



Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system



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SUMMARY

Rising atmospheric CO₂ and resulting warming are expected to impact freshwater resources in the tropics, but few studies have documented how natural stream flow regimes in tropical watersheds will respond to changing rainfall patterns. To address this data gap, we utilized a space-for-time substitution across a naturally occurring and highly constrained (i.e., similar geomorphic, abiotic, and biotic features) model hydrological system encompassing a 3000 mm mean annual rainfall (MAR) gradient on Hawai'i Island. We monitored stream flow at 15 min intervals in 12 streams across these watersheds for two years (one normal and one dry) and calculated flow metrics describing the flow magnitude, flow variability (e.g., flow flashiness, zero flow days), and flow stability (e.g., deviations from Q_{90} , daily flow range). A decrease in watershed MAR was associated with increased relative rainfall intensity, a greater number of days with zero rainfall resulting in more days with zero flow, and a decrease in Q_{90} : Q_{50} . Flow yield metrics increased with increasing MAR and correlations with MAR were generally stronger in the normal rainfall year compared to the dry year, suggesting that stream flow metrics are less predictable in drier conditions. Compared to the normal rainfall year, during the dry year, Q_{50} declined and the number of zero flow days increased, while coefficient of variation increased in most streams despite a decrease in stream flashiness due to fewer high flow events. This suggests that if MAR changes, stream flow regimes in tropical watersheds will also shift, with implications for water supply to downstream users and in stream habitat quality for aquatic organisms.

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1. Introduction

Climate change is projected to have large impacts on watershed function, including changes to the magnitude and frequency of rainfall events (Allen and Ingram, 2002; IPCC, 2013; Muller et al., 2011; Oki and Kanae, 2006), to transpiration and water use by vegetation (Kirschbaum, 2004), and to relative humidity (Still et al., 1999), evaporation, and soil moisture (Seneviratne et al., 2010). These climate driven changes will, in turn, alter the timing and availability of freshwater resources for human and natural systems (Chapin III et al., 2010; Dettinger and Diaz, 2000; Milly et al., 2005; Oki and Kanae, 2006). Across the tropics, climate is changing due to rising greenhouse gases (IPCC, 2013), and emission projections suggest this trend will continue, resulting in substantial changes to the climate system. Rainfall in the tropics is driven by the convergence of Hadley cells within the intertropical convergence zone

(ITCZ) whose location is largely driven by oceanic currents (Sachs et al., 2009; Wohl et al., 2012). Consequently, small changes in sea surface temperature (SST) anticipated in a warmer climate will alter tropical rainfall patterns (Chiang et al., 2001; Haug et al., 2001). Changing SST and air temperature influences total column water vapor (TCWV) with direct implications for moisture, clouds, and total rainfall, while accentuating seasonal and inter-annual variability in rainfall (Lauer et al., 2013; Mimura et al., 2007). Reductions in cloud cover due to the strengthening of Hadley-cell subsidence in the subtropics has resulted in changes in solar radiation affecting potential evapotranspiration (PET). Declines in insolation due to increased cloud cover over windward mountain slopes may also be affecting PET and available surface water (Nullet and Ekern, 1988). As the climate warms, increases in evaporation rates from ocean surfaces will raise atmospheric water vapor, reducing the temperature lapse rate on mountains in the tropics with subsequent effects on condensation level, surface cloud formation, height of the cloudbank, and cloud forest formation (Foster, 2001). Global climate models generally function at

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coarse scales in relation to watersheds (Lauer et al., 2013). Thus, detailed studies of potential climate impacts on hydrological processes, especially in regions with complex topography such as tropical islands, are important for assessing social, economic, and ecological vulnerabilities. While there are on-going efforts to forecast future rainfall and temperature patterns globally, sparingly little is known about how these effects will alter stream flow regimes in the tropics (Suen, 2010).

On Hawai'i Island, daily rainfall events have become more severe with greater extreme events during La Niña years (Chen and Chu, 2014). Projected increases in air and ocean temperatures for the eastern Pacific Region (Ruosteenoja et al., 2003) are expected to alter the ITCZ, and with it, the frequency and duration of El-Niño southern oscillations (ENSO), the magnitude of precipitation extremes (e.g., storm intensity, drought) as well as a decline in total rainfall (Chu et al., 2010; Palmer and Räsänen, 2002; Timm et al., 2011). Downscaling climate models predict a southward shift in the ITCZ and potential reductions in leeward rainfall with little change in windward rainfall, although there is much variation among models (Lauer et al., 2013; Timm and Diaz, 2009). The strong relationship between tropical rainfall intensification and warming SST is likely to result in larger heavy rainfall events and a reduction in light to moderate rainfall in some regions (Lau and Wu, 2011), although the number of heavy rainfall events is not expected to increase in Hawai'i in the 21st Century (Timm et al., 2013). These changes will shift rates of infiltration, PET and the onset and duration of surface runoff with consequences for the availability of freshwater (Wohl et al., 2012). In recent decades (1975–2006), Hawai'i has experienced a $0.163\text{ }^{\circ}\text{C decade}^{-1}$ increase in surface air temperatures (Giambelluca et al., 2008) and a 27.5% decline in annual coastal precipitation (Chu et al., 2010; Kruk and Levinson, 2008). These changes are correlated with a 23% reduction in median base flow in Hawaiian streams from 1943–2008 compared to 1913–1943 (Bassiouni and Oki, 2012). The current trend of a diminishing vertical lapse rate could mean a shift towards a more stable atmosphere and may result in steadily drier conditions (Cao et al., 2007; Chu and Chen, 2005; Timm and Diaz, 2009), reducing groundwater recharge and stream discharge (Johnson, 2012; Milleham et al., 2009). Similarly, an increase in trade wind inversion frequency is projected to increase the number of dry days between storms, increasing the frequency and severity of drought and low or no flow conditions (Cao et al., 2007; Easterling et al., 2000). During ENSO periods, shifts in ocean currents and temperatures have already resulted in prolonged periods of drought (McGregor and Nieuwolt, 1998), with reductions in the capacity of streams and underlying aquifers to support community and ecosystem needs (Burns, 2002; Meehl, 1996; Pounds et al., 1999).

