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RESEARCH ARTICLE

Base flow-driven shifts in tropical stream temperature regimes across a mean annual rainfall gradient

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Abstract

Climate change is expected to affect air temperature and watershed hydrology, but the degree to which these concurrent changes affect stream temperature is not well documented in the tropics. How stream temperature varies over time under changing hydrologic conditions is difficult to isolate from seasonal changes in air temperature. Groundwater and bank storage contributions to stream flow (i.e., base flow [BF]) buffer water temperatures against seasonal and daily fluctuations in solar radiation and air temperature, whereas rainfall-driven runoff produces flooding events that also influence stream temperature. We used a space-for-time substitution to examine how shifts in BF and runoff alter thermal regimes in streams by analyzing hydrological and temperature data collected from similar elevations (400–510 m above sea level) across a 3,500-mm mean annual rainfall gradient on Hawai'i Island. Sub-daily water temperature and stream flow gathered for 3 years were analyzed for daily, monthly, and seasonal trends and compared with air temperature measured at multiple elevations. Results indicate that decreases in median BF increased mean, maximum, and minimum water temperatures as well as daily temperature range. Monthly and daily trends in stream temperature among watersheds were more pronounced than air temperature, driven by differences in groundwater inputs and runoff. Stream temperature was strongly negatively correlated to BF during the dry season but not during the wet season due to frequent wet season runoff events contributing to total flow. In addition to projected increases in global air temperature, climate driven shifts in rainfall and runoff are likely to affect stream flow and groundwater recharge, with concurrent influences on BF resulting in shifts in water temperature that are likely to affect aquatic ecosystems.

KEYWORDS

base flow, Hawaii, hydrology, runoff, stream temperature, tropics

1 | INTRODUCTION

Water temperature is a key indicator of water quality, influencing species distribution, metabolism, and ecosystem function. Water temperature integrates energy fluxes across the water surface, within the streambed and hyporheic zone, and among various internal processes (Kurylyk, MacQuarrie, Caissie, & McKenzie, 2015; Tague, Farrell, Grant, Lewis, & Rey, 2007). These fluxes are influenced by atmospheric conditions (e.g., air temperature, solar radiation, and wind), physical characteristics of the catchment and stream (e.g., groundwater discharge, flow rate, substrate, and channel slope), biology (e.g., riparian canopy cover), and anthropogenic disturbances (e.g., channelized stream bed, culverts, and dams; Brasher, 2003; Larned & Santos, 2000; MacKenzie, 2008; Nelson & Palmer, 2007). Climate change is expected to alter air and sea surface temperature, relative humidity, and atmospheric circulation patterns that affect the magnitude and frequency of rainfall events (IPCC, 2013; Muller, O'Gorman, & Back, 2011; Oki & Kanae, 2006). Warmer air temperatures may result in greater magnitude rainfall events, but also longer dry periods between events (Westra, Alexander, & Zwiers, 2013), likely resulting in changes in stream flow and stream temperature regimes. As a consequence, understanding the interrelationships between stream flow, watershed hydrology, and stream temperature is important to adequately assess the effects of climate change on aquatic ecosystems. With changes in climate likely to move tropical systems beyond their range of current climate variability faster than any other region (Mora et al., 2013), the need for understanding potential changes in stream thermal regimes is necessary for proactive conservation (Timbol & Maciolek, 1978).

On tropical islands, stream flow and its relationship with stream temperature is difficult to characterize due to highly variable atmospheric and runoff conditions, geology, steep gradients, and poorly understood groundwater interactions (Lau & Mink, 2006). Runoff is dependent on rainfall event frequency, intensity, and duration, as well as landscape characteristics (e.g., slope, vegetation, and soils), whereas base flow (BF) is influenced by underlying geology effects on groundwater inputs, shallow sub-surface flows, and bank storage contributions. Perched aquifers may contribute substantially to stream flow in high-elevation reaches but these are poorly characterized on young volcanic islands. In many instances, steep hydraulic gradients of porous volcanic substrates lead to fast depletion of bank storage and shallow groundwater resulting in BF that is vulnerable to drought (Kondolf, Maloney, & Williams, 1987; Oki, 2004). On older islands, valley incision of vertical dike complexes also contribute to BF, but this is less common on younger (<300,000 years old) lava flows (Lau & Mink, 2006). During dry periods, groundwater discharge is the main source of stream flow, resulting in stream water temperature reflecting groundwater temperature. During wet periods, by contrast, stream flow is dominated by runoff, resulting in surface water reflecting rainfall temperatures. Although previous research has identified the effects of groundwater discharge on stream temperature (Constantz, 1998; Kelleher et al., 2012), especially in temperate streams during summer dry periods (Tague et al., 2007) few studies have focused on tropical streams. Understanding the effects of groundwater discharge on stream temperature in tropical island systems is a necessity for effective water resource management (van Vliet et al., 2012).

Modeled results of future rainfall over the tropics predict an increase in the occurrence of very wet and very dry conditions (Lintner et al., 2012). Trends in rainfall extremes vary spatially across Hawai'i (Chen & Chu, 2014), but are often linked to larger circulation patterns over time (Frazier, Giambelluca, Diaz, & Needham, 2016). Norton, Chu, and Schroeder (2011) project an increase in the frequency of heavy rainfall events but a decrease in rainfall intensity (magnitude) in the coming decades. Shifts in rainfall patterns will alter runoff and groundwater recharge, reducing groundwater discharge to streams that will diminish a watershed's capacity to provide various hydrological and ecological functions (Burns, 2002; Meehl, 1996; Larned, 2000).

Although several studies have characterized temperature regimes in temperate streams (for a greater overview see Tague et al., 2007), few studies have focused on tropical island systems (Caissie, 2006). A lack of long-term monitoring of stream temperature has been a major limitation to characterizing natural tropical stream thermal regimes (Arismendi, Johnson, Dunham, Haggerty, & Hockman-Wert, 2012). Changes in water temperature due to increases in air temperature, decreases in stream flow, or seasonal shifts in the relative contribution of groundwater to stream flow are anticipated to alter the ecological function of tropical streams and the behavior of species (Covich, Crowl, & Scatena, 2003). In addition, tropical stream organisms often exhibit a narrower range of thermal tolerance and may be more susceptible to changes in stream temperatures (Leberer & Nelson, 2001; Pringle, Freeman, & Freeman, 2000; Stanley, Fisher, & Grimm, 1997). Increasing our understanding of stream temperature regimes in tropical systems is therefore important to assessing the potential effects of climate change on stream organisms.

