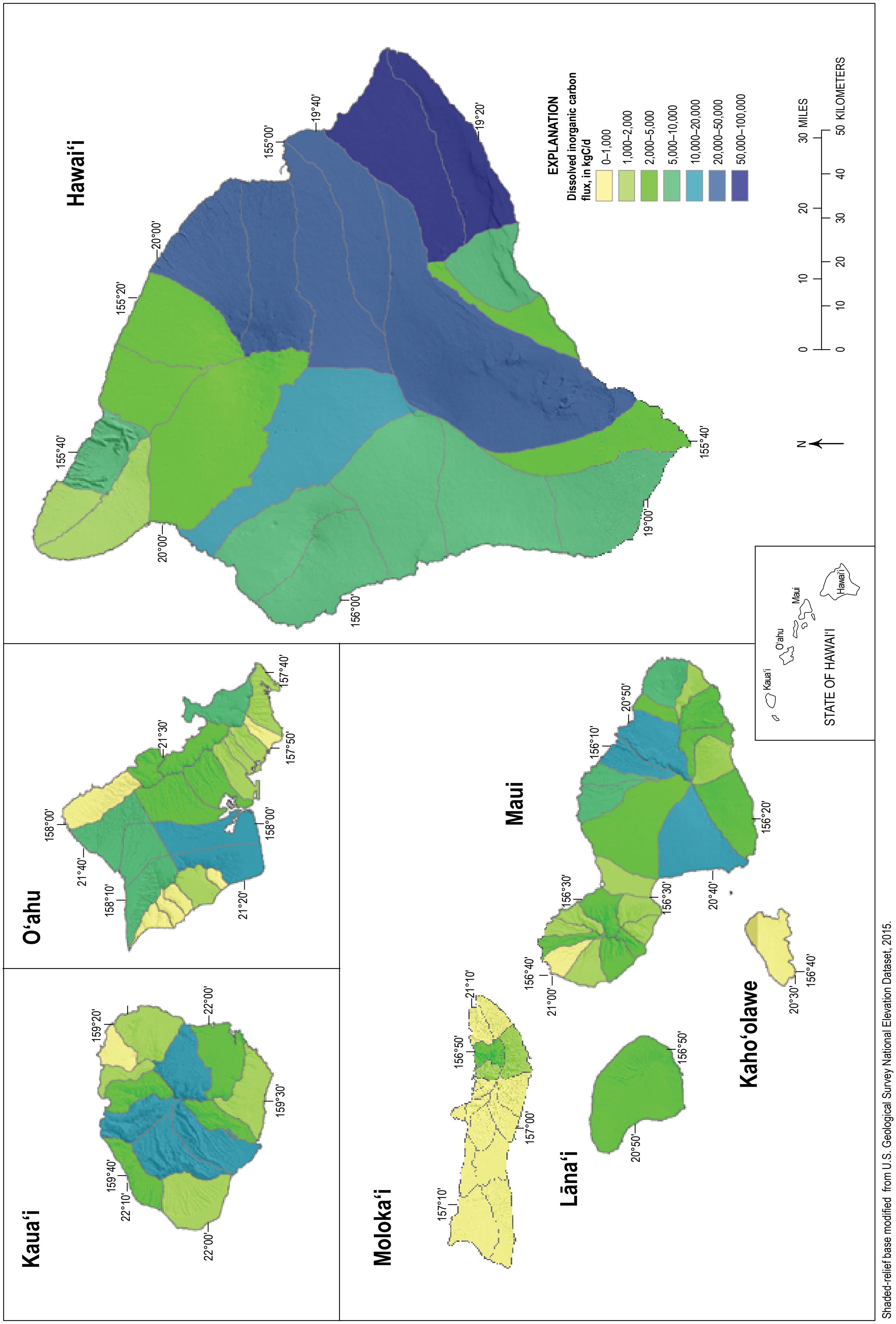
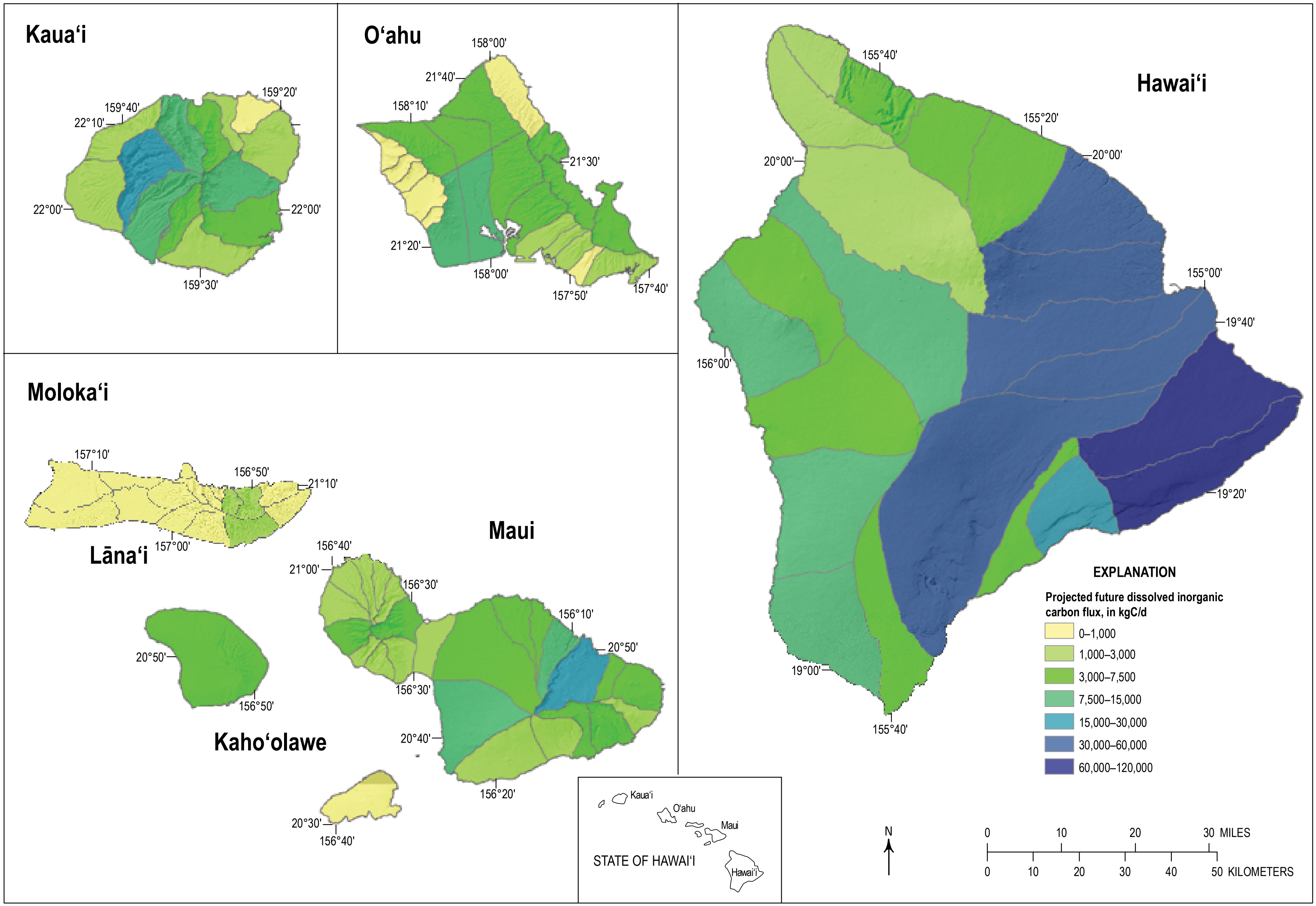


