NERC Open Research Archive
sharing our research

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

Article (refereed) - postprint

This is the peer reviewed version of the following article:

Clilverd, Hannah M.; Tsang, Yin-Phan; Infante, Dana M.; Lynch, Abigail J.; Strauch, Ayron M. 2019. **Long-term streamflow trends in Hawai'i and implications for native stream fauna**. *Hydrological Processes*, 33 (5). 699-719, which has been published in final form at https://doi.org/10.1002/hyp.13356

This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.

© 2018 John Wiley & Sons, Ltd.

This version available http://nora.nerc.ac.uk/522293/

NERC has developed NORA to enable users to access research outputs wholly or partially funded by NERC. Copyright and other rights for material on this site are retained by the rights owners. Users should read the terms and conditions of use of this material at http://nora.nerc.ac.uk/policies.html#access

This document is the authors' final manuscript version of the journal article, incorporating any revisions agreed during the peer review process. There may be differences between this and the publisher's version. You are advised to consult the publisher's version if you wish to cite from this article.

The definitive version is available at http://onlinelibrary.wiley.com/

Contact CEH NORA team at
noraceh@ceh.ac.uk

The NERC and CEH trademarks and logos ('the Trademarks') are registered trademarks of NERC in the UK and other countries, and may not be used without the prior written consent of the Trademark owner.

Long-term streamflow trends in Hawai‘i and implications for native stream fauna

Running title: Long-term streamflow trends in Hawai‘i

Hannah M. Clilverd[1, 2], Yin-Phan Tsang[1], Dana M. Infante[3], Abigail J. Lynch[4], Ayron M. Strauch[1,5]

[1]Department of Natural Resources and Environmental Management, University of Hawai‘i at Mānoa, Honolulu, HI, 96822, USA.

[2]Centre for Ecology and Hydrology, Bush Estate, Penicuik, UK.

[3] Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, 48824, USA.

[4]National Climate Adaptation Science Center, USGS, Reston, VA, 20192, USA.

[5] State of Hawai‘i Department of Land and Natural Resources, Honolulu, HI, 96813, USA.

Acknowledgments

The project described in this publication was supported by Grant No. G16AC00132 from the United States Geological Survey (USGS). Its contents are solely the responsibility of the authors and do not necessarily represent the views of the National Climate Adaptation Science Center or the USGS. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This manuscript is submitted for publication with the understanding that the U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes. Special thanks are extended to Abby Frazier, Glen Higashi, and Ralph Tingley for their assistance with acquisition of metrological and biological data. Abby Frazier, additionally, served as an internal USGS reviewer on an earlier version of this manuscript.

Abstract

Climate change has fundamentally altered the water cycle in tropical islands, which is a critical driver of freshwater ecosystems. To examine how changes in streamflow regime has impacted habitat quality for native migratory aquatic species, we present a 50-year (1967-2016) analysis of hydrologic records in 23 unregulated streams across the five largest Hawaiian Islands. For each stream, flow was separated into direct runoff and baseflow, and high and low flow statistics (i.e., Q10, Q90) with ecologically important hydrologic indices (e.g., frequency of flooding, low flow duration) derived. Using Mann-Kendall tests with a running trend analysis, we determined the persistence of streamflow trends through time. We analyzed native stream fauna from ~400 sites, sampled from 1992-2007, to assess species richness among islands and streams. Declines in streamflow metrics indicated a general drying across the islands. In particular, significant declines in low flow conditions (baseflows), were experienced in 57% of streams, compared with a significant decline in storm flow conditions for 22% of streams. The running trend analysis indicated that many of the significant downward trends were not persistent through time, but were only significant if recent decades (1987-2016) were included, with an average decline in baseflow and runoff of 10.90% and 8.28% per decade, respectively. Streams that supported higher native species diversity were associated with moderate discharge and baseflow index, short duration of low flows, and negligible downward trends in flow. A significant decline in dry season flows (May–Oct.) has led to an increase in the number of no-flow days in drier areas, indicating that more streams may become intermittent, which has important implications for mauka to makai

(mountain to ocean) hydrological connectivity, and management of Hawai‘i’s native migratory freshwater fauna.

Keywords: Streamflow trends Hawaii Running trend analysis Mann-Kendall Intermittent streams Goby

Introduction

Climate change is expected to impact the structure and functioning of tropical streams by altering hydrological, thermal, and chemical (e.g., dissolved oxygen) conditions (Strauch, MacKenzie, Bruland, & Giardina, 2015; Taniwaki, Piggott, Ferraz, & Matthaei, 2017). Stream systems are particularly important in Hawai‘i because they provide more than 50% of irrigation water to the islands (Oki, 2003), host endemic stream fauna, and influence the condition of nearshore coastal habitats. Understanding how climate change affects these resources is of economic, ecological, and cultural importance, which may also translate to the many other Pacific Islands with similar climatic and hydrological stressors that are affecting island ecology (Harter et al. 2015; Herring et al. 2016). In Hawai‘i, recent departures in temperature and rainfall from long-term averages are expected to continue (Mora et al., 2013). Mean surface temperature in Hawai‘i has increased 0.163°C decade^{-1} from 1975-2006, with expected increases in potential evapotranspiration (Giambelluca, Diaz, & Luke, 2008). Recent studies show a decline in total rainfall affecting groundwater recharge and the groundwater contribution to surface flow in many regions of Hawai‘i (Bassiouni & Oki, 2013) as well as a decline in rainfall intensity (Chu, Chen, & Schroeder, 2010; Chen & Chu, 2014; Frazier & Giambelluca, 2017), reducing runoff to streams (Oki, 2004; Bassiouni & Oki, 2013; Leta et al., 2017). Additionally, recent increases in the frequency of trade wind inversion (TWI) days in Hawai‘i indicates more consistent rainfall on windward coasts, a decline in high elevation rainfall, an increase in the number of dry days between storms and a decrease in leeward rainfall (Cao, Giambelluca, Stevens, & Schroeder, 2007; Longman, Diaz, & Giambelluca, 2015). Consequently, the duration of low or no-flow conditions in leeward regions are likely to be affected.

Changes in climate have direct effects on streamflow, which is highly variable across the Hawaiian Islands. Differences in rainfall and topography drive runoff. Steep topography, short peak to ocean distances, and low-order stream systems combined with intense tropical rainfall events lead to flashy hydrographs with time to peak discharge on the order of hours (e.g., Sahoo, Ray, & De Carlo, 2006). Whereas, underlying geology (e.g., substrate age and composition), which varies with island age and level of erosion, influences groundwater contributions to baseflows. Vertical dike formations, i.e., low-permeability volcanic intrusions, and perched aquifers maintain high elevation groundwater that can contribute substantially to stream flows in deeply incised valleys (Lau & Mink, 2006).

Shifts in rainfall will affect both groundwater recharge and streamflow patterns in Hawaiʻi (Leta El-Kadi, & Dulai, 2018). Statistical and dynamical downscaling of global climate model outputs indicate strong dipolar rainfall patterns, with greater contrast between windward and leeward areas due to increased orographic rainfall in windward areas and reduced rainfall in leeward areas (Zhang, Wang, Hamilton, & Lauer, 2016; Lauer, Zhang, Elison Timm, Wang, & Hamilton, 2013; Elison Timm, Giambelluca, & Diaz, 2015). However, there is uncertainty in the future rainfall projections for Hawaiʻi. For instance, statistical downscaling model outputs show some windward areas with no change and others with drier conditions, principally on Oʻahu and Kauaʻi (Elison Timm et al., 2015). Freshwater in leeward regions can be limited, such that extensive ditch networks are employed to divert surface water from wet to dry areas (see Oki, Wolff, & Perreault, 2010; Cheng, 2016). Reduced rainfall in currently dry areas which already have limited freshwater resources and high municipal or agricultural demands, will likely have severe influences on stream habitats. For instance, since 1971 streamflow in Mākaha Stream on leeward Oʻahu has reduced 19–22%, and the extent of perennial flow has reduced from sea level to around 424 m, whereas before the 1990's near-continuous streamflow conditions occurred (mean 9 d yr^{-1} zero-flow) (Mair & Fares, 2010). This is attributed primarily to groundwater pumping, and secondly to declining rainfall (Mair & Fares, 2010), which together have reduced available habitat for aquatic fauna and impacted upstream-downstream hydrological connectivity. Such impacts will likely be exacerbated in the future for leeward streams and may result in streams becoming ephemeral, particularly in small catchments, with consequences for native stream biota (e.g., Levick et al., 2008; Taylor et al., 2013).