Natural fluctuations in stream flow, including the magnitude and frequency of floods and droughts, play an important role in the evolution and life history strategies of freshwater organisms, and in structuring communities and economic systems. Such variation provides natural 'disturbances' that affect the persistence of species and regulate population sizes, as well the physical and biological structure of the habitat (Lytle and Poff, 2004). In contrast to temperate continental systems, tropical island watersheds are spatially compact and tend to be characterized by steep slopes and low stream order. As a result, tropical hydrographs tend to be flashier and highly responsive to rainfall; flow can shift by orders of magnitude within hours (Wu, 1969). Shifts in the distribution of rainfall over time are expected to alter watershed runoff characteristics, with consequences for the transport of sediment or pollutants in runoff (Strauch et al., 2014). These flood events are important to the flux of nutrients within streams (Aalto et al., 2003) or to near

shore environments (Mead and Wiegner, 2010; Wiegner et al., 2009), the creation or maintenance of habitat (McIntosh et al., 2002; Wolff, 2000), and the life history traits of native species (Radtke and Kinzie III, 1996; Radtke et al., 1988; Smith et al., 2003).

For example, amphidromous gobies, shrimps, and snails that are the dominant organisms in tropical island streams (Resh and Deszalay, 1995) require flood events so that newly hatched stream larvae can quickly reach the ocean and juveniles developing in the near-shore waters can find streams to recolonize (McDowall, 2007; Radtke and Kinzie III, 1996). Hence evolutionarily rapid deviations from these regimes, or fundamental changes to regime amplitudes, can threaten the survival of species or whole communities (Ha and Kinzie III, 1996; Radtke and Kinzie III, 1996). Changing flow variability can also result in unpredictable erosion–deposition processes affecting channel morphology and habitat availability; reducing macroinvertebrate species richness and biomass, and affecting habitat and substrate stability (Cobb et al., 1992; Layzer and Madison, 1995; Munn and Brusven, 1991). Reductions in dry season (summer) flows will generate more pool-like conditions, resulting in the proliferation of pest species (e.g. mosquitoes) and the growth of generalist non-native fish species that can tolerate a variety of conditions (e.g., low dissolved oxygen; Pusey and Arthington, 2003) with potential negative consequences for Hawaiian stream ecosystems (Holitzki et al., 2013). Further, understanding how flow variability responds to changes in rainfall is critical for the construction and maintenance of climate resilient water supply infrastructure (e.g., water intake, diversions, effective culvert size and design, bridges and stream crossings).

Given the centrality of freshwater to society, enormous efforts in temperate regions have been directed at modeling stream flow and forecasting the effects of climate change on water supply. These models are complex, highly parameterized, and robustly validated (see Clausen and Biggs, 2000). In the tropics however, the availability of basic information required for model parameterizations have greatly limited the ability to forecast possible future changes to flow regimes (Wohl et al., 2012), and yet many regions of the tropics are exactly where the biggest effects of climate change will be expressed (Mora et al., 2013).

To increase our understanding of how changes in rainfall might influence flow regimes and the flashy nature of Pacific Island streams, we used a space-for-time hydrological study system that encompasses watersheds with mean annual rainfall (MAR) values spanning 3000 mm. A space-for-time substitution utilizes a naturally occurring environmental gradient to test hypotheses related to the effects of the gradient variable (independent) on other variables (dependent). In this system, other factors important to watershed function vary minimally across the project area: similar watershed shape and slope, >85% of stand basal area dominated by one canopy species and one mid-story species, upper elevations (above 700 m) are closed-canopy forest, and all soils are similar aged Hydudands of volcanic origin (Mauna Kea). This level of constraint across such an enormous rainfall gradient is unique (Vitousek, 1995). While little is known about the extent of perched and dike-impounded groundwater supplies in this region (Lau and Mink, 2006), we assumed the influence of subsurface geology was consistent throughout the study area based on trends in other islands (Sherrod et al., 2007). We hypothesized that declines in long-term MAR would: reduce the daily mean rainfall and increase the number of zero rainfall days, resulting in a decline in flow yield (H1); and drive an increase in relative rainfall intensity and a decrease in rainfall stability resulting in greater flow variability and instability (H2). We also hypothesized the number of zero rainfall days will increase in the dry year compared to the normal year resulting in more zero flow days (H3).

2. Methods

2.1. Study system

Stream flow for windward Hawai'i Island was measured continuously for 8 streams in water year (WY) 2012 (Oct 1 to Sept 30) and 12 streams in WY2013 (Table 1). Gaging sites were located at the lower boundaries of native forest with individual sites determined by elevation, topography, and MAR (Fig. 1). Gages were sited in stable reaches with no noticeable changes in stream bed conditions during the study period. Watershed catchment area was measured as the upstream area from the gaging station. Soil type (all Andisols with most being Hydrudands) is consistent and the underlying geology is similar across watersheds with Hamakua Volcanics underlying Laupāhoehoe Volcanics of similar age ranges (Vitousek, 1995; Supplemental Fig. S1).