Figure 7.5. Map showing dissolved inorganic carbon flux from each hydrologic sector of Hawaiʻi. kgC/d, kilograms of carbon per day.



Shaded-relief base modified from U.S. Geological Survey National Elevation Dataset, 2015.

Figure 7.6. Maps showing projected future total CO_2 or dissolved inorganic carbon flux from each hydrologic sector of Hawai‘i based on predicted future submarine groundwater discharge. kgC/d, kilograms of carbon per day.

streambeds by terrestrial organisms or photo-degradation can continue to occur (Austin and Vivanco, 2006; Corti and others, 2011). When flow returns to these intermittent streams, that carbon is quickly transported to the ocean at initial concentrations that can be much higher than those observed in baseflow or in lower flowing streams (Jacobson and others, 2000; Larned and others, 2010; Corti and Datry, 2012). Lastly, LOADEST underestimated particulate carbon flux from three streams where we were able to do a direct comparison between actual observed and modelled values and the level of inaccuracy appeared to increase with decreasing watershed area, rainfall, and median flow. This is likely due to the fact that flow is more variable in the drier streams (Strauch and others, 2015), which would increase the level of uncertainty in the output of the LOADEST model. LOADEST was also developed for continental watersheds, so it is possible that this model may not be adequate for the steeply sloped and spatially compact Pacific-island watersheds that respond more rapidly to rainfall events than larger continental watersheds.