Hawaiian stream fauna includes five species of amphidromous (i.e., freshwater-marine-freshwater migratory) fishes, two species of amphidromous shrimp, and two species of amphidromous snails. Island endemism has made these species susceptible to competition, disease, parasites, and predation stresses from introduced species, particularly in streams impacted by anthropogenic disturbance in water quality, catchment-scale factors such as flow diversion, or instream structures that interrupt longitudinal connectivity (Brasher, Luton, Goodbred, & Wolff, 2006; Holitzki, MacKenzie, Wiegner, & McDermid, 2013; Gagne et al., 2015). With increasing urbanization and land cover changes across the tropics, undisturbed habitats are being lost and streams are becoming more suitable for introduced, generalist species that are able to tolerate broad environmental conditions (Brasher et al., 2006). With additional stressors from changes in climate, native species are in a precarious position.

Hence, where native species persist under future climate conditions may depend on the presence and distributions of healthy populations within climate refugia.

The response of stream hydrology to changing climate in Hawai‘i is a highly uncertain and challenging ecohydrological issue. Understanding patterns across broad rainfall gradients can help to identify trends across biomes, and can be used to develop hydrological models of future habitat availability, which can be used to better inform habitat management and conservation at landscape scales. This research examined 23 streams that were minimally impacted by anthropogenic influences, principly ditch diversion, located across five of the main Hawaiian Islands, which spatially encompassed a diverse range of climatological and geological conditions. We conducted a running trend analysis of current and historical streamflow regimes: (1) to examine the hydrographic record for evidence of changes in flow regimes; and (2) to determine regions where streams that provide refugia for native species may be more susceptible to the impacts of climate change.

Methods

Study area

The study was conducted on the five largest Hawaiian Islands (Kaua‘i, O‘ahu, and Moloka‘i Maui, and Hawai‘i), USA, located in the central Pacific Ocean between 19° and 22°N, and 155° and 160°W. Geology of the islands is dominated by volcanic basalt of varying-aged lava flows (Macdonald, Abbott, & Peterson, 1970). Mean annual temperatures range from 4 to 24°C (Giambelluca et al., 2014) and mean annual rainfall ranges from 200 to over 10,000 mm (Giambelluca et al., 2013). Many regions experience distinct rainy (November–April) and dry (May–October) seasons. Most precipitation falls as rain, however cloud water or fog can also contribute a significant input of water to precipitation in mountain forests (Scholl, Giambelluca, Gingerich, Nullet, & Loope, 2007; Giambelluca, DeLay, Nullet, Scholl, & Gingerich, 2011). Climate in Hawaiʻi is strongly influenced by the Hadley Cell atmospheric circulation pattern in the Pacific Ocean, which drives the northeasterly trade winds (Lau & Mink, 2006). Descending air from the Hadley Cell results in an atmospheric inversion layer known as the trade wind inversion, which caps cloud growth around 2,200 m and results in dry conditions at high elevations (Longman et al., 2015).

Perennial streams mostly occur on the windward sides of the higher elevation, geologically younger islands (Maui and Hawaiʻi Island) due to the exposure of these regions to persistent northeasterly winds and high orographic rainfall (> 5,000 mm yr^{-1}), while the leeward sides of islands mostly have low precipitation (< 600 mm yr^{-1}) and intermittent streams (Figure 1). Due to valley incision driving greater groundwater contributions to flow, perennial streamflow can occur on leeward slopes on lower elevation, older islands. It is important to emphasize though, that baseflows in catchments that drain young, porous lava flows (e.g., on Hawaiʻi Island) are dominated by rainfall and thus streams respond quickly to reduced rainfall in these geologic settings.

Rainfall is also driven by large-scale inter-annual patterns of climate variability, such as the El Niño-Southern Oscillation (ENSO) which sharply reduces rainfall during the El Niño phase and increases rainfall during the La Niña phase, with phases recurring every 3 to 7 years, and the Pacific Decadal Oscillation (PDO) which operates on 20 to 30-year intervals (Chu & Chen, 2005; Frazier, Elison Timm, Giambelluca, & Diaz, 2017). Negative (cool) PDO regimes dominated from 1890-1920, 1947-1976, while positive (warm) PDO regimes occurred from 1925-1946, and 1977-1998. From 1998-2014 these decadal phases became fragmented, with a sequence of negative-positive-negative phases lasting between 3-6 years, until entering a positive phase in 2014 (www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/ca-pdo.cfm, accessed 2017; www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/PDO/, accessed 2017).

Climatological and hydrological data

We examined a total of 390 stream reaches gauged by the U.S. Geological Survey (USGS) for which daily streamflow and annual peak streamflow (the largest recorded instantaneous flow event in a given year) are available from the USGS National Water Information System, to select streams with long-term (≥ 50 years) continuous (< 4 years of missing data) stream discharge records. In order to assess climate-driven changes in streamflow, the streams also needed to be minimally impacted by anthropogenic influences, principly by ditch diversion upstream of the gaging station. Based on these criteria, 30 streams were identified as unregulated by surface water diversion, and of these we selected 23 USGS stations with nearly continuous stream discharge records across the Hawaiian Islands, which encompassed 17 windward catchments and 6 leeward catchments.

To determine relative changes in storm flow and low-water flow, we separated mean daily flow into direct runoff and baseflow with the ‘lfstat’ separation procedure in R (Koffler, Gauster, & Laaha, 2016), which employs the Institute of Hydrology (1980) standard baseflow separation procedure of 5-day blocks to identify minimum flow, called a turning point. The turning points are then connected to obtain the baseflow hydrograph. The volume of baseflow for the period is estimated by the area beneath the hydrograph. Baseflow index (BFI), the ratio of baseflow volume to total volume of streamflow, was also calculated using ‘lfstat’ R package. Baseflow is the proportion of total flow which originates from stored sources, thus values of the baseflow index range from 0.15-0.2 for an impermeable catchment with a flashy flow regime, to greater than 0.95 for catchments with high storage capacity and a stable flow regime (Gustard & Tallaksen, 2009).

Climate and landscape data were obtained for each watershed from gridded data using watershed boundaries upstream of the gaging stations delineated using the “Hydrology” toolset in ArcGIS. Annual Penman-Monteith Potential Evapotranspiration and mean annual rainfall were averaged from 234 × 250 m grids of annual PET (Giambelluca et al., 2014) and daily rainfall (Longman et al., in review), respectively. Soil permeability were obtained from 30 × 30 m grids (Rea & Skinner, 2012). Similarly, average area weighted habitat degradation downstream of the gaging station, which indicates habitat quality for passage of aquatic organisms, was obtained from the Hawai‘i Fish Habitat Partnership (Crawford et al., 2016). This habitat degradation score is based on multiple measures of anthropogenic landscape and stream channel disturbances, e.g., urban and agricultural land use, surface water diversions, and fragmentation.

Trend analysis

A total of 23 study locations with unregulated streamflow andnearly continuous records were included in the trend analysis. We selected a 50-year period from 1967-2016 to represent long-term historical conditions, and a 30-year period from 1987-2016 to represent recent hydrological conditions and a time of significant global and regional warming (Giambelluca et al., 2008; IPCC 2013). Kundzewicz and Robson (2004) recommend 50 years to detect significant change in hydrological conditions, although caution must be used in a given period to identify long-term patterns of inter- or multidecadal variability (i.e., PDO) (Wilby, 2006; Hannaford, 2015).

We analyzed trends in discharge (baseflow, runoff, total flow) and flow indices with the non-parametric Sen's slope estimator (Sen 1968) and Mann-Kendall test (Mann, 1945; Kendall, 1948) for significance using the R package 'trend' (Pohlert, 2017). In contrast to linear regression, these tests are recommended for analyzing environmental time series data as they are distribution-free, are robust against outliers, and allow missing data (Hess et al., 2001). These methods have been widely used for quantifying and testing the significance of trends in hydrological data (e.g., Marengo, Tomasella, & Uvo, 1998; Burn & Hag Elnur, 2001; Bassiouni & Oki, 2013; Murphy, Harrigan, Hall, & Wilby, 2013). We computed trends for two periods: 50 years from 1967-2016; and 30 years from 1987-2016, annually and seasonally for the 'wet season' from November–April and 'dry season' from May–October. Hamed and Rao (1998) show that positive or negative autocorrelation in a time series can confound detection of significant trends. We accounted for autocorrelation using the modified Mann-Kendall test (Hamed & Rao, 1998). A comparison of original and modified Mann-Kendall tests identified the adequate performance of the original Mann-Kendall trend test, and thus the original Mann-Kendall tests are presented throughout. The $m^3 s^{-1}$ per year Sen's slopes were multiplied by 10, and divided by the 1978-2007 mean to give percent change in discharge per decade. The 1978-2007 time-period was chosen to coincide with the Rainfall Atlas of Hawai‘i 1978-2007 reference period (Giambelluca et al., 2013; Frazier & Giambelluca, 2017).