2.2. Rainfall

Rainfall was monitored at 15 min intervals in four watersheds at approximately 490 m a.s.l. using Onset® data logging rain gages (MAN-RG3). Long-term MAR for each rain gage (Giambelluca et al., 2013) was used for comparison to actual rainfall measurements. Watershed MAR was calculated using an average MAR (Giambelluca et al., 2013) for the area of the watershed upstream of the gaging station. Four watersheds (Honoli'i, Ka'awali'i, Waikaumalo, 'Uma'uma) had regions above the lower bounds of the inversion layer at 1830 m (6000 ft) in elevation where PET exceeds rainfall, resulting in a net loss of water and skewing the watershed's the effective MAR (Ehlmann et al., 2005; Erasmus, 1986). These regions were eliminated from the MAR estimation shifting the MAR for Honoli'i from 5653 mm to 5751 mm, for Ka'awali'i from 2646 mm to 3015 mm, for Waikaumalo from 3005 mm, to 3774 mm, and for 'Uma'uma from 2959 mm to 4906 mm.

2.3. Stream flow

All streams were classified as perennial based on Parham et al. (2008), but when zero flow conditions were observed, such streams are referred to in this paper as intermittent. In young tropical islands, even perennial stream flows can be dominated by runoff. Instantaneous flow was measured at 15 min intervals. Daily and monthly mean flows are generally used to characterize stream flow regimes (see Clausen and Biggs, 2000 and Olden and Poff, 2003), but by using 15 min interval data, we were better able to

capture flow behavior. At Honoli'i, stream flow is monitored by a US Geological Survey (USGS) gaging station (station number 16717000). Stage at Ka'awali'i, Kaiwilahilahi, Kapu'e, Kolekole, Makahiloa, Manoloa, Pāhale, Pāhoehoe and Waikaumalo were all measured using non-vented HOB0® U20 depth sensors (Onset, Bourne, MA), while stage in 'Uma'uma and Manowai'ōpae streams were measured by vented WaterLOG® Model H-312 (Design Analysis Associates Inc, Logan, UT) depth sensors with data stored in CR295X data loggers (Campbell Scientific Inc, Logan, UT). Non-vented sensors were corrected for changes in barometric pressure by placing an additional HOB0® sensor in the adjacent forest. Flow was then calculated by developing a rating curve for each stream. Rating curves were generated by taking 11 to 16 stream flow measurements across a wide range of flows as in Gore (2007) and Turnipseed and Sauer (2010). Measurements represented flows as high as the 2% (Pāhoehoe), 1.7% ('Uma'uma), 1.55% (Kolekole), 0.22% (Kapu'e), 0.04% (Manoloa), 0.03% (Manowai'ōpae) and 0.01% (Ka'awali'i) percentile flows based on mean daily flow duration curves. The number of zero flow days for each stream was determined by summing up the number of days where mean daily flow was $<0.014 \text{ m}^3 \text{ s}^{-1}$ ($0.5 \text{ ft}^3 \text{ s}^{-1}$) which was considered the lowest flow that could be accurately measured using given field techniques.

2.4. Data analysis

Daily rainfall values were calculated for each rain gage and mean daily rainfall and total annual rainfall were calculated for each water year. Relative rainfall intensity was calculated as the maximum daily rainfall ($R_{\max}$) divided by the median daily rainfall (R_{50}) and rainfall stability was calculated as R_{50} divided by the 10th percentile largest daily rainfall (R_{10}), thus $R_{50}:R_{10}$ will always be less than 1.0. Using instantaneous flow data for each water year (1 Oct to 30 Sept), low flow (Q_{90}), storm flow (Q_{10}) and median flow (Q_{50}) were calculated as the flow that is equaled or exceeded 90%, 10% and 50% of the time, respectively. Mean annual flow yield was calculated as the average of all flow values for each water year divided by the upstream watershed area. Low flow yield (Q_{90} Yield) and storm flow yield (Q_{10} Yield) were calculated by dividing by upstream catchment area as were the yields of other metrics. Stream flashiness (QF) was determined as the frequency (yr^{-1}) of storm flows that were $\geq 2\times$ the long-term median flow, as determined by USGS regression equations for estimating stream flow in Hawai'i using drainage area, mean altitude of the main stream channel, and the mean annual precipitation of the watershed

Table 1

Upstream drainage area description for each gaging station on windward, Hawai'i Island. Intermittent streams in bold.

Watershed name	Stream order	Mean slope (%)	Elevation of gaging station (m)	MAR ^a (mm)	Catchment area (km ²)	Modeled Q_{50} ^b (m ³ s ⁻¹)	Observed Q_{50} ^c (m ³ s ⁻¹)	Estimated Q_{50} ^d (m ³ s ⁻¹)	% Upstream forest cover
Honoli'i	2	6.2	470	5751	30.36	0.862	1.062	1.133	100
Pāhoehoe	1	6.4	430	5856	1.30	0.114	–	–	94
Kapu'e	2	6.7	460	5696	20.69	0.484	0.527	0.562	82
Kolekole	2	6.1	500	6426	17.23	0.542	0.468	0.499	96
'Uma'uma	3	8.5	490	4906	74.43	0.717	0.769	0.820	42
Waikaumalo	2	8.0	450	3774	35.95	0.526	–	–	67
Manoloa	1	8.8	420	5205	2.56	0.142	–	–	86
Makahiloa	2	8.8	400	4663	9.60	–	0.066	0.070	98
Pāhale	1	8.9	510	4026	10.14	–	0.015	0.016	99
Kaiwilahilahi	1	14.4	670	3640	14.92	–	–	–	70
Manowai'ōpae	1	11.6	470	4689	3.84	–	0.005	0.005	87
Ka'awali'i	2	9.9	475	3015	33.10	–	0.0002	0.0002	73