In Hawai'i, climate change has already affected drought length and storm intensity, which has altered groundwater recharge and runoff (Chen & Chu, 2014; Ward, 1985) with implications for stream flow (Bassiouni & Oki, 2012; Webster, Holland, Curry, & Chang, 2005) and, subsequently, stream temperature. In this study, we used a space-for-time substitution along a model hydrological system that isolates the effect of changing hydrologic conditions (i.e., mean annual rainfall [MAR] varied across a relatively short distance) but keeps underlying geology, watershed shape and slope, land cover, and air temperature constant to examine the consequences of climate-driven shifts in BF to tropical stream thermal regimes. We hypothesize that reductions in MAR will result in reduced groundwater delivery (i.e., BF) to streams leading to greater mean stream temperature (Hypothesis 1; H1); and greater stream temperature variability (H2), especially in wet seasons, when stream flow is heavily influenced by runoff (H3).

2 | METHODS

2.1 | Study system

Stream flow and stream temperature (10 sites) were monitored continuously starting in 2011 or 2012 on the windward coast of Hawai'i Island in the Pacific Ocean. Monitoring sites were located at the lower boundaries of native-dominated forests, with individual sites determined by elevation, topography, and MAR (Table 2; Figure 1). All sites were located between 400 and 510 m in elevation in stable reaches with no noticeable changes in stream bed condition during the study period. Watershed catchment area was measured as the upstream area from the gaging station as in Strauch, MacKenzie, Bruland, and Giardina (2015). Soil type (all Andisols with most being Hydrudands) and geology were generally consistent (USDA, 2008) across watersheds with Hamakua Volcanics underlying Laupāhoehoe Volcanics of similar age ranges (11,000–300,000; USDA, 2008; Vitousek, 1995). Upstream watershed mean annual temperature (MAT) and mean annual solar radiation (MASR) were calculated based on Giambelluca et al. (2014). Maximum watershed elevation was derived from U.S. Geological Survey geospatial data (Rea & Skinner, 2012). Reach canopy cover was determined by taking five canopy photographs at 10-m intervals in the center of the stream with the camera of an iPhone (version 5, Apple Inc) face-up and leveled using the internal gyroscope. Photos were then processed using the CanopyApp software (version 1.0.2, University of New Hampshire Research Computing Center). Wetted width was measured 20 times at 5–10-m intervals, depending on the size of the reach.

2.2 | Climate monitoring

Five different climate monitoring stations were utilized for rainfall and air temperature at varying elevations along the windward coast (Table 1). Rainfall was monitored in three locations using tipping bucket (Onset MAN-RG3) rain gages (resolution 0.254 mm). Air temperature (resolution 0.01°C) was monitored at these locations with a temperature and relative humidity probe (HMP45C-L, Campbell Scientific, Logan, UT), whereas at Kolekole station, temperature was monitored with a barometric pressure and temperature (resolution 0.1°C) logger

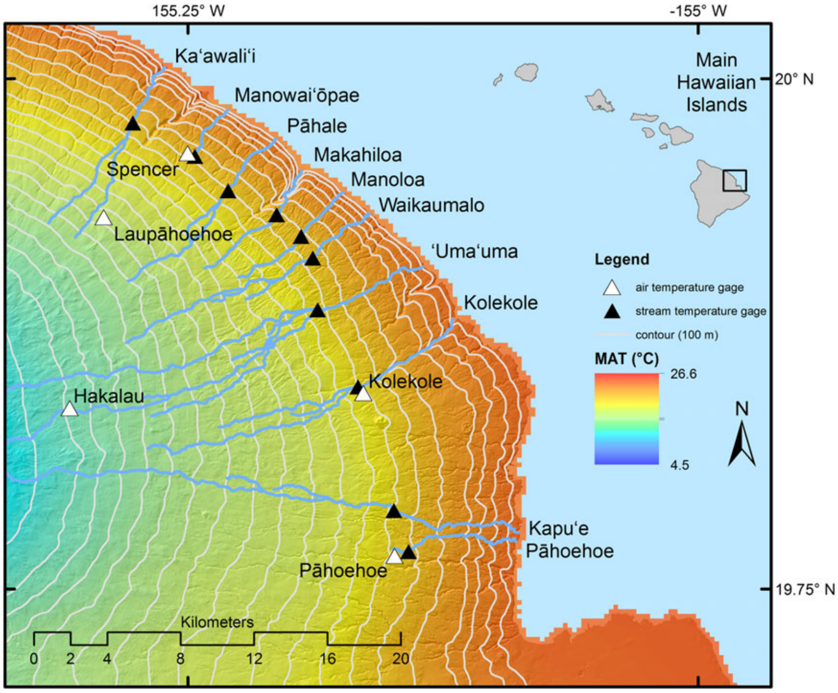

FIGURE 1 Map of windward Hawai'i Island depicting stream gaging stations, air temperature stations, elevation, and mean annual air temperature (MAT) at 12.00 (°C) based on Giambelluca et al. (2014)

TABLE 1 Climate monitoring sites, modeled mean annual rainfall (from Giambelluca et al., 2013), modeled mean annual air temperature (from Giambelluca et al., 2014), total rainfall (mm), and mean temperature (°C) for calendar years 2011 to 2014

				Total rainfall (mm)				Mean temperature (°C)			
Station name	Elevation (m)	Mean annual rainfall (mm)	Mean annual air temperature (°C)	2011*	2012	2013	2014	2011	2012	2013	2014
Hakalau Forest	1,951	1,940	10.6	1,412	2,333	1,487	853	11.4	11.1	11.5	11.0
Laupāhoehoe Tower	1,145	4,237	15.3	4,958	4,904	4,915	4,474	15.4	15.0	15.9	16.6
Spencer	454	4,689	19.6	2,748	1,933	3,761	5,143	19.6	19.7	20.3	20.7
Kolekole	500	6,723	18.6					18.3*	18.0	18.4	17.7
Pāhoehoe	449	5,615	19.2						19.6	20.4	20.2

*only includes data after April 1, 2011.

(Onset Hobo® U20 logger). Air temperature was also available at a station near Pāhoehoe using the (Onset MAN-RG3) rain gage. Long-term MAR modeled for each rainfall monitoring site (Giambelluca et al., 2013) was used for comparison with actual annual rainfall measurements. Watershed MAR was calculated using an average MAR for the area of the watershed upstream of the gaging station, as in Strauch et al. (2015). Mean daily and monthly air temperature were calculated for each climate station and compared with long-term MAT. Canopy short-wave solar radiation was available from the Laupāhoehoe climate tower using a four-component net radiometer (NR01-L, Campbell Scientific, Logan, UT), and total daily short-wave radiation was calculated as the sum of measurements at 10-min intervals for each day.