Running trend analysis

We conducted a running trend analysis from 1967-2016 to assess the dependency of the trend on the selected period of record, and the persistence of the trend through time. For each stream, first we calculated the Sen's slope and Mann-Kendall statistic for a 20-year window starting in 1967. Next, we increased the window size incrementally to the end of the series period to give window sizes ranging between 20 and 50 years. Last, we increased the starting year, and calculated the trend for window sizes up to 49 years (1968 – 2016). To visualize the results, running trend plots in the style of Brunetti et al., (2012) and Frazier and Giambelluca (2017) were used.

Stream taxa

Presence/absence of native stream taxa collected from 1992 to 2010 using standardized visual surveys were provided by the Hawai‘i Division of Aquatic Resources. Visual presence/absence of species were determined at discrete points in each stream by a stationary observer, in an area no larger than 0.91 × 0.91 m and for a duration 3-7 minutes (Higashi & Nishimoto, 2007). Data were available for 404 stream reaches across five of the main Hawaiian Islands. In some cases, a few reaches were revisited and contained fish surveys for multiple dates. Where this happened, taxa presence within a reach were based on a taxa representation in at least one sample (following Steen, Seelbach, & Schaeffer 2008). These data included 11 of our study stream sites, one of which recorded no species, and were selected from reaches (n=11) located immediately upstream of the USGS gaging station. These data include indigenous amphidromous fishes (*Lentipes concolor, Sicyopterus stimpsoni*, *Awaous stamineus*, *Stenogobius hawaiiensis*, and *Eleotris sandwicensis*), freshwater shrimp (*Atyoida bisulcata*, *Macrobrachium grandimanus*), and snails (*Neritina granosa*); and two *Kuhliidae* marine fish species (*Kuhlia sandvicensis* and *Kuhlia xenura*) that facultatively feed in streams.

Streamflow characterization and multivariate analysis

We selected a range of ecologically important hydrologic indices (n=16) that characterize natural streamflow regimes using five components of flow: magnitude, frequency, duration, timing and rate of change of streamflow from mean daily streamflow (date range: 1967-

2016), defined by Olden and Poff (2003) (Table 2). These data were compiled using the R package 'EflowStats' (Thompson & Archfield, 2015) for input into a multivariate analysis (described below). Prior to the multivariate analyses, hydrologic indices shown in Table 2 were tested for normality using Quantile-Comparison Plots, and the Shapiro-Wilk Normality Test with the R packages 'Car' (Fox & Weisberg, 2011) and 'stats' (R Core Team, 2016), respectively. Where necessary, data were log10 transformed to achieve normality. Multicollinearity among the environmental variables was tested using matrices of Pearson and Spearman correlation coefficients in the R Package 'corpcor' (Schafer et al., 2017), and correlated variables ($r > 0.5$) were removed. The above steps removed indices that were not independent of each other, and reduced the streamflow metrics from 16 to the following six variables: mean daily discharge (MA1), flood frequency (FH6), low flow duration (DL16), baseflow index (defined above), stream flashiness (MA8), and constancy (TA1) (a measure of temporal invariance) (see Table 2). Principal Components Analysis (PCA) (linear method) was then employed to assess variability in the hydrologic indices among streams and identify potential resiliance to climate change for certain flow regimes. The resulting ordination axes correspond to the directions of the greatest variability within the data set (Lepš & Šmilauer, 2003).

Results

Climate and hydrology

Precipitation and streamflow were tightly coupled, with streamflow responding rapidly to rainfall at all site locations at sub-daily intervals, which is shown in Figure 2 using Punaluʻu Stream, Oʻahu, as an example. Large, rapid streamflow events were common with heavy rainfall and occurred in any season. Mean annual stream flows ranged from 0.07-6.27 $m^3 s^{-1}$, and BFI averaged 0.36 (range: 0.12 – 0.75), indicating fairly low, though differing, groundwater contributions to discharge (Table 1). Upper elevation streams (> 1,000 m) all had low BFI, likely due to lack of incision into perched water bodies or dike impounded aquifers, and slope steepness, which affects transmission rates of rainfall to the stream network, and the proportion of rainfall that is retained in the soil (Table 1). High BFI (> 0.5) occurred on older islands, particularly in areas with known dike formations (Figure 1; Table 1). Total precipitation was on average two-fold greater than potential evapotranspiration in windward locations, whereas in some leeward areas, potential evapotranspiration exceeded total precipitation.

Annual and seasonal streamflow trends

Annual baseflows and runoff declined across the Hawaiian Islands from 1967-2016, indicating a reduction in water availability in most of the study streams (Table 3). Declines in outflows were stronger over the 30-year period from 1987-2016, where baseflows and runoff decreased on average 10.90% and 8.28% per decade, respectively. Significant ($p < 0.05$) 30-year period downward trends in baseflows and runoff occurred in 57% (13/23) and 22% (5/23) of streams, respectively (Table 3, see also Appendix 1). Baseflows and runoff declined on all islands during the wet season (November to April), although not all of these trends were statistically significant (Figure 3). Overall, streams exhibit declining trends in wet season baseflows of 11.83% per decade, and runoff of 10.35% per decade, which were significant ($p < 0.05$) in 57% and 13% of streams, respectively, consistent with annual trends (Table 3). Dry season (May to October) streamflow trends across the islands were similar to that observed during the wet season. In the dry season, baseflows declined on average 11.47% per decade, and runoff declined 10.65% per decade, which were significant ($p < 0.05$) in 48% and 26% of streams, respectively (Table 3).

Alakahi Stream, Hawai‘i Island, had the largest decline in baseflows for the state, at -38.37% (dry season) and -46.06 % (wet season) per decade ($p < 0.05$) (Figures 3a-b). Indeed, all four study streams on windward of Hawai‘i Island exhibited strong (> 10% change per decade) negative trends in baseflows, which were all significant in the dry season ($p < 0.05$), this included Wailuku River, which drains a basin of 570 km^2, ~5.5% of the island area. Significant ($p < 0.05$) percent per decade declines in baseflows also occurred in north-east (windward) Maui (W. Wailuaiki: dry season = -18.83%, wet season = -15.20%; Honokohau Stream: wet season = -10.81%), and in all but one study stream on Kaua‘i during the wet season (mean: -10.68%), and four out of seven streams during the dry season (mean: -9.20%). Declines in baseflow were not significant in the majority of streams located on O‘ahu, which had some of the lowest detectable baseflow and runoff trends of the five main Hawaiian Islands. However, a significant ($p < 0.05$) decline in baseflow occurred in Waiakeakua Stream (-14.25% and -18.07% per decade in the dry and wet season, respectively), which is located in leeward O‘ahu. Significant ($p < 0.05$) percent per decade declines in runoff were detected in the dry season in windward and leeward Kaua‘i (Wainiha River: -13.97%, and Kawaikoi Stream: -20.24%, respectively), windward Maui (Hanawï Stream: dry season = -29.00%, wet season = -17.49%; W. Wailuaiki Stream: dry season = -24.86%), and windward Kohala Mountain, North Hawai‘i Island during the wet season (Kawainui Stream: -14.42%; Alakahi Stream: -18.51%), and on windward Hawai‘i Island during the dry season (Wailuku Stream: -27.10%; Honolii Stream: -22.26%) (Figures 3c-d). Furthermore, comparisons of the 50-year and 30-year dry-season trends, which averaged -1.24% and -11.47%, respectively for baseflow, and -1.58% and -10.65%, respectively for runoff, indicate a marked (average 9 and 10%) decline in dry-season flows in recent decades (Table 3). We observed a smaller difference of 4 and 6% on average, respectively, for baseflow and runoff between the 50-year and 30-year wet-season trends.