7.5.2. Submarine Groundwater Discharge

The DIC flux from each island was primarily controlled by the SGD, which varied by nearly three orders of magnitude. Windward Hawaiʻi Island, with high rates of rainfall and large watersheds, was the dominant source of DIC from groundwater to the ocean. In particular, the surfaces of Mauna Loa and Kīlauea, with little soil development and the intrinsic high permeability of basalt lava flows, result in very high rates of groundwater recharge to rainfall (Engott, 2011). The predicted increase in SGD for Hawaiʻi Island is greater than the combined SGD of Kauaʻi, Oʻahu, Molokaʻi, Lānaʻi, and Kahoʻolawe, emphasizing the importance of understanding the hydrology of Hawaiʻi Island. Although this study assumed that all SGD flows out of basal aquifers, deep confined aquifers have been identified (Thomas and others, 1996). However, little is known about the distribution, magnitude of flow, or geochemistry of these deep aquifers. Further studies that refine our understanding of island hydrology will improve estimates of SGD and DIC fluxes, particularly for the rainfall at high elevation that seems to feed these confined aquifers.

Several limitations to the DIC flux estimate were identified with this study. First is the lack of groundwater DIC data. Here, we used available alkalinity and pH data to calculate DIC, but there are significant uncertainties in this method: not having paired pH and alkalinity measurements (and sometimes using data from different wells), the low resolution of the pH data (only to one decimal point), and unknown temperature of analyses. DIC is critical in studying the carbon cycle and the flow of carbon between systems. In Hawaiʻi, the statewide mean DIC was less than the DIC of surface seawater near Hawaiʻi (~23.7 mgC/L; Brix and others, 2004). Thus, SGD flowing into the coastal ocean will likely reduce the aragonite saturation, which will reduce the ability of organisms to form calcium carbonate structures. This has the potential to enhance the effects of ocean acidification in the coastal ocean. DIC should be a parameter that is explicitly measured.

There was also a paucity of alkalinity measurements, with 36 percent of aquifer sectors statewide lacking alkalinity measurements and only 39 percent having more than two measurements. A concerted effort to collect data statewide and analyzed with a consistent method (such as DIC analysis) would be a great improvement. Given the importance of SGD on the flux of DIC to the ocean, locations with the highest SGD that are lacking DIC data should be priority sites for gathering data. These include the Hilo, Anaehoomalu, and Kaapuna systems on Hawaiʻi Island and Waikamoi and Keanae systems on Maui. For DOC, statewide measurements are needed, but again, based on the importance of SGD, sites on Hawaiʻi Island and east Maui should have the highest priority.

Unfortunately, the SGD estimates were calculated using a variety of different spatial modeling methods. For example, some of the data from Maui did not include fog drip in the hydrologic budget (Shade, 1997; Engott and Vana, 2007). Further, the model for Oʻahu was not defined along aquifer sectors, requiring further analysis to be similar to the other islands. No recent studies of SGD are available for Kahoʻolawe. Fortunately, the USGS is presently updating the hydraulic budgets of the main Hawaiian Islands, which will help refine this model (Engott and others, 2015).

7.5.3. Projected Future Changes in Stream and SGD Carbon Fluxes

Using HRCM predictions of changes in rainfall, reanalysis of both stream and SGD datasets revealed that both stream and SGD carbon fluxes would increase under future climate conditions as predicted by the HRCM. This was largely due to increases in stream and SGD fluxes from Hawaiʻi and Maui Islands, where the HRCM predicted significant increases in rainfall along wet, windward coasts. Although the HRCM predicts increased rainfall on the wetter side of Hawaiian Islands, changes in the distribution of this increased rainfall remain unclear. Other models have predicted similar scenarios with an increase in rainfall events, but this increase is due to fewer but more intense storms, with a greater number of dry days in between (Chu and Chen, 2005; Chu and others, 2010; Timm and others, 2011). Although our models suggest increased carbon fluxes, it's not entirely clear how changes in timing of surface water flow will impact carbon dynamics or TOC versus DIC dynamics. Decreased flow rates during dry days will likely increase breakdown rates of particulate organic matter (Corti and others, 2011; Roberts and others, 2016) and potentially shift the proportion of TOC versus DIC fluxes from streams. Another limitation to our model is that it does not take into account warming-related shifts in the riparian community and the impact this will have on hydrological and organic matter cycling in Hawaiian streams (Ayron M. Strauch, Hawaii Department of Land and Natural Resources, unpublished data; MacKenzie and others, 2013). This is of particular concern in Hawaiʻi as exotic species are taking over native ecosystems at alarming rates (Asner and others, 2008; Denslow and others, 2009) and this is expected to have severe consequences on stream function (Kominoski and others, 2013).

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