2.3 | Stream flow

Instantaneous flow was measured as described in Strauch et al. (2015). In this study, mean daily stream flow was separated into runoff and BF using a BF separation procedure with a recursive digital filter parameter of 0.98 and a maximum BF index of 0.80 for perennial streams (Eckhardt, 2005) with porous aquifers using Lim et al. (2005). Although this approach was developed for temperate continental stream systems, previous uses of a recursive digital filter coupled with the smoothed minima approach developed by Wahl and Wahl (1995) for BF separation have been used in Hawai'i (see Oki, 2004). Median (Q_{50}) flow and the 90% exceedance flow (Q_{90}) were calculated for BF and total flow (TF); BF yields were calculated by dividing flow by upstream watershed area (Oki, 2004). BF yield flow duration curves were generated using all available data from gage installation to October 2014. Flow values were log-transformed for analysis and regressed against watershed MAR.

2.4 | Stream temperature

Stream temperature was monitored concurrently with stage in each stream using Hobo™ U-20 dataloggers (Onset Corp, Inc, Bourne, MA) except for 'Uma'uma and Manowai'ōpae streams where temperature and stage were monitored by vented WaterLOG® Model H-132 pressure transducers (Design Analysis Associates Inc, Logan UT). In the rare case that stream flow ceased and water evaporated so that the sensor was exposed to the atmosphere, these values were eliminated. At monthly intervals, stream temperature was also measured using a handheld YSI™ 85 multiparameter (Yellow Springs Inc., Yellow Springs, OH, USA) and were strongly correlated to gage measurements (Table S1).

2.5 | Data analysis

We first used Pearson correlations to examine whether patterns in BFQ_{50} and TFQ_{50} were influenced by maximum watershed elevation, MASR, MAT, or mean wetted width. The relative contribution of BF to TF was calculated as the ratio of BFQ_{50}:TFQ_{50} expressed as a percent (%). Correlations between daily runoff and daily stream temperature were calculated for each stream. Daily maximum, minimum, range, and mean stream temperatures were calculated from 15-min interval data for each stream. Monthly, seasonal, and total values were then calculated based on daily stream temperatures. Mean stream temperature was compared with BFQ_{50} and BFQ_{50} yield with Pearson correlations. Seasonal (based on Department of Health, 2013) mean, maximum, and minimum temperatures were calculated for wet season (November to April) and dry season (May to October) for each stream, and relationships with BFQ_{50} and TFQ_{50} were examined using Pearson correlations. Variability in seasonal temperature was assessed using coefficient of variation. Statistical differences in mean seasonal and mean monthly temperatures across streams were determined with a one-way repeated measures analysis of variance (RM-ANOVA) with a Tukey's HSD post hoc comparison test using a Bonferroni correction for multiple comparisons (adjusted $\alpha = 0.005$). Monthly data were limited to 15 consecutive months where there were no disruptions to the monitoring data for all streams. Relationships between canopy cover and mean maximum stream temperature were examined for the warmest month (September 2013).

Because of the concurrent availability of air temperature at Kolekole, Manowaiʻōpae, and Pāhoehoe streams, the effect of air temperature was examined using a simple linear air-water temperature regression. Then a multiple linear regression model was used to examine the effect of time of year and time of day, air temperature, and stream flow on stream temperature for all 15-min data from October 2012 to August 2014; time of day and day of year were converted to circular statistics as in Zar (1999). Mean daily stream temperatures at Kolekole and Manowaiʻōpae streams were also compared with total daily solar radiation at the Lāupahoehoe Climate Tower using Pearson correlations. Analyses were done in SigmaPlot version 12.0 (Systat Software, Inc).

3 | RESULTS

3.1 | Climatological and hydrological data

Maximum watershed elevation was not correlated with BFQ_{50} ($r = -.26$, $p > .05$) or TFQ_{50} ($r = -.13$, $p > .05$), and BFQ_{50} was not correlated with watershed MAT ($r = -.36$, $p > .05$) or MASR ($r = .22$, $p > .05$; Table S2). Rainfall varied substantially between years and

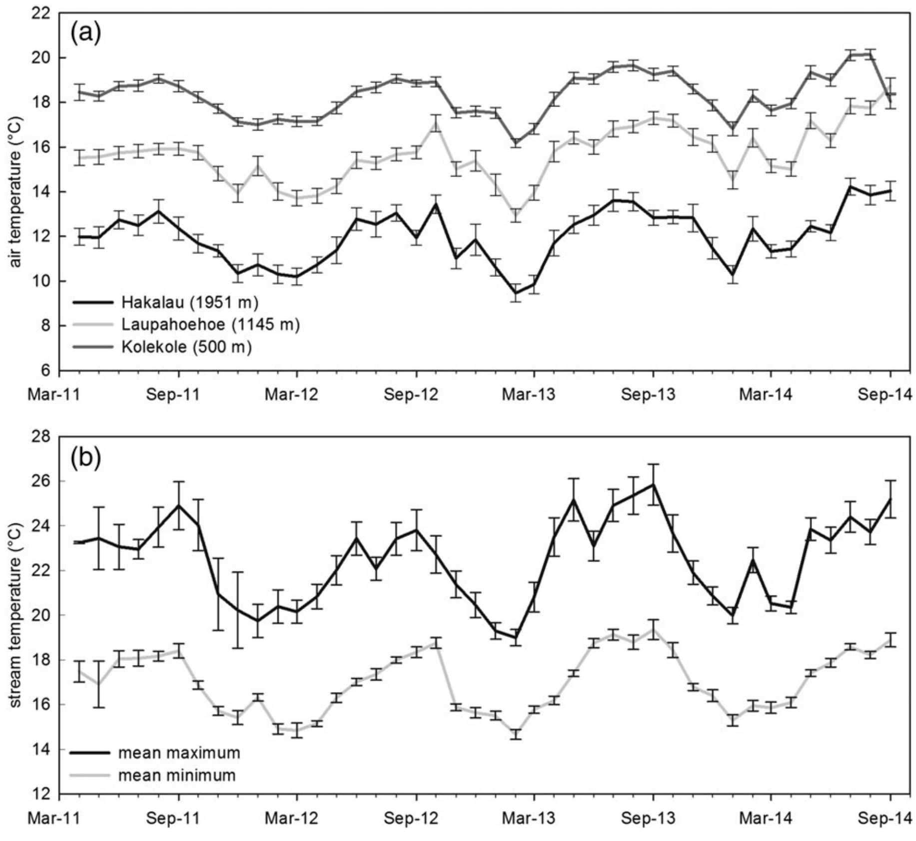

FIGURE 2 Mean ± standard error (±SE) air temperature from three monitoring stations at differing elevations (a) and mean (±SE) maximum and minimum stream temperatures from daily maximum and minimum stream temperatures (b) for 10 monitoring stations between 400 and 510 m in elevation on windward Hawaiʻi Island from April 2011 to September 2014