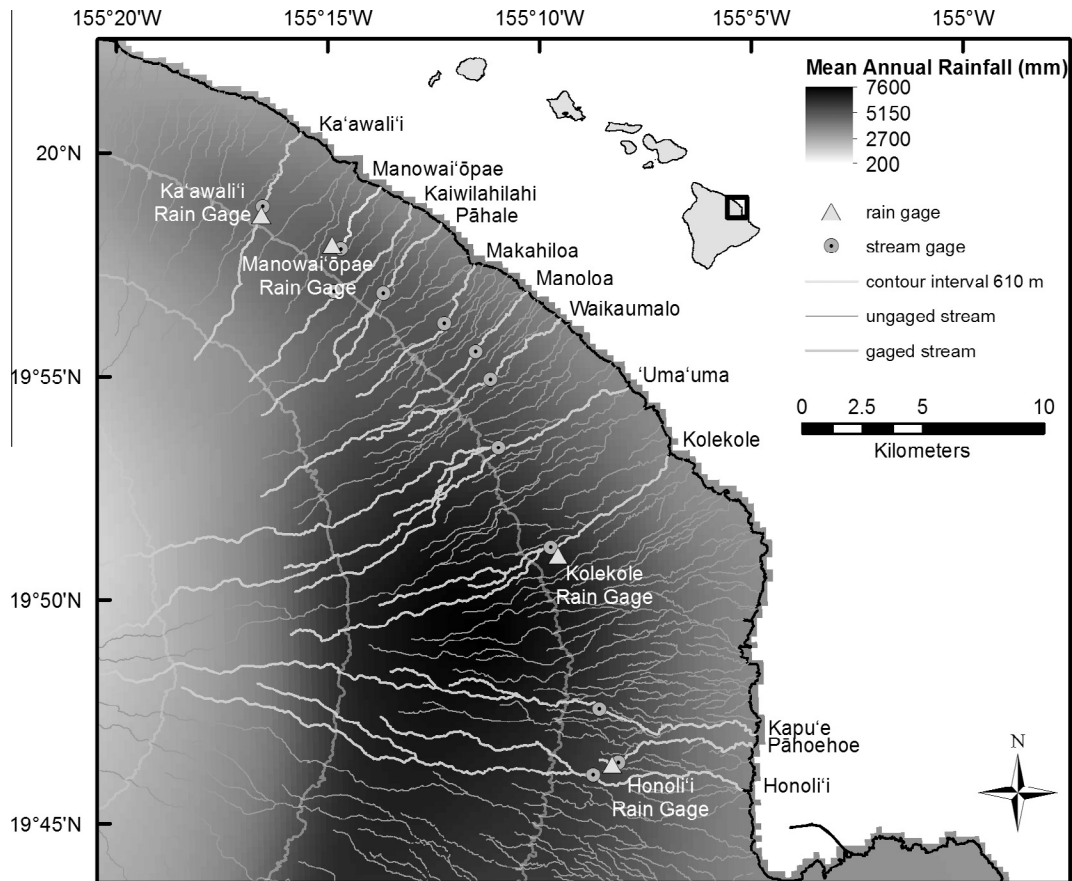
– Data not available due to incomplete water year 2012 dataset.

^a Based on Giambelluca et al. (2013) for the entire upstream catchment below the inversion layer elevation.

^b Based on USGS regression models for perennial streams (Fontaine et al., 1992).

^c Mean of Q_{50} from water years 2012 and 2013.

^d Converted using the ratio of Q_{50} during study period to the long-term Q_{50} from USGS Honoli'i station 16717000.



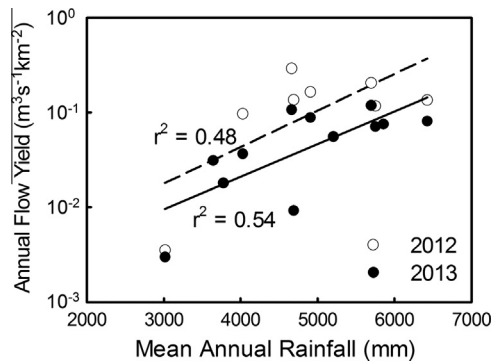


Fig. 2. Annual flow yield ($\text{m}^3 \text{s}^{-1} \text{km}^{-2}$) across a mean annual rainfall gradient (mm) for water years 2012 and 2013 on windward Hawai'i Island.

2013, while Q_{10} ranged from 0.002 to $10.770 \text{ m}^3 \text{s}^{-1}$ in 2012 and from 0.004 to $4.565 \text{ m}^3 \text{s}^{-1}$ in 2013 (Table 3). Both Q_{90} and Q_{50} decreased in most streams in 2013 compared to 2012. As expected, Q_{90} Yield and Q_{10} Yield were positively correlated with watershed MAR (Fig. 3a and c), although there were no significant slope differences between years for either parameter (Table 4). Of all the metrics, low flow (Q_{90}) yield had the strongest correlation with MAR for both years. Similarly, Q_{50} Yield declined with decreasing MAR, although there was little change among watersheds with the highest MAR (Fig. 3b). Q_{10} , Q_{50} and Q_{90} flow yields tended to be more strongly correlated with watershed MAR during the higher rainfall year (2012).