Running trend analysis

We present running trend plots from 1967-2016 in Figure 4, for five representative gaging stations across the islands. Moreover, we have included supplementary plots for all study streams, five of which have historical data of up to 92 years in length (see Appendices 2-6). Decreases in baseflows dominate the trends and strengthen with time, and for streams on Kaua‘i, Maui and Hawai‘i were significant though time if the last decade of record is included. These negative trends were not significant throughout all stream records i.e., O‘ahu and Moloka‘i, but were detected predominately in recent decades associated with stronger downward trends (Figure 4), whereas positive trends tended to dominate the early records. Leeward streams on O‘ahu, such as Waiakeakua and Kaukonahua, showed greater number of analysis windows with significant ($p < 0.05$) negative trends than windward streams. However, limited data for leeward streams on other islands prevented an assessment of this pattern elsewhere. Similar to Wailuku Stream, other windward streams on Hawai’i Island in areas that receive lower annual rainfall, such as Alakahi and Kawainui Streams (Figure 1), exhibited significant ($p < 0.05$) declines in baseflow (~12-42%) and runoff (~13-17%) in many trend windows, and thus the trends persisted through time (Figure 4; see also Appendix 5). Halawa Stream, the only unregulated stream gage for Moloka‘i (Figure 1), exhibited significant ($p < 0.05$) declines in runoff, and a tendency to declining baseflow trends in recent decades, which were not significant (Figure 4).

Decadal cycles of alternating negative and positive trends are evident in all streams for baseflows and runoff, particularly in the longer-term trends (Appendix 6), and generally coincide with respective negative (cool) and positive (warm) cycles of the PDO (described above in methods) (Figure 4). Strong (> 10 % per decade) declining baseflows and runoff trends were experienced from the late 1970s, and encompass a 21-year positive phase of the PDO, which is known to be negatively correlated with rainfall (Chu & Chen, 2005). However, the decline in baseflows is present in many streams throughout the record, and the marked decline in flows are not constrained to the positive PDO phases alone, but continue a downward trend to present day, despite recent alternating shifts in the PDO between positive to negative. The significant ($p < 0.05$) declining trends in baseflow and runoff on windward Hawai‘i Island are unaffected by changes to the start year of analysis, and persist throughout the flow record to the 2010s.

Flow intermittence

Low-flow indicators, in particular, are dominated by decreasing trends. For the 50-yr and 30-yr periods, 50% and 92% of streams show decreasing trends in the low flow statistic Q_{90}, respectively, 29% and 38% of which are significant ($p < 0.05$) (Table 3). Three study streams experienced flow intermittence, where flow ceased for a day or more (Figure 5). No-flow days occurred frequently in Kaluanui Stream, a small watershed on windward O‘ahu, and Ōpae’ula Stream on the leeward side of the Ko‘olau Mountains, O‘ahu (Figure 5). Both streams exhibit interannual variability in flow intermittence, but no trends were observed. Alakahi Stream, a similar size stream, on the windward coast of Hawai‘i Island, has begun to exhibit no-flow days since 2014, which was unprecedented in the 50-year record, with greater than 50-days of no-flow in 2015 (Figure 5).

Peak stream flows

Annual peak streamflow is on average two orders of magnitude greater than mean annual flow (Table 1). This underlines the rapid response rate of streamflow to high precipitation events, where storm pulses may last only a few hours. Peak streamflow did not show significant trends over time on most islands, with the exception of Hawai‘i Island (Figure 6).

On this island, the magnitude of the highest storm flow has significantly decreased since 1967, on average 6-16% per decade ($p < 0.05$) among four gaged streams, with fewer large events during the last two decades. Wailuku Stream, Hawai‘i Island, which has the greatest drainage area of the study sites (570 km^2) and is located in an extremely wet part of Hawai‘i (total precipitation can reach 10,000 mm yr^{-1}), shows decreasing peak flows of 12.45% per decade (Figure 6a).

Hydrological regime and native stream organisms

PCA of the hydrological regime of study streams indicated gradients in baseflow index and flashiness, in opposite directions along the principle component Axis 1, accounted for 48% of the variation among stream sites (Figure 7). Low flow duration, and discharge, were also important environmental variables along Axis 2, which cumulatively accounted for 79% of the total variability among stream sites (Table 4). Significant declines in baseflow, which may affect habitat availability, occurred in streams of differing hydrological regimes. However, study streams on Hawai‘i Island, which drain younger, more permeable soils (Table 1) were characterized by low baseflow index (< 0.23), and a strong response to climate change (Figures 3 and 7). In addition, it is notable that streams with high baseflow (BFI > 0.5; i.e., Punalu‘u, He‘eia, and Waiakeakua on O‘ahu) appear to be more resilient to declining streamflow (Figure 7).

The native freshwater fauna were dominated by *Awaous stamineus, Atyoida bisulcata, Sicyopterus stimpsoni,* and *Lentipes concolor,* which were present in 46%, 38%, 36%, and 36%, respectively, of 404 surveyed streams (Figure 8). Similar species assemblages were found in a subset of the study streams (n=12), with *Atyoida bisulcata, Lentipes concolor and*

Awaous stamineus most often present (Table 5). These species are known to prefer fast-moving water in upper reaches (Kido, 2008), which is where the majority of the study sites are located due to requirement of more natural, unregulated streams for the climate assessment. Across the islands, native species richness followed the pattern: Molokaʻi > Kauaʻi > Maui and Hawaiʻi Island > Oʻahu. Very few stream reaches (*n*=3) were sampled on Molokaʻi, however high native species presence on this island is consistent with other studies (e.g., Kudo, 2013).

Kaluanui and Punaluʻu streams, on windward Oʻahu, and Wainiha stream, which drains a basin along the Nā Pali Coast of Kauaʻi, had notably higher presence of native species (3-5 species; Table 5). These streams exhibit “very low” habitat degradation along the river corridor (Crawford et al., 2016; Table 1). Punaluʻu and Wainiha streams are characterized by high baseflow index (≥0.5), whereas Kaluanui stream has a very different hydrological regime, with a low baseflow index of 0.17, indicative of a very flashy hydrograph (Table 1; the site aligns with high flood frequency and flashiness in Figure 7). The similarity in community composition of these sites reflects the adaptability of native Hawaiian fish to variable hydrological conditions. Small streams with similar hydrology, such as Kalihi and ʻŌpaeʻula, Oʻahu, and Honopou, Maui (Figure 7), may be susceptible to reductions in flow, further impacting habitat for native species, especially where periods of no-flow may already occur (e.g., ʻŌpaeʻula).

Discussion

Streamflow regime

Changes in the hydrological conditions of streams due to climate warming and changing atmosphere-circulation patterns are likely to be diverse and complex as catchment hydrology responds to shifts in precipitation, evapotranspiration, and altered vegetation assemblages (Safeeq & Fares, 2012; Elison Timm et al., 2015; Strauch et al., 2017a). Climate model projections predict that after 2050, most of the tropics will experience average temperatures outside of their historic range every month (Mora et al., 2013). This is of greatest concern for island species, which are adapted to narrow climate variability. However, there is uncertainty in the direction and significance of hydrological changes resulting from climate shifts in the future (e.g., Zhang et al., 2016; Elison Timm et al., 2015). This extends to the many islands across the Pacific and elsewhere that are experiencing declining precipitation, increased occurrence of extreme climatic events (i.e. droughts/floods), increased water shortages and municipal demands, and sea level rise, which threaten ecosystem functioning and structure of unique biological communities (Covich, Crowl, & Scatena, 2003; Nurse et al., 2014; Polhemus, 2017; Werner, Sharp, Galvis, Post, & Sinclair, 2017). For instance, Covich et al. 2006 report significant reductions in the abundance of *Macrobrachium spp.* in Puerto Rican streams due to reduced habitat quality during drought conditions, whereas extreme high flows associated with hurricanes and storm events had little influence on species abundance.

In the present study, we identified declines in streamflow regimes over the last 50 years (1967-2017) with significant trends toward lower flow conditions over the past three decades. The running trend analysis highlighted that many of the significant trends did not persist through time, but were only significant if the last few decades of record were included in the analysis. Our findings are supported by similar patterns in rainfall trends, which have significantly declined across the Hawaiian Islands from 1920 to 2012 (Frazier & Giambelluca, 2017).