between elevations (Table 1) with rainfall in 2012 generally greater than the modeled MAR, but in 2011, 2013, and 2014, rainfall was less than the modeled MAR at the high-elevation (1951 m a.s.l.) and low-elevation (454 m a.s.l.) stations. Annual MATs were consistently near the modeled MAT from 2011 to 2013, but in 2014 were up to 1.0°C warmer for some stations. Monthly minimum air temperatures were generally lowest in January and greatest in September for all stations, although the lowest recorded mean monthly air temperature was in February 2013. Monthly MATs ranged from 8.91–13.06°C at 1950 m a.s.l. and from 16.17–19.66°C at 450 m a.s.l. Monthly air temperature was more variable at higher elevations, but seasonal trends in monthly MAT followed similar patterns among all stations (Figure 2). There was a consistent difference in air temperature between the two stations at roughly the same elevation (Kolekole & Spencer) that supports their modeled differences in MAT, with the Kolekole station measuring slightly lower air temperatures than the Spencer station due to small differences in elevation, vegetation cover, and MASR. Upstream reach canopy cover varied from 0.0% to 58.4% (Table 2), with differences negatively correlated with mean wetted width ($r = -.72$, $p < .05$) and BFQ_{50} ($r = -.68$, $p < .05$), but not MAR ($r = -.29$, $p > .05$). Mean reach wetted width was positively correlated with BFQ_{50} ($r = .82$, $p < .05$) and TFQ_{50} ($r = .85$, $p < .05$).

As expected, BFQ_{50} and BFQ_{50} yields declined with MAR (Figure 3), and five streams had zero flow at least 10% of the time (Figure 4a). Perennial streams exhibited typical flow-duration curves dominated by BF (relatively flat between the 30% and 70% exceedance; Figure 4a blue lines), whereas non-perennial streams dominated by runoff demonstrated steep declines in flow typical of streams with little groundwater supported BF (Figure 4a red/orange lines). As a percentage of total median flow, BFQ_{50} ranged from as much as 91.7% in Manoloa to as little as 50.0% in Pāhale, with a significant positive relationship with MAR ($r = .69$, $p < .05$).

3.2 | Stream temperature

For the period of record, mean monthly stream temperature varied from 18.49–21.20°C with standard deviations ranging from 0.79–2.53°C (Figure 4b). Mean monthly maximum and minimum stream temperature varied with monthly air temperature (Figure 2b). The streams with the lowest mean temperature were Kolekole, Pāhoehoe, Kapu‘e and ‘Uma‘uma, which also coincided with the streams with the greatest BFQ_{50} and BFQ_{50} yields (Figure 5). Base flow and total flow were more strongly correlated with stream temperature during the dry season than during the wet season (Table 3). There were significant negative relationships between mean stream temperature and BFQ_{50} ($r = -.72$, $p < .01$) or BFQ_{50} yield ($r = -.93$, $p < .001$). There was no relationship between stream temperature standard deviation and BFQ_{50} ($r = -.26$, $p > .05$) but a significant negative relationship with BFQ_{50} yield ($r = -.79$, $p < .01$). Monthly mean temperature varied by stream (RM-ANOVA $F = 34.97$, $df = 15, 9$, $p < .001$), with greater temperatures in streams with lower BFs (Figure 4b), especially during drier months and months with greater air temperature. Mean daily stream temperature was significantly ($p < .05$) negatively correlated with runoff for all streams (data not presented).

TABLE 2 Watershed characteristics and hydrology of stream temperature monitoring sites on windward Hawai‘i Island based on Giambelluca et al. (2014, 2013)

Stream name	Elevation of gaging station (m)	Mean annual rainfall (mm)	Mean annual solar radiation (W m^{-2})	Mean annual air temperature (°C)	Catchment area (km^2)	Maximum catchment elevation (m)	Mean wetted width (m)	Sensor depth at BFQ_{50} (m)	Upstream main channel length (km)	Reach canopy cover (%)	Hydrology BFQ_{50} (L/s)	TFQ_{50} (L/s)	BFQ_{90} (L/s)	TFQ_{90} (L/s)
Ka‘awali‘i	475	3,015	224.7	14.6	33.10	6,150	2.2	0.511	17.1	58.44	0.00	0.28	0.00	0.00
Waikaumalo	450	3,774	224.1	12.8	35.95	2,710	5.3	0.252	24.6	0.01	5.10	6.51	2.55	2.83
Pāhale	510	4,026	198.0	16.1	10.14	1,768	3.1	0.126	14.3	19.54	0028	0.57	0.00	0.00
Makahiloa	400	4,663	193.5	17.1	9.60	1,600	4.0	0.646	14.1	0.00	39.36	52.10	1.13	1.13
Manowai‘ōpae	470	4,689	208.8	17.9	3.84	1,131	1.5	0.137	5.8	29.53	2.27	2.83	0.28	0.28
‘Uma‘uma	490	4,906	236.8	11.3	74.43	3,780	7.0	0.748	33.0	0.00	399.0	571.2	73.6	82.7
Manoloa	420	5,205	192.1	18.2	2.56	914	3.2	0.622	5.9	48.48	11.04	12.18	6.23	7.08
Kapu‘e	460	5,696	192.7	14.3	20.69	2,582	9.0	0.092	27.5	0.09	314.9	438.6	80.19	102.1
Pāhoehoe	430	5,856	174.1	18.4	1.30	585	3.3	0.500	1.7	42.37	42.19	49.84	23.22	27.75
Kolekole	500	6,426	200.8	14.0	17.23	1,612	10.3	0.455	16.9	0.00	314.0	402.1	124.6	136.4

Note. BF = base flow; Q_{50} = median flow; TF = total flow.