3.3. Flow variability

The number of zero flow days was negatively correlated with MAR and all streams with zero flow days in 2012 experienced an increase in zero flow days in 2013 (Table 3). There was a strong

negative correlation between flow variability ($Q_{10}:Q_{90}$) and MAR (Fig. 3d). Flashiness (QF) was lower in the drier year for all streams except for Ka'awali'i (Table 3) and was positively correlated with MAR (Fig. 3e) in 2012 ($F = 13.14$, $df = 1,6$, $P = 0.011$) and 2013 ($F = 17.17$, $df = 1,10$, $P = 0.002$). Flow stability ($Q_{90}:Q_{50}$) was significantly positively correlated with MAR (Fig. 3f) in 2012 ($F = 13.82$, $df = 1,6$, $P = 0.01$) and in 2013 ($F = 9.41$, $df = 1,10$, $P = 0.012$). In perennial streams, $Q_{90}:Q_{50}$ tended to be greater (more unstable flow) in the dry year (2013) than in the wet year (2012), but there were fewer high flow events in 2013. By contrast, with increasing number of zero flow days leading to a Q_{90} of zero, $Q_{90}:Q_{50}$ in intermittent streams was zero. The CV of stream flow tended to be negatively correlated with MAR for both years, with small increases in CV from 2012 to 2013 for high MAR watersheds, and decreases in CV from 2012 to 2013 for low MAR watersheds. This was likely due to longer dry periods resulting in more consistent flow (zero) days in lower MAR watersheds. There were no significant differences in regression slopes between years for any flow statistic (Table 4). Total annual flow instability and total annual flow deviation were both negatively correlated with watershed MAR for perennial streams (Fig. 4) with no significant differences in slopes between years for flow instability ($F = 1.06$, $df = 1,4$, $P = 0.33$) or flow deviation ($F = 2.07$, $df = 1,9$, $P = 0.19$), although flow deviation was more closely linked to declines in watershed MAR in the higher rainfall year.

4. Discussion

Across the tropics future changes in rainfall amount and distribution coupled with warming will have consequences for freshwater availability critical to human and natural systems (Chapin III et al., 2010). The frequency and severity of both flash floods and drought continue to grow as do their impacts on industry, agriculture, tourism, human health, and ecosystem function (Milly et al.,

Table 2
Rainfall (mm) statistics from four rain gages across the mean annual rainfall (MAR) gradient of the windward coast, Hawai'i Island.

MAR ^a (mm)	Kolekole 6723		Honoli'i 5958		Manowai'ōpae 4689		Ka'awali'i 4334	
	2012	2013	2012	2013	2012	2013	2012	2013
Days with zero rainfall	42	67	55	67	102	116	110	119
Total annual rainfall (mm)	6370	4269	5374	3734	2732	2762	3540	2840
Mean daily rainfall (mm)	17.4	11.7	14.7	10.2	7.5	7.6	9.7	7.8
Relative rainfall intensity ($R_{\max}:R_{50}$)	24.8	32.7	26.9	54.0	142.9	139.0	171.6	289.7
Rainfall stability ($R_{50}:R_{10}$)	0.22	0.15	0.21	0.12	0.09	0.06	0.08	0.04

^a MAR at rain gage based on Giambelluca et al. (2013).

Table 3
Storm flow (Q_{10}), median flow (Q_{50}), low flow (Q_{90}) values ($\text{m}^3 \text{s}^{-1}$), number of zero flow days, flow stability ($Q_{90}:Q_{50}$), coefficient of variation (CV) of stream flow, and flow flashiness (QF) for watersheds along the windward coast, Hawai'i Island for water years 2012 and 2013. Intermittent streams in bold.

Watershed	Water Year 2012							Water Year 2013						
	Q_{10} ($\text{m}^3 \text{s}^{-1}$)	Q_{50} ($\text{m}^3 \text{s}^{-1}$)	Q_{90} ($\text{m}^3 \text{s}^{-1}$)	Zero flow days	$Q_{90}:Q_{50}$	CV	QF (yr^{-1})	Q_{10} ($\text{m}^3 \text{s}^{-1}$)	Q_{50} ($\text{m}^3 \text{s}^{-1}$)	Q_{90} ($\text{m}^3 \text{s}^{-1}$)	Zero flow days	$Q_{90}:Q_{50}$	CV	QF (yr^{-1})
Honoli'i	5.663	1.416	0.368	0	0.26	2.08	161	3.511	0.708	0.396	0	0.56	2.36	75
Pāhoehoe	–	–	–	–	–	–	–	0.130	0.048	0.031	0	0.65	1.86	24
Kapu'e	8.161	0.756	0.130	0	0.17	2.51	173	3.607	0.298	0.298	0	0.26	3.03	82
Kolekole	3.643	0.643	0.154	0	0.24	2.36	123	1.807	0.293	0.148	0	0.50	2.86	60
'Uma'uma	10.770	1.207	0.123	0	0.10	4.32	175	4.565	0.331	0.097	0	0.29	4.33	83
Waikāmalalo	–	–	–	–	–	–	–	0.171	0.007	0.003	237	0.38	5.49	20
Manoloa	–	–	–	–	–	–	–	0.050	0.010	0.007	229	0.65	4.90	21
Makahiloa	1.019	0.100	0.010	43	0.10	9.11	67	0.436	0.031	<0.001	112	<0.01	4.69	37
Pāhale	0.890	0.031	<0.001	152	<0.01	3.23	71	0.142	0.000	0.000	297	0.00	4.71	29
Kaiwilāhilahi	–	–	–	–	–	–	–	0.602	0.001	0.000	211	0.00	3.99	45
Manowai'ōpae	0.205	0.008	<0.001	244	0.02	6.65	50	0.004	0.002	0.000	335	0.00	4.81	14
Ka'awali'i	0.002	<0.001	<0.001	335	0.05	6.86	11	0.006	0.000	0.000	343	0.00	5.48	12