Our running trend analysis also highlighted the decadal variability in baseflow and runoff, which both closely tracked short-term 20-30 year fluctuations between drying and wetting rainfall trends. These were attributed to the approximate recurrence of alternating positive – negative PDO phases (Figure 4; Appendix 6) (see also Diaz & Giambelluca, 2012; Frazier & Giambelluca, 2017), which highlight the difficulty of separating natural multidecadal variability from underlying consequences of climate change. Interestingly, declining trends in baseflows continued downward to present day despite the fragmented nature of the last PDO shift (from ca. 1998-2014) (www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/ca-pdo.cfm, accessed 2017). This adds support to the suggestion by Diaz and Giambelluca (2012) that the relationship between PDO and rainfall has decoupled in recent years, though further data is needed to confirm this result. There is some uncertainty about whether the declines in streamflow could be attributed to natural variability associated with PDO, which has also been described in the rainfall data (Frazier et al., 2017), and thus continued monitoring is of paramount importance in this respect. Nevertheless, our results indicate a close coupling between changes in rainfall and hydrological regime. By examining trends in moving windows, we were able to limit bias associated with the start year and length of analysis to provide a robust assessment of trends in streamflow through time. This adds to a previous times series analysis that identified significantly decreasing stream flows from 1913 to 2008 (Bassiouni & Oki, 2013).

Low flow conditions (i.e., baseflows), in particular, exhibited significant downward trends, with implications for habitat availability and the sustainability of water resources. A decline in baseflow indicates reduced groundwater recharge from rainfall and fog drip (Lau & Mink, 2006). Fog drip, or cloud water interception contributes a substantial portion of the total recharge in Hawaiʻi (Giambelluca et al., 2011). Significant and marked reductions in baseflow and runoff occurred on Hawaiʻi Island and Maui, which correlates with spatial patterns noted by Frazier and Giambelluca (2017), who showed that Hawaiʻi Island and northeastern Maui have experienced significant changes in rainfall amounts.

That said, not all streams exhibited significant trends. Baseflow trends on Oʻahu and Molokaʻi were mostly non-significant. These findings are corroborated by generally non-significant rainfall trends on Oʻahu and Molokaʻi, with the exception of some mountainous areas in the Koʻolau Range on Oʻahu (Frazier & Giambelluca, 2017). While other studies have reported downward trends in extreme rainfall events for Oʻahu (classified as rainfall > 25.4 mm day^{-1}; Chu et al., 2010; Chen & Chu, 2014), these analyses were restricted to leeward areas of the island. The dampened baseflow trends on Oʻahu and Molokaʻi may also, in part, be the result of differences in soil substrate characteristics that influence catchment-wide recharge. These islands have more developed soil substrates, lower soil permeability (Table 1), and exposed dike complex formations (Figure 1) compared to younger Hawaiian Islands, which is likely to increase the residence time of water in soils, increase infiltration and recharge to groundwater aquifers that supply streamflow, and therefore delay the response to decreased precipitation.

Conversely, younger islands such as Hawaiʻi and Maui, are more likely to exhibit a rapid response in streamflow to changing rainfall due to young volcanic substrates that are characterized by high permeability and shallow groundwater. We also note that two of the streams on Hawai‘i Island exhibiting some of the strongest declines in streamflow (i.e., Alakahi and Kawainui) were located at high elevation (>1000 m) above the valley incision, whereas most other gages from our study sites are at the base of gulches where substantial groundwater (dike or perched) can contribute to baseflow. The results of this study show that watersheds on Maui and Hawai‘i Island are exhibiting a particular vulnerability to drying conditions. The 30-year decreasing trends in dry season (May–October) baseflow and runoff were more severe than the 50-year trends (1967-2016), and if these strong declines continue into the future, this may reduce water availability during periods of lower rainfall, exacerbating hydrological drought, and affecting the provision of ecosystem services. Episodes of severe to extreme drought, which are closely linked to El Niño events (Giambelluca, 1991; Chu, Yan, & Fujioka, 2002), periodically occur across large areas (up to 55%) of the state, particularly in leeward areas of Hawai‘i Island, and have worsened in the recent past, lasting for multiple years (http://droughtmonitor.unl.edu/; accessed 12/14/2017). Given the reported dominance of drought in Hawai‘i and the reduced baseflows during the dry season presented herein, declining groundwater recharge may result in enhanced seasonality of lower flow conditions. In the current study, we observed an increase in the number of no-flow days that is consistent with the increase in the number of consecutive dry days between storms, particularly since the 1980’s (Chu et al., 2010; Kruk et al., 2015). A possible driver is an abrupt positive shift in the trade wind inversion frequency of occurrence around 1990, which has led to drier conditions in high elevations (Longman et al., 2015), with ecological responses in endemic vegetation (e.g., Krushelnycky et al., 2016). Observed shifts in forest species composition from native dominated to non-native dominated species is also likely to alter watershed hydrology, increasing canopy evaporation and runoff while decreasing groundwater recharge (Strauch et al., 2017a).

Native stream taxa and interacting stressors

Changing patterns of streamflow observed in this study, such as declining baseflow and recharge, decreasing magnitude of storm flows, and increasing flow intermittence, will likely have multifaceted ramifications for stream organisms. We found that differences in baseflow index and stream flashiness were dominant hydrological variables separating the streams (Figure 7). Baseflow index indicates groundwater contributions to streamflow, important for sustaining habitats during interstorm periods. Stream flashiness and flood pulses have important controls on the ecological functioning and productivity of streams, e.g., by influencing channel formation and heterogeneity, downstream transport of sediments and nutrients, and flushing of coarse woody debris from river channels (Junk, Bayley, & Sparks, 1989; Larned 2000; Tockner & Stanford, 2002). In addition, flood pulses may induce ecological responses, as they lead to freshets in stream mouths and estuaries that may be an important signal for juvenile native fish to transition from the ocean and into streams (Nishimoto & Kuamo‘o, 1997; Radtke et al., 2001; Murphy & Cowan, 2007). Declines in peak flows were significant in streams on Hawai‘i Island (see Figure 6), if these trends continue into the future, particularly in small watersheds, they may lead to hydrological changes that impact native fish recruitment and migration behavior.

PCA indicated that streams of differing hydrological regimes show declining flow, indicating that climate-driven declines in streamflow are likely to affect a diversity of stream environments across Hawai‘i. Interestingly, Kaluanui Stream, O‘ahu, one of the smallest in this study (2.85 km^2), with low mean annual flow of 0.13 $m^3 s^{-1}$ (Table 1), supported the most native species (in terms of species presence/absence) (Table 5), but exhibited a small number of no-flow days, typically less than 10 consecutive days yr^{-1} (maximum 25 days yr^{-1}), which occurred irregularly in dry and wet seasons (Figure 5). Seemingly, a short period of flow intermittence is sustainable for native freshwater species without substantially impacting migration, with this stream providing sanctuary for a diverse community of native species. Streamflow on windward O‘ahu is driven by orographic rainfall. However, declines in baseflow are correlated with increases in stream temperature (Strauch, MacKenzie, & Tingley 2017b), which may affect the suitability of certain habitats to support native fauna. That said, there appears to be limited groundwater supply to support baseflows in Kaluanui Stream (BFI = 0.15), which could present a vulnerability in the future should rainfall decline in the dry season, though predictions for the mid-late 21st century point to an increase in windward rainfall (Zhang et al., 2016; Elison Timm et al., 2015). Of particular concern are streams in drier areas that, conversely, are expected to get drier under future climate conditions (Zhang et al., 2016; Elison Timm et al., 2015).

The effects of climate change on native stream species are likely to be compounded by other threats to habitat quality such as water abstraction and diversion that impede movement, pollution, land use change, and competition from more generalist invasive species (Brasher, 2003; Gingerich & Wolff, 2005; McIntosh, Schmitz, Benbow & Burky, 2008; Craig et al., 2017). Streamwater diversion and abstraction is of particular concern in Hawai‘i. For example, comparisons of diverted streams on east Maui show reductions in habitat availability to as low as 27% of natural conditions (Gingerich & Wolff, 2005). Other studies report the consequences of baseflow removal of all or nearly all baseflows and thus on available habitat for native stream biota (e.g., Mair & Fares, 2010; Oki et al., 2010).