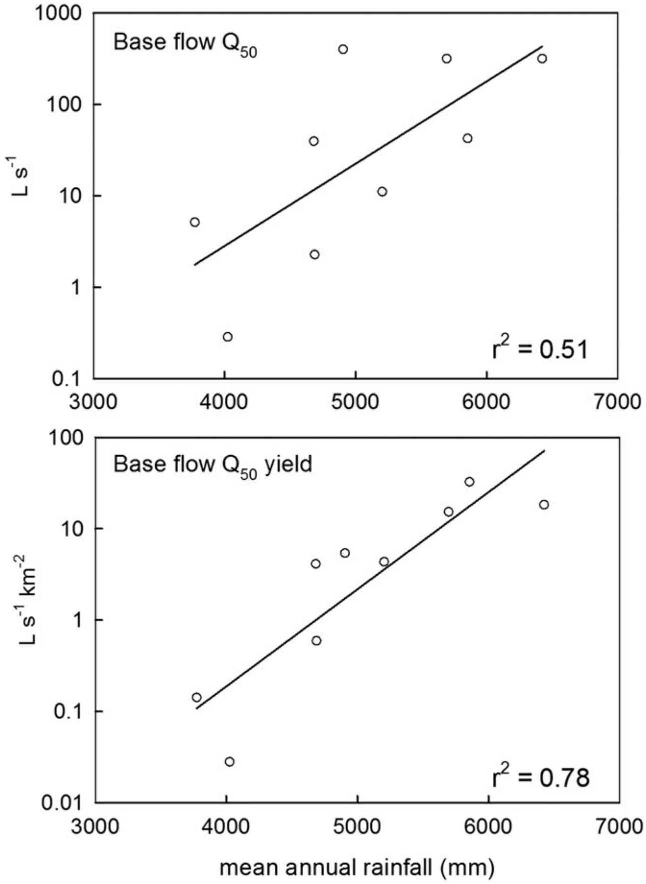

FIGURE 3 (a) Median (Q_{50}) base flow (L s^{-1}) and (b) Q_{50} base flow yield (L·s^{-2}·km^{-2}) for 10 streams on the windward coast, Hawai'i Island from 2011 to 2014 versus upstream catchment mean annual rainfall (mm) based on Giambelluca et al. (2013)

Using a simple linear regression model, the effect of air temperature ($T = 5.231 + 0.738 * T_{air}$) was a strong (adj. $r^2 = .601$) predictor of stream water temperature in Kolokole, but not in Manowai'ōpae ($T = 15.065 + 0.244 * T_{air}$; adj. $r^2 = .258$) or Pāhoehoe ($T = 17.457 + 0.0646 * T_{air}$; adj. $r^2 = .092$). The multiple linear regression model, accounted for a large amount of the variability in stream temperature (adj. $r^2 = .645$) for Kolekole with significant air temperature ($p < .001$), stream flow ($p < .001$), and time of day ($p < .001$) effects (Table 4) but not day of year ($p = .082$). For Manowai'ōpae, air temperature ($p < .001$), stream flow ($p < .001$), time of day ($p < .001$), and day of year ($p = .012$) were each significant effects in the regression model, but this accounted for less variability in stream temperature (adj. $r^2 = .326$). At the Pāhoehoe station, air temperature ($p < 0.01$), stream flow ($p < 0.01$), time of day ($p < 0.01$), and day of year ($p < 0.01$) were each significant effects but did not explain as much of the variability in stream temperature (adj. $r^2 = 0.165$). Total daily solar radiation at the Laupāhoehoe Climate Tower was correlated to daily mean stream temperature at the Manowai'ōpae station ($r = .51$, $p < .05$) but not at the Kolekole station ($r = .34$, $p > .05$). Minimum and maximum stream temperatures occurred in January and September for most streams, respectively, coinciding with minimum and maximum air temperatures (Table S3). However, stream temperature patterns did not always follow air temperature patterns (Figure 2), and in many cases, monthly stream temperature varied much more than air temperature. Maximum stream temperatures ever recorded were greatest in Manowai'ōpae (32.20°C), Ka'awali'i (30.26°C), Waikaumalo (30.26°C), Pāhale (29.45°C), and Makahiloa (28.75°C). These values generally occurred during dry months with declining BF and increased water residence time. Overall, Pāhoehoe (6.86°C) and Manoloa (7.92°C) streams had the smallest differences between maximum and minimum stream

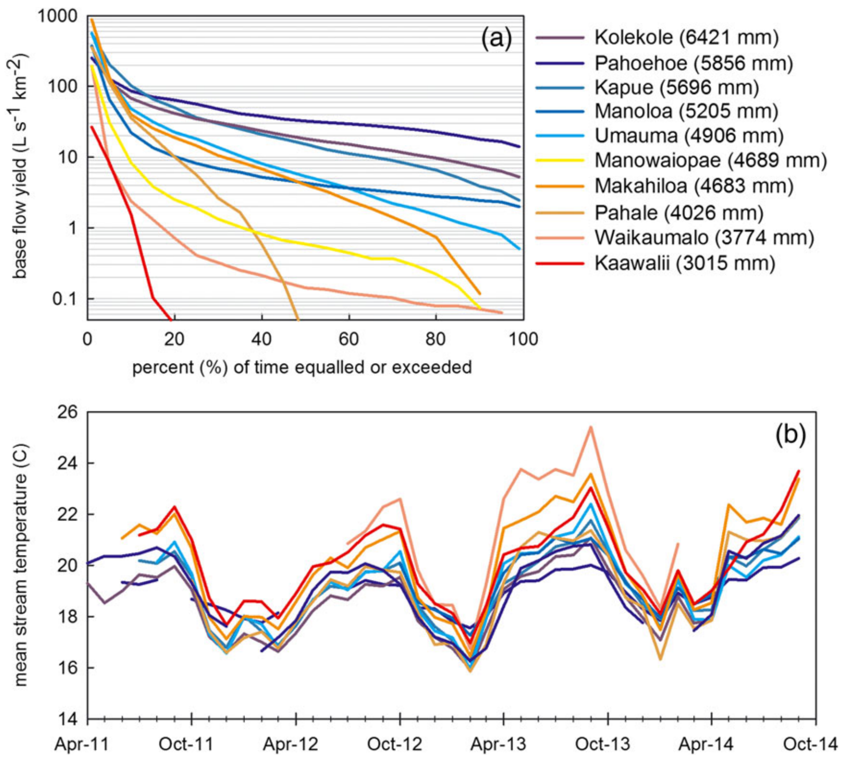

FIGURE 4 (a) Base flow yield (L·s^{-1}·km^{-2}) exceedance curves for 10 streams on the windward coast, Hawai'i Island from 2011 to 2014 colored by watershed mean annual rainfall (mm) based on Giambelluca et al., 2013. Blue colors are perennial streams and orange-red colors are non-perennial streams. (b) Mean stream temperature for each of 10 streams on the windward coast, Hawai'i Island between April 2011 and September 2014. Colors as in (a)