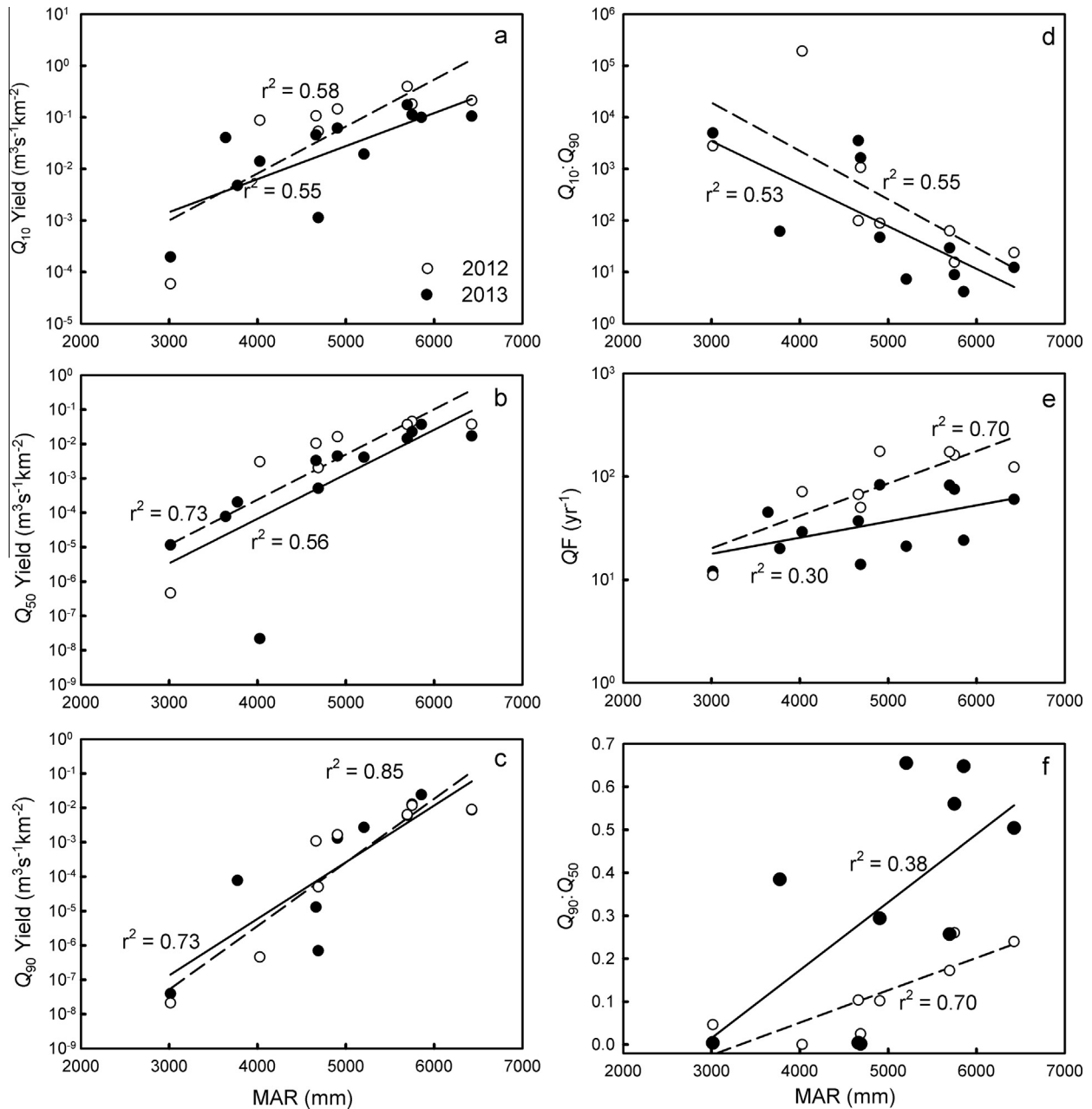


Fig. 3. (a) Storm flow yield (Q_{10} Yield), (b) low flow yield (Q_{90} Yield), (c) median flow yield (Q_{50} Yield), (d) $Q_{10}:Q_{90}$, (e) stream flashiness (QF), and (f) $Q_{90}:Q_{50}$ for water years 2012 and 2013 from streams on windward Hawai'i Island across a mean annual rainfall (MAR) gradient. Note the log-scale y-axis in (a)–(c).

Table 4

Water years 2012 and 2013 linear regression slopes between flow statistics (graphed in Fig. 3) and mean annual rainfall (MAR) with analysis of covariance (ANCOVA) F -values ($df = 1,1$) testing the null hypothesis that slopes are not different between years.