Surface water diversions in streams on Molokaʻi corresponded to lower abundances of native fishes, and greater species overlap in assemblages along the reaches attributed to disruptions to downstream dispersal and upstream migration (Brasher, 1997). In addition, Mair & Fares (2010) report that Mākaha Stream, located on leeward Oʻahu, no longer flows perennially to the ocean, with long durations of no-flow (> 4 months) during dry weather, attributed to high groundwater pumping rates in Mākaha Valley. Consequently, no native species are present (Parham et al. 2008), presumably due to poor habitat availability through higher water temperatures in remaining pools, habitat fragmentation, and disruption of connectivity along the river corridor to the ocean. This is detrimental to migratory native aquatic fauna, which require adequate flow conditions for dispersal to the ocean and recruitment to streams as juveniles (Radtke, Kinzie, & Shafer, 1998; Brasher, 2003). Groundwater abstraction and water diversion have fundamental impacts on the functioning of Hawaiian streams that can far exceed the percent declines observed in this study (e.g., Gingerich & Wolff, 2005; Mair & Fares, 2010; Oki et al., 2010). Thus, if we are to effectively buffer systems against the impacts of climate change, streamflow protection and restoration efforts that return flows to diverted streams and improve habitat quality, will become increasingly important for the persistence of key native species.

Conclusions

We have described the long term changes in streamflow using running trend analysis, and evaluated native species richness and differences in the natural flow regime among stream sites across five of the main Hawaiian Islands. Running trend analysis has enabled assessments of the potential impacts of climate on streamflow regime and the possible consequences on freshwater habitats across Hawaiʻi and has highlighted dominant trend directions linked with the starting point and length of analysis. Although periodicities associated with the PDO could explain the observed temporal variability of streamflow, the significant decline in baseflows and increase in no-flow days in streams located in drier areas are cause for concern. Impacts of reduced flows on habitat quality pose added stresses to native species that are already threatened by urbanization, pollutants, changes in land use, and invasive species. Notably, streams with high baseflow on O‘ahu were more resistant to declining streamflow, which in pristine streams could provide refuge for native species. Streams on Maui and Hawaii Island had higher native species richness, but also exhibited more vulnerability to climate change. The findings in this study indicate the importance of returning natural flows to streams, particularly where water abstraction and diversion have significantly reduced flows, so that we may plan now for future changes in the hydrological regime of streams.

References

Bassiouni, M., & Oki, D. S. (2013). Trends and shifts in streamflow in Hawai‘i, 1913-2008. *Hydrological Processes*, *27*(10): 1484-1500.

Brasher, A. M. 1997. Habitat Use by Fish (Oopu), Snails (Hihiwai), Shrimp (Opae) and Prawns in Two Streams on the Island of Moloka'i. Honolulu: Cooperative National Park Resources Studies Unit.Technical Report. 116.

Brasher, A. M. (2003). Impacts of human disturbances on biotic communities in Hawaiian streams. *AIBS Bulletin*, *53*(11), 1052-1060.

Brasher, A. M., Luton, C. D., Goodbred, S. L., & Wolff, R. H. (2006). Invasion patterns along elevation and urbanization gradients in Hawaiian streams. *Transactions of the American Fisheries Society*, *135*(4), 1109-1129.

Brunetti, M., Caloiero, T., Coscarelli, R., Gullà, G., Nanni, T., & Simolo. C. (2012). Precipitation variability and change in the Calabria region (Italy) from a high resolution daily dataset. *International Journal of Climatology, 32*, 57–73.

Burn, D. H., & Hag Elnur, M. (2002). Detection of hydrologic trends and variability. *Journal of Hydrology, 55*, 107-122.

Cao, G., Giambelluca, T. W., Stevens, D. E., & Schroeder. T. A. (2007). Inversion variability in the Hawaiian trade wind regime. *Journal of Climate*, *20*, 1145-60.

Chen, Y. R., & Chu., P. S. (2014). Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate. *International Journal of Climatology, 34*, 3913-3925.

Cheng, C. L. (2016). Low-flow characteristics for streams on the Islands of Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i, State of Hawai‘i. *U.S. Geological Survey Scientific Investigations Report 2016-5103*, 36 p., http://dx.doi.org/10.3133/sir20165103.

Chu, P. S., Yan, W., & Fujioka. F. (2002). Fire-climate relationships and long-lead seasonal wildfire prediction for Hawaii. *International Journal of Wildland Fire*, *11*(1), 25-31.

Chu, P. S., & Chen., H. (2005). Interannual and interdecadal rainfall variations in the Hawaiian Islands. *Journal of Applied Meteorology and Climatology, 18*, 4796-4813.

Chu, P. S., Chen, Y. R., & Schroeder, T. A. (2010). Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate, 23*(18), 4881-900.

Covich, A. P., Crowl, T. A. & Scatena, F. N. (2003). Effects of extreme low flows on freshwater shrimps in a perennial tropical stream. *Freshwater Biology*, *48*(7), 1199-1206.

Covich, A. P., Crowl, T. A. & Heartsill-Scalley, T., 2006. Effects of drought and hurricane disturbances on headwater distributions of palaemonid river shrimp (Macrobrachium spp.) in the Luquillo Mountains, Puerto Rico. *Journal of the North American Benthological Society*, *25*(1), 99-107.

Craig, L. S., Olden, J. D., Arthington, A. H., Entrekin, S., Hawkins, C. P., Kelly, J. J., . . . Wooten, M. S. (2017). Meeting the challenge of interacting threats in freshwater ecosystems: A call to scientists and managers. *Elementa Science of the Anthropocene, 5*.

Crawford, S., Whelan, G., Infante, D. M., Blackhart, K., Daniel, W. M., Fuller P. L., . . . Ruhl, P. (2016). Through a Fish's Eye: The Status of Fish Habitats in the United States 2015. National Fish Habitat Partnership. http://assessment.fishhabitat.org/.

Diaz, H. F., & Giambelluca, T. W. (2012). Changes in atmospheric circulation patterns associated with high and low rainfall regimes in the Hawaiian Islands region on multiple time scales. *Global and Planetary Change, 98,* 97-108.

Elison Timm, O. E., Giambelluca, T. W. & Diaz, H. F. (2015). Statistical downscaling of rainfall changes in Hawai‘i based on the CMIP5 global model projections. *Journal of Geophysical Research Atmospheres*, *120*(1), 92-112.

Fox, J., & Weisberg, S. (2011). An {R} Companion to Applied Regression, Second Edition. Thousand Oaks CA: Sage. http://socserv.socsci.mcmaster.ca/jfox/Books/Companion.

Frazier, A. G., & Giambelluca, T. W. (2017). Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. *International Journal of Climatology, 37*(5), 2522-2531.

Frazier, A. G., Elison Timm, O., Giambelluca, T. W., & Diaz, H. F. (2017). The influence of ENSO, PDO and PNA on secular rainfall variations in Hawai‘i. *Climate Dynamics,* 1-14.

Gagne, R. B., Hogan, J. D., Pracheil, B. M., McIntyre, P. B., Hain, E. F., Gilliam J. F., and Blum, M. J. (2015). Spread of an introduced parasite across the Hawaiian archipelago independent of its introduced host. *Freshwater Biology, 60*(2), 311-322.

Giambelluca, T. W. (1991). *Drought in Hawai'i*. Hawaii Department of Land and Natural Resources, Commission on Water Resource Management.

Giambelluca, T. W., Diaz, H. F., & Luke., M. S. A. (2008). Secular temperature changes in Hawaiʻi. *Geophysical Research Letters*, 35, L12702, doi:10.1029/2008gl034377.

Giambelluca, T. W., DeLay, J. K., Nullet, M. A., Scholl, M. A., & Gingerich, S. B. (2011). Canopy water balance of windward and leeward Hawaiian cloud forests on Haleakalā, Maui, Hawai'i. *Hydrological Processes, 2*5, 438-447.

Giambelluca, T. W., Chen, Q., Frazier, A. G. J., Price, P., Chen, Y-L., Chu, P-S., . . . Delparte, D. M. (2013). Online Rainfall Atlas of Hawaiʻi. Bulletin of the American Meteorological Society, 94, 313-316.

Giambelluca, T. W., Shuai, X., Barnes, M. L. Alliss, R. J., Longman, R. J., Miura, T., . . . Businger, A. D. (2014). *Evapotranspiration of Hawaiʻi*. Final report submitted to the U.S. Army Corps of Engineers—Honolulu District, and the Commission on Water Resource Management, State of Hawaiʻi.

Gingerich, S. B., & Wolff, R. H. (2005). Effects of surface-water diversions on habitat availability for native macrofauna, northeast Maui, Hawaii: U.S. Geological Survey *Scientific Investigations Report 2005-5213*, 93.

Gustard, A., & Tallaksen, L. (2009). Low-flow indices, p.43-49. In A. Gustard, & S. Demuth [Eds], *Manual on Low-flow – Estimation and Prediction* – World Metrological Organization. No 1029.