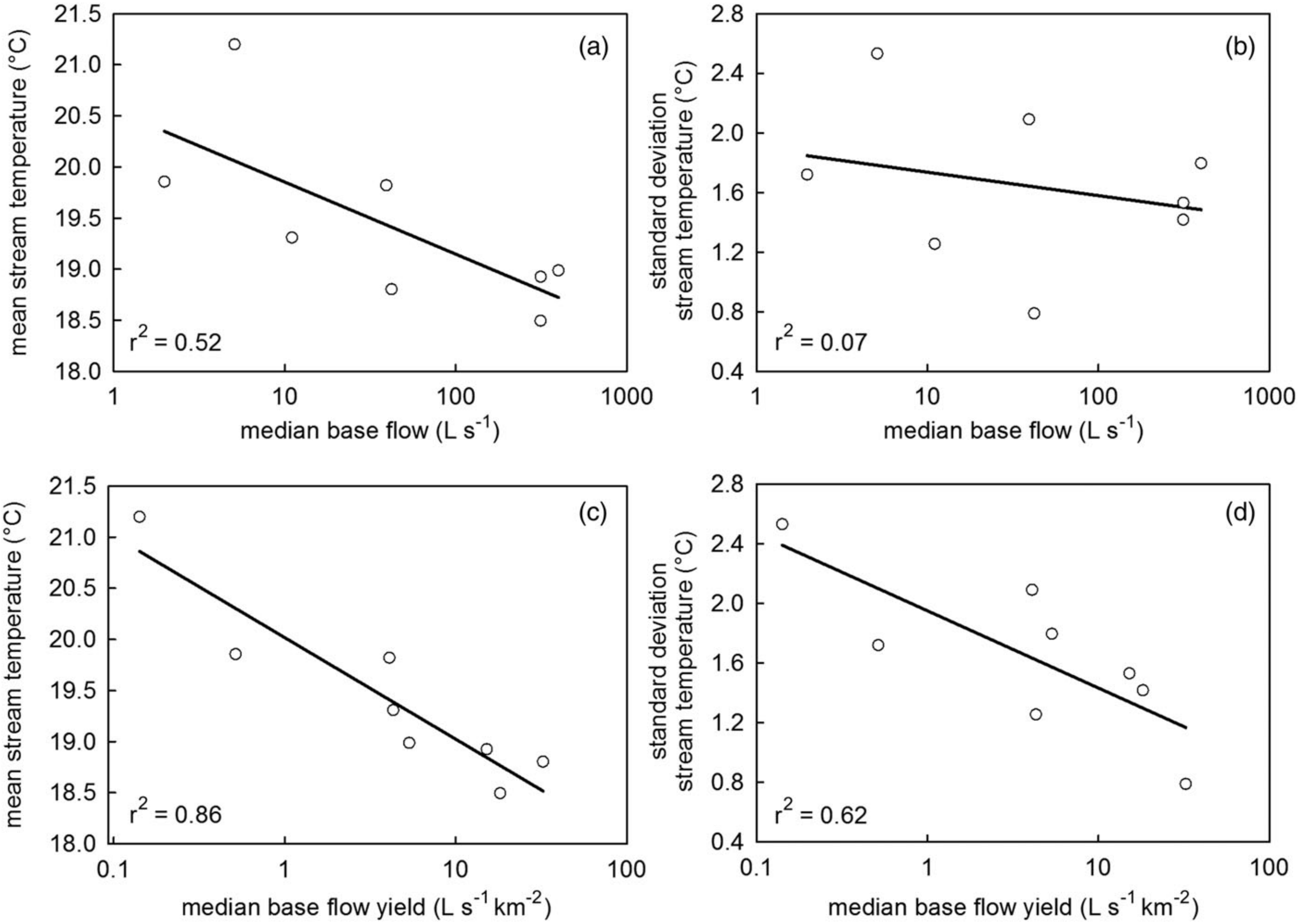

FIGURE 5 Mean (left) and standard deviation (right) stream temperature versus base flow Q_{50} (L/s; top) and base flow Q_{50} yield ($L \cdot s^{-1} \cdot km^{-2}$; bottom) at similar elevations for 10 streams with temperature data from 2011 to 2014 on windward Hawaiʻi Island. Only non-zero data graphed

TABLE 3 Pearson product moment correlations (*r*) between log-transformed seasonal median base flow (BFQ_{50}) or median total flow (TFQ_{50}) and minimum, mean, and maximum monthly stream temperature for 10 streams by season

	BFQ_{50}	TFQ_{50}
Dry season		
Minimum stream temperature	−0.67*	−0.66*
Mean stream temperature	−0.68*	−0.66*
Maximum stream temperature	−0.70*	−0.68*
Wet season		
Minimum stream temperature	0.17	−0.26
Mean stream temperature	−0.21	−0.66*
Maximum stream temperature	−0.20	−0.25

*$p < .05$.

TABLE 4 Constant and individual model effect results from a multiple linear regression model examining the diel and seasonal variation in stream temperature (°C) in Kolekole, Manowaiʻōpae, and Pāhoehoe streams based on nearby air temperature (°C), stream flow (L/s), time of day (hr) and day of year (d) using data gathered at 15 min intervals from October 2012 to October 2014. Time of day and day of year were transformed into circular statistics

	Kolekole	Manowaiʻōpae	Pāhoehoe
Constant	5.465**	14.755**	17.288**
Air temperature (°C)	0.735**	0.220**	0.0543**
Flow (L/s)	−0.0017**	−0.00987**	−0.00426**
Time (hr)	−0.000464**	0.0046**	0.00238**
day of year (d)	−0.000780	0.0022*	−0.00197**

*$p < .05$.

**$p < .01$.

temperatures, whereas Manowaiʻōpae (17.50°C), Kaʻawaliʻi (16.03°C), Waikaumalo (15.93°C), and Pāhale (15.80°C) had the largest differences, resulting in a significant negative correlation between stream temperature range and BFQ_{50} yield ($r = -.73$, $p < .01$) but not with BFQ_{50} ($r = -0.50$, $p > .05$). Maximum daily stream temperature exceeded 30°C during the study period in Waikaumalo (2 days), Manowaiʻōpae (5 days), and Kaʻawaliʻi (1 days) streams.

There were clear seasonal differences in stream temperature in all streams, with dry season temperatures greater than wet season temperatures (Figure 6) resulting in a significant season effect (RM-ANOVA $F = 142.9$, $df = 9, 1$, $p < .001$). In the dry season, BFQ_{50} was significantly ($p < .05$) correlated to minimum, mean, and maximum stream temperatures, whereas wet season BFQ_{50} was not correlated

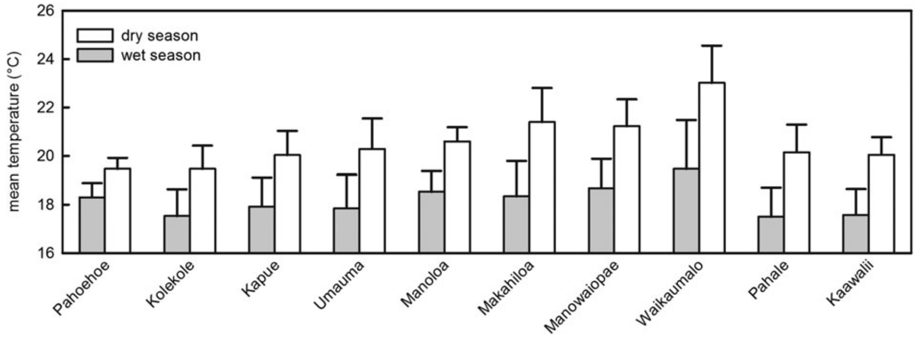

FIGURE 6 Seasonal differences in mean (± standard deviation) daily stream temperature for 10 streams on the windward coast, Hawaiʻi Island between April 2011 and October 2014. Wet season was defined as November to April, dry season as May to October. All seasonal differences are significantly ($p < .001$) different based on Tukey's post hoc HSD test

to these metrics (Table 3). Wet season mean temperature was, however, strongly negatively correlated with TF. Mean temperature range during the wet season varied from 2.34°C in Pāhale to 7.51°C in Waikaumalo and during the dry season from 2.03°C in Pāhoehoe to 7.23°C in Manowaiʻōpae. During the warmest month (September 2013), mean maximum stream temperature was not correlated to % canopy cover ($r^2 = .44$, $p > .05$). The coefficient of variation in stream temperature was much greater during the wet season than the dry season (Figure S1).