Statistic	2012 Slope	2013 Slope	ANCOVA F (slopes)
Annual flow yield	4.25 ^a	3.44 ^a	0.13
Q_{90} Yield	21.2 ^a	20.5 ^a	0.37
Q_{50} Yield	15.1 ^a	15.9 ^a	2.42
Q_{10} Yield	10.4 ^a	9.49 ^a	2.49
$Q_{10}:Q_{90}$	−9.38 ^b	−8.25 ^b	0.87
QF	31.4 ^b	15.7 ^b	0.04
$Q_{90}:Q_{50}$	7.54 ^b	15.8 ^b	1.99

^a In $10^{-4} \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2} \text{ mm}^{-1}$.

^b In 10^{-6} .

2005). As in temperate climates, species sensitivity to changes in water availability is very pronounced in the humid tropics (Engelbrecht et al., 2007; Feeley et al., 2011; Foster, 2001). Understanding how flow regime will change with climate is important for predicting the availability and variability of freshwater and for increased effective management of watersheds and hydrological output (Wohl et al., 2012). Current climate models for Hawai'i predict a potential change in the number of days with trade wind inversions and a change in the trade wind inversion height, while the RCP8.5 scenario outcome suggests both an increase in the trade wind inversion frequency and a decrease in trade wind inversion height, potentially increasing rainfall in some regions (Lauer et al., 2013). With our model hydrological study system, we found that as watershed MAR declined, mean daily rainfall and rainfall stability decreased while there was an increase in relative rainfall

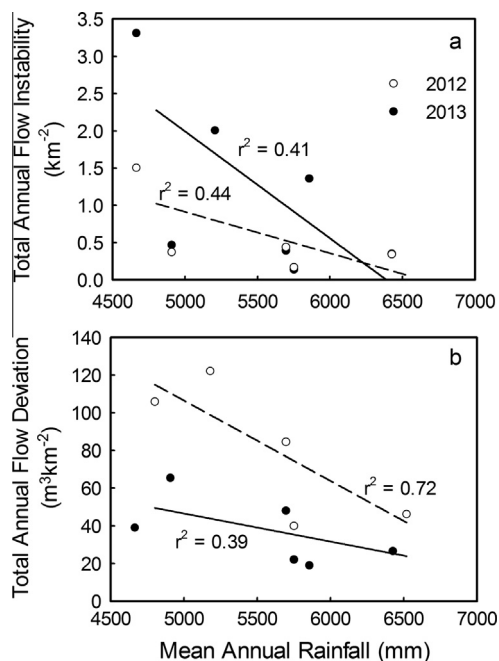


Fig. 4. Perennial stream (a) log-transformed total annual flow instability (km^2) and (b) total annual flow deviation ($\text{m}^3 \text{km}^{-2}$) across a mean annual rainfall gradient for water years 2012 and 2013 on windward Hawai'i Island.

intensity and the number of days with zero rainfall. As a consequence, declining MAR resulted in reductions in low (Q_{90}) and storm (Q_{10}) flow yield (H1) and an increase in flow variability ($Q_{10}:Q_{90}$) and instability (H2). Higher streamflow CV values in the lower MAR watersheds points to greater inconsistencies in flow in drier watersheds. Additionally, within perennial streams, flows were more stable (based on $Q_{90}:Q_{50}$) and less variable (based on $Q_{10}:Q_{90}$) in the dry year (2013) due to fewer storm events and more days of low flow (H3). In the dry year, four intermittent streams had Q_{90} values of $0.00 \text{ m}^3 \text{s}^{-1}$ resulting in unusable $Q_{10}:Q_{90}$ and $Q_{90}:Q_{50}$ metrics. Stream flashiness among perennial streams also declined from 2012 to 2013 for all watersheds.

4.1. Modeled vs observed rainfall patterns

There is substantial uncertainty surrounding how future climate change will affect precipitation in Hawai'i, although down-scaled climate models predict less rainfall with increased intensity of storms and a greater number of intervening dry days, especially on the leeward sides of islands (Chu et al., 2010; Timm and Diaz, 2009; Timm et al., 2011). Such climate projections are likely to result in associated changes in surface run-off and flow regimes, including flash flood frequency and low flow conditions (Bassiouni and Oki, 2012). While 2012 was an average rainfall year (2.4% below long-term mean at Hilo Airport), there was substantially less rainfall in 2013 (24.1% below long-term mean). Thus, we were able to not only use a space-for-time substitution to examine how decreased rainfall would impact stream flow, but we also were able to compare inter-annual differences between a relatively normal year and dry year, and compare inter-annual changes with spatial changes in MAR. This exercise affirmed that decreased mean daily rainfall will result in reduced flows across the system and that relative rainfall intensity was greater in lower MAR watersheds (H2). Chu et al. (2010) demonstrated that from 1950 to 2007, the simple daily rainfall intensity increased and the number of consecutive dry days increased in Hilo. Interestingly, the magnitude of rainfall events based on the annual

maximum consecutive 5-day precipitation amount declined in Hilo (the wetter region) but increased in Laupāhoehoe (drier region) during this period (Chu et al., 2010). Within rainfall stations, rainfall intensity increased and stability decreased in the dry year compared to the wetter year, which also supports this hypothesis.

4.2. Flow yield across a mean annual rainfall gradient

Honoli'i Stream Q_{50} for the study period was within 6.2% of the long-term Q_{50} suggesting that flow measurements across the gradient reasonably represent Q_{50} values. Observed Q_{50} flow values were also modeled closely by Fontaine et al. (1992) for perennial streams, with deviations ranging from -15.8% to 18.8%. Flow yields declined with decreasing watershed MAR (H1) and the decline was more substantial in the dry year (2013) than in the average rainfall year (2012), suggesting stream flows in lower MAR watersheds are more vulnerable to drought than in higher MAR watersheds. We also found that as the number of zero rainfall days increased for a watershed, the number of zero flow days increased (H3). Interestingly, while relative rainfall intensity was negatively correlated with MAR, QF was positively correlated with MAR, suggesting that $R_{\text{max}}:R_{50}$ is not a good indicator of rainfall amounts that result in flows greater than $2 \times Q_{50}$.