Hamed, K. H., & Rao., A. R. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology, 204,* 182-196.

Hannaford, J. (2015). Climate-driven changes in UK river flows: A review of the evidence. *Progress in Physical Geography, 39*(1), 29-48.

Harter, D. E. V., Irl, S. D. H., Seo, B., Steinbauer, M. J., Gillespie, R., Triantis, K. A., Fernández-Palacios, J-M., & Beierkuhnlein, C. (2015). Impacts of global climate change on the floras of oceanic islands–Projections, implications and current knowledge. *Perspectives in Plant Ecology, Evolution and Systematics*, 17(2), 160-183.

Herring, S. C., Christidis, N., Hoell, A., Kossin, J. P., Schreck III, C. J. & Stott, P. A. (2018). Explaining Extreme Events of 2016 from a Climate Perspective. *Bulletin of the American Meteorological Society*, 99(1), S1–S157.

Hess, A., Iyer, H., & Malm, W. (2001). Linear trend analysis: a comparison of methods. *Atmospheric Environment, 35*, 5211-5222.

Higashi, G. R., & Nishimoto, R. T. (2007). The point quadrat method: a rapid assessment of Hawaiian streams. *Bishop Museum Bulletin in Cultural and Environmental Studies*, *3*, 305-313.

Holitzki, T. M., MacKenzie, R. A., Wiegner, T. N., & McDermid, K. J. (2013). Differences in ecological structure, function, and native species abundance between native and invaded Hawaiian streams. *Ecological Applications*, *23*(6), 1367-1383.

IPCC. (2013). *Working Group I Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis*. United Nations Environmental Program, Geneva.

Junk, W. J., Bayley, P. B., & Sparks, R. E. (1989). The flood pulse concept in river-floodplain systems. *Canadian Journal of Fisheries and Aquatic Sciences*, *106*, 110-127.

Kendall, M. G. (1948). *Rank Correlation Methods*. Griffin: London.

Kido, M. H. (2008). A persistent species assemblage structure along a Hawaiian stream from catchment-to-sea. *Environmental Biology of Fishes, 82*, 223-235.

Kinzie, R. A. (1988). Habitat utilization by Hawaiian stream fishes with reference to community structure in oceanic island streams. *Environmental Biology of Fishes, 22,* 179-192.

Koffler, D., Gauster, T., & Laaha, G. (2016). Calculation of Low Flow Statistics for Daily Stream Flow Data. R Package ‘lfstat’ version 0.9.4 [online]. Available from: https://cran.r-project.org/web/packages/lfstat/lfstat.pdf

Kruk, M. C., Lorrey, A. M., Griffiths, G. M., Lander, M., Gibney, E. J., Diamond, H. J., & Marra, J. J. (2015). On the state of the knowledge of rainfall extremes in the western and northern Pacific basin. *International Journal of Climatology, 35*(3), 321-336.

Krushelnycky, P. D., Loope, L. L., Giambelluca, T. W., Starr, F., Starr, K., Drake, D., . . . Robichaux R. H. (2013). Climate-associated population declines reverse recovery and threaten future of an iconic high-elevation plant. *Global Change Biology*, *19,* 911-922.

Kundzewicz, Z. W., & Robson, A. J. (2004). Change detection in hydrological records—a review of the methodology/revue méthodologique de la détection de changements dans les chroniques hydrologiques. *Hydrological Sciences Journal*, *49*(1), 7-19.

Larned, S. (2000) Dynamics of coarse riparian detritus in a Hawaiian stream ecosystem: A comparison of drought and post-drought conditions. *Journal of the North American Benthological Society*, *19*(2), 215-234.

Lau, L. S., & Mink, J. F. (2006). *Hydrology of the Hawaiian Islands*. University of Hawaii Press.

Lauer, A., Zhang, C., Elison Timm, O., Wang, Y., & Hamilton, K. (2013). Downscaling of climate change in the Hawaii region using CMIP5 results: on the choice of the forcing fields. *Journal of Applied Meteorology and Climatology. 26,* 10006-10030.Lepš, J., &

Šmilauer. P. (2003). *Multivariate Analysis of Ecological Data using CANOCO.* Cambridge: Cambridge University Press.

Leta, O. T., El-Kadi, A. I., & Dulai. H. (2017). Implications of Climate Change on Water Budgets and Reservoir Water Harvesting of Nuuanu Area Watersheds, Oahu, Hawaii. *Journal of Water Resources Planning and Management, 143*(11), 05017013.

Leta, O. T., El-Kadi, A. I., & Dulai, H. (2018). Impact of Climate Change on Daily Streamflow and Its Extreme Values in Pacific Island Watersheds. *Sustainability*, *10*(6), 1-22.

Levick, L., Fonseca, J., Goodrich, D., Hernandez, M., Semmens, D., & Stromberg, J. (2008). *The Ecological and Hydrological Significance of Ephemeral and Intermittent Streams in the Arid and Semi-arid American Southwest*. U.S. Environmental Protection Agency and USDA/ARS Southwest Watershed Research Center, EPA/600/R-08/134, ARS/233046, 116 pp.

Longman, R. J., Diaz, H. F., & Giambelluca, T. W. (2015). Sustained increases in lower tropospheric subsidence over the central tropical North Pacific drives a decline in high elevation rainfall in Hawai‘i. *Journal of Climate, 28,* 8743-59.

Longman, R. J., Frazier, A. G., Newman, A. J., Giambelluca T. W., Schanzebach, D., Kagawa-Viviani A.,…& Clark, M. P. (in review). High-resolution gridded daily rainfall and temperature for the Hawaiian Islands (1990-2014). Journal of Hydrometeorology

Macdonald, G. A., Abbott, A. T., & Peterson, F. L. (1970). *Volcanoes in the Sea – The Geology of Hawaii (2nd Ed.).* University of Hawaii Press.

Mair, A., & Fares, A. (2010). Influence of groundwater pumping and rainfall spatio-temporal variation on streamflow. *Journal of Hydrology, 393(3),* 287-308.

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica. 13*, 245-259.

Marengo, J. A., Tomasella, J., & Uvo, C. R. (1998). Trends in streamflow and rainfall in tropical South America: Amazonia, eastern Brazil, and northwestern Peru. *Journal of Geophysical Research, 103*(D2), 1775-1783.

McIntosh, M. D., Schmitz, J. A., Benbow, M. E., & Burky, A. J. (2008). Structural and functional changes of tropical riffle macroinvertebrate communities associated with stream flow withdrawal. *River Research and Applications,* 24(8), 1045-1055.

Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., . . . Giambelluca, T. W. (2013). The projected timing of climate departure from recent variability. *Nature, 502,* 183-187.

Murphy, C. A., & Cowan, J. H. (2007). Production, marine larval retention or dispersal, and recruitment of amphidromous Hawaiian gobioids: issues and implications, p. 63-74. In N. L. Evenhuis, & J. M. Fitzsimons [Eds.], Biology of Hawaiian streams and estuaries. *Bishop Museum Bulletin in Cultural and Environmental Studies.*

Murphy, C., Harrigan, S., Hall, J., & Wilby, R. L. (2013). Climate-driven trends in mean and high flows from a network of reference stations in Ireland. *Hydrological Sciences Journal, 58*(4), 755-772.

Nishimoto, R. T., & Kuamoʻo, D. G. K. (1997). Recruitment of goby postlarvae into Hakalau Stream, Hawaiʻi Island. *Micronesica, 30*, 41-49.

Nurse, L.A., McLean R.F., Agard, J. Briguglio, L.P. Duvat-Magnan, V. Pelesikoti, N. Tompkins, E. & Webb, A. 2014. Small islands. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N.

Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1613-1654.

Oki, D. S. (2003). *Surface water in Hawaii*. U.S. Geoglogical Survey Fact Sheet 045-03, 6 p. Honolulu, Hawaii.

Oki, D. S. (2004). *Trends in streamflow characteristics at long-term gaging stations, Hawaii.* U.S. Geological Survey Scientific Investigations Report 2004–5080, 120 p. Honolulu, Hawaii.

Oki, D. S., Wolff, R. H., & Perreault, J. A. (2010). *Effects of Surface-Water Diversion on Streamflow, Recharge, Physical Habitat, and Temperature, Nā Wai ʻEhā, Maui, Hawaiʻi*. U.S. Geological Survey Scientific Investigations Report 2010-5011, 154.