4 | DISCUSSION

4.1 | Overview of results and support of hypotheses

Across the Hawaiian archipelago, alterations to the natural flow and temperature regimes of streams are multifold and are anticipated to magnify throughout the 21st century (Brasher, 2003; Walter et al., 2012). Shifts in the distribution of rainfall may result in smaller or fewer runoff events and longer droughts leading to declines in groundwater recharge, bank storage, and the groundwater contributions to BF (Bassiouni & Oki, 2012; Chu, Chen, & Schroeder, 2010). Increases in air and ocean temperatures that have occurred in the Eastern Pacific since the 1960s have already impacted the distribution, frequency, and intensity of rainfall events (Chen & Chu, 2014; Chu & Chen, 2005), which in turn has contributed to declines in stream flow (Oki, 2004). However, few studies have isolated the effect of changing hydrology on stream temperature, especially in the tropics where climate change is expected to affect stream flow and groundwater recharge (Oki, 2004; Safeeq & Fares, 2012). As expected, declines in MAR resulted in reductions in BF yield. Streams with greater BF generally had lower mean temperatures and smaller fluctuations in daily, monthly, and seasonal temperatures (H1 and H2). Median BF was more closely linked to stream temperatures during the dry season due to the higher proportion of groundwater discharge to stream flow. During the wet season, runoff contributes more to flow, resulting in a dilution of the groundwater heat flux. As a consequence, stream temperature was more variable during the wet season than during the dry season (H3).

Daily fluctuations in air temperature were important drivers of water temperature for both perennial Kolekole and Pāhoehoe streams and the non-perennial Manowaiʻōpae stream, whereas seasonal variations were only significant for Manowaiʻōpae. However, air temperature alone was a poor predictor of water temperature in streams with lower BFs. In temperate systems, streams have lower thermal inertia due to reduced water volume during the dry season and therefore have increased temperature variability. We demonstrate that the increased runoff during the wet season drives greater thermal variability in tropical streams. Riparian vegetation, which controls canopy cover and subsequent shading of stream channels, has been shown to alter stream water temperature in the tropics (Macedo et al., 2014); however, there was no correlation between mean stream temperature and canopy cover. Differences in canopy cover are likely to have minimal influence on stream temperature in steeply sloped tropical watersheds except during low flow periods due to the short residence time of stream water (Maher, 2011).

Groundwater is a critical resource that supports stream flow during dry periods, maintaining hydrological and ecological functions in tropical island streams (Konikow, 2011). Isolating the BF component of surface flow is important for examining the relationship between aquifer structure and its association with stream flow (Oki, 2004; Thomas, Vogel, & Famiglietti, 2015). Few studies have examined the hyporheic zone of tropical island streams and its interaction with surface flows. On young volcanic islands, stream banks may be dominated by bedrock and riparian sediments that are frequently transported downstream by flash floods, limiting water storage capacity and the development of a hyporheic zone. Bank storage on older volcanic islands probably contributes to surface flow and exchange with the hyporheic zone, especially in lower elevations where unconfined alluvium is deposited along the stream channel from upslope regions. On Hawaiʻi Island, frequent flash flooding may temporarily increase subsurface storage of water, but there are few flood plains that would provide the appropriate geomorphology for a true hyporheic zone formation. Although Kasahara and Wondzell (2003) suggest that hyporheic exchange in low-order streams is primarily occurring at pool-step sequences rather than pool-riffle, there is no evidence to support this in Hawaiʻi, especially when reach gradients can regularly exceed 10% and a pool might be a run or a riffle might be a run at higher flows. Julius (2007) suggested that the lack of sediment development in low-order Hawaiian streams limited the formation of a hyporheic zone and that under some conditions, the zone may be nonexistent. Thus it is unclear whether groundwater inputs driving stream temperatures may be interacting with the hyporheic zone in young volcanic islands.

4.2 | Climate change impacts on hydrology and tropical stream temperatures

Since the 1970s, Hawaiian climate patterns have been changing, with coastal air temperature increasing at 0.163°C decade^{-1} (Giambelluca, Diaz, & Luke, 2008). Climate factors that may influence stream temperature include differences in cloud cover, air temperature, and solar radiation. In this study, upstream catchments varied little in topography, geology, or vegetation, but watersheds varied in maximum elevation, affecting the exposure of surface water to atmospheric heat flux (advection from air masses), solar radiation, and the potential contribution of high-elevation rainfall or snow melt on surface flows. However, there was no significant correlation between BFQ_{50} and MAT or MASR indicating they are not likely to substantially bias stream temperature across the gradient. Monthly minimum stream temperatures were lowest in watersheds that had the greatest maximum elevation on Mauna Kea: 14.00°C in ʻUmaʻuma, 14.13°C in Kāpue, 14.33°C in Kolekole, and 14.33°C in Waikaumalo (Table S3). It likely that they receive colder runoff at higher elevations due to a decrease in air temperature. Differences in linear regression model results between the perennial Kolekole and non-perennial Manowaiʻōpae streams suggest that simple air temperature correlations do not affectively predict stream temperature. Differences in regression modeled outcomes between streams are also likely related to the more pronounced seasonal and daily effects of solar radiation on low flow streams due to lower thermal inertia. Alternative methods for predicting stream temperature utilize statistical regression-based models with air temperature (Arismendi, Safeeq, Dunham, & Johnson, 2014; Caldwell et al., 2015). However, such methods ignore the influence of underlying hydrology (Ward, 1985).