The high permeability of young basaltic lava flows conveys seepage deep into aquifers, limiting the development of perched water that supplies groundwater to the surface (Tribble, 2009). Some shallow, perched water exists in the Kau District on Hawai'i Island due to ash bed formation, but the extent of such formation across the island is unknown (Stearns and Clark, 1930). Ground water likely contributes to base flow in some watersheds, but such conditions are dependent on persistent rainfall and some reaches may even lose flow downslope. As such, stream flow in Hawai'i is generally dominated by surface runoff leading to large fluctuations in flow. Stream flow differences among watersheds could also be due to dike-impounded groundwater that contributes to base flow (Gingerich and Oki, 1999; Takasaki and Mink, 1985). Unfortunately, little is known about dike formations on Hawai'i Island, as dikes have only been identified in the Kohala Mountain (Stearns and Clark, 1930). While dike-impounded groundwater could have contributed to the observed shift from perennial to intermittent flowing streams across the rainfall gradient, on other islands, dike-rich intrusive rock formations tend to form consistent bands across rift zones or around calderas (Sherrod et al., 2007). Additionally, substrate age is fairly consistent across the system (Wolfe and Morris, 2009) and groundwater contributions to flow are not likely to be biased by geology across the rainfall gradient, although more detailed subsurface geologic data would be useful.

4.3. Consequences of changing flow regimes for the structure of tropical freshwater ecosystems

Shifting flow regimes, defined by a change in the ratio of flows and the number of zero flow days, may have repercussions for stream function. For example, decreasing rainfall resulted in an increase in the number of zero flow days and flow variability ($Q_{10}:Q_{90}$), and a decrease in flow stability ($Q_{90}:Q_{50}$). All of these flow regime shifts are due to decreased low flows that will permit siltation, decrease dissolved oxygen, increase mineralization of organic material, expose the streambed, and ultimately stress native organisms while providing habitat conditions more conducive to non-native aquatic animals (Brasher, 1997; McIntosh et al., 2002). Shifts in the size and frequency of storm flows alter stream channel structure, disturb in-channel and riparian vegetation, create new erosion (runs) and deposition (riffles, pools) areas, scour stream and riverbeds, redistribute sediment and organic material within the river, and ultimately transport it to the near

shore environment (Hoover and Mackenzie, 2009; Wiegner et al., 2009). While there is substantial uncertainty in future climate scenarios for Hawai'i, there is potential that as the magnitude or frequency of storm flow events change, this will shift erosion and deposition patterns. As terrestrial organic material is an important source of dissolved and particulate carbon and nutrients for near-shore food webs (Atwood et al., 2012; Capriulo et al., 2002), such flow regime shifts could also change the bioavailability of nutrients (Wiegner et al., 2009) and challenge the stability of the structure and function of tropical stream ecosystems (Wright et al., 2004).

4.4. Impacts of changing flows on tropical stream organisms

Although few long-term biological datasets exist to compare with natural stream flow shifts, altered flow regimes due to stream diversions or dams have been shown to have negative consequences for native freshwater biota (Brasher, 2003; Lytle and Poff, 2004). For example, reduced stream flow on O'ahu Island has resulted in warmer, slower moving, lower oxygenated waters, which results in habitat that is not suitable for native species resulting in the absence or decreased densities of those species (Brasher et al., 2006; Lutton et al., 2005). Decreased flow also affects recruitment of native species (Hau, 2007; March et al., 2003; McIntosh et al., 2008) as well as decreased biomass of invertebrate communities (Leberer and Nelson, 2001; McIntosh et al., 2002). Changing the frequency or intensity of storm flows may also affect amphidromous species highly dependent on such flows to carry larvae to the ocean (Radtko and Kinzie, 1996). Results from this space-for-time substitution suggest that as watershed MAR decreases, we should expect decreased flow yields, increased number of days with zero flow, and negative consequences for the function of aquatic ecosystems.

5. Conclusions

Understanding how flow yields and flow regimes will change with future climate projections is of great importance to water users and for developing protection strategies for freshwater ecosystems alike across the globe. While variability in tropical stream flow is likely to increase under future climate scenarios as the frequency of extreme climatic events (rainfall or drought) increases, future trends in stream flow from tropical watersheds are difficult to predict. What is not clear is how changes in flow regime will directly or indirectly alter other geological or ecological functions of tropical streams, such as impacts to channel morphology, nutrient and sediment loads, organic matter dynamics, species diversity, food-web structure, or overall fitness of native organisms. This model hydrological system provides a unique opportunity to develop hypotheses focused on climate driven alterations to ecological, hydrological and geomorphic features of watersheds. We conclude that under drying conditions forecasted by various climate models: (1) decreases in low flow will be substantial; (2) flow stability will decrease and flow variability will increase resulting in a greater strain on both ecological and human communities; and (3) there is a need for long-term datasets in tropical regions to better quantify the diverse controls on water availability. While the two years of flow data presented here provide a robust snapshot of differences between normal and dry years, data should continue to be collected to better characterize inter-annual flow variability.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.jhydrol.2015.01.045>.

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