Concurrent increases in air temperature and shifts in rainfall patterns are likely to be accompanied by changes in relative humidity, solar radiation, evapotranspiration, groundwater recharge, and runoff, each with ramifications for water temperature and stream flow (IPCC, 2013; Wohl et al., 2012). Thus, isolating the effects of warming air temperatures from changes in hydrology can be a challenge, especially outside of computer models (Strauch et al., 2016). Additionally, predicted shifts in the elevation of the temperature inversion layer, the atmospheric layer produced by the interaction between the subsiding upper troposphere, and rising convection-driven air masses that signals a shift in the temperature–elevation relationship will have consequences for local climate patterns and the water cycle (Cao, Giambelluca, Stevens, & Schroeder, 2007; Giambelluca & Nullet, 1991). A rise in the number of days with trade wind inversions may disproportionately affect rainfall in watersheds with higher maximum elevations by increasing the capture of orographic rainfall (Lauer, Zhang, Elison-Timm, Wang, & Hamilton, 2013). Although some climate models predict few changes in MAR for windward coasts of the Hawaiian Islands (Lauer et al., 2013; Timm, Giambelluca, & Diaz, 2015), this does not address shifts in the intensity and distribution of rainfall events, which may result in fewer large storm events, or increases in wet season rainfall with concurrent decreases in dry season rainfall, which may exacerbate the seasonal effects observed in this study (Chen & Chu, 2014; Chu et al., 2010). At the same time, some statistical models suggest there will be declines in MAR and changes in seasonal rainfall for many areas of Hawaiʻi in the near future (Chu & Chen, 2005). Finally, the increase in air temperature will affect heat fluxes from the streambed, shallow substrates, and shallow groundwater discharge (Kurylyk et al., 2015; Memberg, Blum, Kurylyk, & Bayer, 2014). Other studies have shown that dry season water temperature is more variable because reduced water volume leads to lower thermal inertia (Tague et al., 2007). This highlights an important difference between large temperate and small tropical stream systems, because runoff (at much greater proportions of TF) drives water temperature variability in tropical streams.

Unlike lake temperatures, which generally exhibit a coherent response to meteorological variables across large areas (e.g., Baines, Webster, Kratz, Carpenter, and Magnuson (2000) or Magnuson, Benson, and Kratz (1990)), stream temperatures reflect the integration of heat fluxes that differ widely in space and time. Intense rainfall events, low order stream systems, and steep gradients on tropical islands accelerate the movement of runoff, with hydrologic processes occurring on the order of minutes to hours (Mimura et al., 2007; Oki & Brasher, 2003; Ringuet & Mackenzie, 2005). Such runoff events are driven by intense orographic rainfall, which may temporarily reduce stream temperature due to the high-altitude origin (lower atmospheric temperatures) of rainfall. This contrasts with continental systems, where more stable thermal regimes are driven by seasonal patterns in snowmelt, runoff, and groundwater discharge (Craig, 2003). Thus, predicting the long-term consequences of changing climatic conditions on stream temperature in the tropics must consider both the thermal and the hydrologic effects.

4.3 | Importance of stream temperature for aquatic ecosystems

Increases in stream temperature have been shown to affect the structure and function of stream ecosystems in temperate climates (Kernan, Battarbee, & Moss, 2010; Yvon-Durocher, Montoya, Trimmer, & Woodward, 2011). However, tropical stream systems differ greatly in geology, topography, and climate, resulting in more event-driven systems that are relatively unpredictable driving aquatic ecosystems (Smith, Covich, & Brasher, 2003). Isolating temperature effects from flow in the tropics is challenging because such datasets often covary with factors such as latitude or elevation (e.g., Jacobsen, Schultz, and Encalada (1997)) or are confined to small microcosm laboratory experiments (e.g., Dang, Schindler, Chauvet, and Gessner (2009)). Utilizing a field experiment to examine shifts in thermal regimes as a result of changing hydrology is an important step in understanding if ecological or hydrological models developed for temperate streams are applicable to tropical systems (Boulton, Boyero, Covich, Dobson, & Person, 2008). Native and endemic gobioid fishes, shrimps, and snails are commonly dominant in tropical island stream faunal assemblages, but the degree to which temperature affects behavior or fitness in these species is not well defined. Declines in stream flow and increases in temperature are expected to affect the viability of habitat for these species (Gingerich & Wolff, 2005; Timbol & Maciolek, 1978). For example, Couret (1976) observed normal behavior of the Hawaiian mountain shrimp *Atoyida bisulcata* up to 31°C in the lab, but that at 31.8°C, he noted excessive activity and the cessation of feeding, and at 34.5°C, he noted signs of heat coma. This is interesting because it would suggest that low flow streams are getting close to the thermal tolerance of this species, and projected increases of 2 to 3 degrees (IPCC, 2013) will push populations over the tolerable threshold. These results are occurring at high elevations, and effects on other species may be even more pronounced at lower elevations that would require additional study of thermal regimes and thermal tolerances.

4.4 | Implications for water management

It is essential that environmental flow standards consider the flows necessary for maintaining the thermal ranges that are important to particular aquatic ecosystems (Lessard & Hayes, 2003; Poole & Berman, 2001). Since the late 1800s, BFs in many Hawaiian streams have been diverted for hydropower or irrigation. This dewatering, in conjunction with channelization, land-use change, and otherwise habitat degradation, have reduced the availability of habitat for native stream fauna, resulting in some of Hawaii's amphidromous fishes being listed as "threatened" or "endangered" (Radtke & Kinzie, 1996). These diversions also likely impact thermal regimes, but there is limited data currently available to examine such impacts (Brasher, 2003; McIntosh, Benbow, & Burky, 2002). Stream flow restoration to protect aquatic species also needs to consider the time of year when water temperatures are likely to reach critical points. The strong relationship between dry season BF and stream temperature signifies the importance of maintaining BFs for aquatic ecosystems during peak dry season months when maximum stream temperatures are most likely to affect species survival.

5 | CONCLUSIONS

The consequences of increased stream temperatures for aquatic ecosystems will likely be amplified by global changes in the distribution of water. Although increases in global air temperatures are expected to result in similar increases in surface water temperature, the degree to which climate-driven changes in hydrology influence stream temperature is largely unknown. This is especially true in the tropics where shifts in the distribution and intensity of rainfall events will affect runoff and groundwater recharge. To this date, no studies have isolated the influence of changing runoff and groundwater discharge on thermal regimes utilizing a space-for-time substitution. We demonstrate that increases in runoff events in tropical watersheds decreases surface water temperature and temperature variability independent of changes in air temperature. Further, as declines in total rainfall, rainfall event frequency, or rainfall intensity affects groundwater recharge, BFs will decline with consequences for stream temperature. Improved monitoring of air temperatures across the rainfall gradient will improve our understanding of how changes in hydrology and air temperature interact to influence stream temperature. As development of tropical locations has increased the demand for freshwater supplies and altered landscapes, the interactive effects of reduced BFs on stream temperatures need to be quantified to protect aquatic species habitats. Here, we demonstrate that climate-driven shifts in runoff and groundwater discharge will alter stream thermal regimes, independent of air temperature.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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