Parham, J. E., Higashi, G. R., Lapp, E. K., Kuamo'o, D. G. K., Nishimoto, R. T., Hau, S., Fitzsimons, J. M., Polhemus, D. A. & Devick, W. S. (2008). Atlas of Hawaiian watersheds & their aquatic resources. *Bishop Museum & Division of Aquatic Resources, Island of Maui, 866*.

Pohlert, T. (2017). trend: Non-Parametric Trend Tests and Change-Point Detection. R package version 1.0.0. https://CRAN.R-project.org/package=trend.

Polhemus, Dan. A. 2017. Drought in the U.S.- Affiliated Pacific Islands: A Multi-level Assessment. https://doi.org/10.21429/C9ZS74.

R Core Team. (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org/.

Radtke, R. L., Kinzie III, R. A., & Shafer, D.J. (2001). Temporal and spatial variation in length of larval life and size at settlement of the Hawaiian amphidromous goby *Lentipes concolor*. *Journal of Fish Biology, 59,* 928-938.

Rea, A., & Skinner, K. D. (2012). Statewide datasets for Hawaii StreamStats. https://water.usgs.gov/lookup/getspatial?ds680_statewidelayers_.Reston, VA.

Safeeq, M., & Fares, A. (2012). Hydrologic response of a Hawaiian watershed to future climate change scenarios. *Hydrological Processes, 26*(18), 2745-2764.

Sahoo, G. B., Ray, C., & De Carlo, E. H. (2006). Use of neural network to predict flash flood and attendant water qualities of a mountainous stream on Oahu, Hawaii. *Journal of Hydrology, 327*(3), 525-538.

Schafer, J., Opgen-Rhein, R., Zuber, V., Ahdesmaki, M., Silva, A. P. D., & Strimmer, K. (2017). corpcor: Efficient Estimation of Covariance and (Partial) Correlation. R package version 1.6.9. https://CRAN.R-project.org/package=corpcor.

Scholl, M. A., Giambelluca, T. W., Gingerich, S. B., Nullet, M. A., & Loope, L. L. (2007). Cloud water in windward and leeward mountain forests: The stable isotope signature of orographic cloud water. *Water Resources Research, 43*(12).

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall’s Tau. *Journal of the American Statistical Association, 63,* 1379-1989.

Singh, K. P. (1968). Some factors affecting baseflow. *Water Resources Research, 4*(5), 985-999.

Steen, P. J., Zorn, T. G. Seelbach P. W. & Schaeffer, J. S. (2008). Classification tree models for predicting distributions of Michigan stream fish from landscape variables. *Transactions of the American Fisheries Society*, 137: 976-996.

Strauch, A. M., MacKenzie, R. A., Bruland, G. L., & Giardina, C. P. (2015). Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system. *Journal of Hydrology, 523*, 160-169.

Strauch, A. M., Giardina, C. P., Giambelluca, T., Bruland, G. L., Heider, C., Salmonin, E., & MacKenzie, R. A. (2017a). Modeled effects of climate change and plant invasion on watershed function across a steep tropical rainfall gradient. *Ecosystems, 30*(3), 583-600.

Strauch, A. M., MacKenzie, R. A., & Tingley III, R. W. (2017b) Base flow-driven shifts in tropical stream temperature regimes across a mean annual rainfall gradient. *Hydrological Processes, 31*(9), 1678-1689.

Taniwaki, R. H., Piggott, J. J, Ferraz, S. F. B., & Matthaei, C. D. (2017). Climate change and multiple stressors in small tropical streams. *Hydrobiologia, 793*(1), 41-53.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., . . . Treidel, H. (2013). Ground water and climate change. *Nature Climate Change, 3,* 322-329.

Thompson, J., & Archfield, S. (2015). The EflowStats R package [online]. Available from: https://github.com/USGS-R/EflowStats.

Tockner, K., & Stanford, J. A. (2002). Riverine flood plains: present state and future trends. *Environmental Conservation, 29*(3), 308-330.

Werner, A. D., Sharp, H. K., Galvis, S. C., Post, V. E. & Sinclair, P. (2017). Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs. *Journal of Hydrology, 551,* 819-844.

Wilby, R. L. (2006). When and where might climate change be detectable in UK river flows? *Geophysical Research Letters, 33*(19), doi: 10.1029/2006GL027552.

Zhang, C., Wang, Y., Hamilton, K., & Lauer, A. (2016). Dynamical Downscaling of the Climate for the Hawaiian Islands. Part II: Projection for the Late Twenty-First Century. *Journal of Climate, 29*(23): 8333-8354.

Tables

Table 1: Watershed characteristics: elevation at the stream gage, drainage area, and soil permeability (top 61 cm); and mean annual streamflow, instantaneous peak streamflow, baseflow index (BFI), Penman Monteith potential evapotranspiration (PET), total annual rainfall, and average area weighted habitat degradation downstream. Note that EB = east branch; NF = north fork; LB = left branch; W = west.

Stream	**USGS Gage #**	**Elevation (m)**	**Drainage area (km^2)**	**Soil per-meability (cm hr^{-1})[a]**	**Annual flow (m^3 s^{-1})[b]**	**Peak flow (m^3 s^{-1})[c]**	**BFI**	**Annual PET (mm)[d]**	**Annual rainfall (mm)[e]**	**Habitat degrad-ation[f]**
KAUA ‘I:										
Kawaiköï	16010000	1042	9.89	17.79	0.88	99.00	0.24	2,402	2,924	Low
Wai‘alae	16019000	1164	5.41	17.88	0.54	55.78	0.22	2,388	2,963	Low
EB, NF Wailua	16068000	152	16.16	8.53	1.31	107.29	0.50	2,364	2,856	Moderate
LB ‘Ōpaeka‘a	16071500	140	1.94	4.25	0.07	7.74	0.63	2,832	2,300	Moderate
Halaulani	16097500	119	3.11	8.94	0.32	43.57	0.54	2,687	2,891	Moderate
Hanalei	16103000	18	47.94	8.29	6.27	456.01	0.47	2,051	3,830	Moderate
Wainiha	16108000	293	27.07	13.31	3.57	156.39	0.45	1,821	4,230	Very Low
O‘AHU:										
NF Kaukonahua	16200000	351	3.57	10.16	0.41	50.13	0.25	2,762	4,926	Moderate
Kalihi	16229000	142	6.63	7.40	0.16	39.52	0.38	3,317	2,757	Very High
Waiakeakua	16240500	90	2.72	9.89	0.13	18.73	0.61	3,126	3,258	Very High
He‘eia	16275000	83	2.49	4.73	0.07	12.94	0.72	2,629	2,502	Moderate
Punalu‘u	16301050	65	7.20	8.90	0.68	62.66	0.75	2,406	4,342	Very Low
Kaluanui	16304200	34	2.85	9.33	0.13	24.79	0.15	2,330	3,949	Very Low
‘Ōpae‘ula	16345000	341	7.80	10.16	0.38	59.58	0.17	2,751	3,829	Moderate
MOLOKA‘I:										
Hälawa	16400000	64	12.12	10.80	0.83	73.84	0.23	2,347	2,664	Very Low
MAUI:										
Hanawï	16508000	402	8.52	20.32	0.66	72.35	0.22	1,944	5,657	Very Low
W Wailuaiki	16518000	472	9.30	15.41	0.83	116.19	0.21	1,984	4,147	Very Low
Honopou	16587000	368	1.53	13.58	0.14	28.15	0.38	3,316	3,296	Low
Honokōhau	16620000	265	10.83	10.53	1.02	74.34	0.47	1,853	4,520	Very Low
HAWAI‘I:										
Wailuku	16704000	332	569.80	25.45	6.16	589.26	0.22	1,834	2,090	High
Honoli‘i	16717000	469	31.18	32.98	3.38	293.69	0.22	1,648	5,244	High
Kawainui	16720000	1237	3.99	2.35	0.39	26.30	0.12	2,071	3,011	Low
Alakahi	16725000	1189	2.15	2.34	0.21	11.15	0.14	2,048	2,937	Low

[a]Rea and Skinner 2012; [b]USGS mean annual flow from 1987-2016; [c]USGS instantaneous peak annual flow from 1987-2016; [d]Giambelluca et al., 2014; [e]mean annual rainfall from 1987-2014: Longman et al (in review); [f]habitat degradation from Crawford et al., 2016.

Table 2: Stream flow metrics defined by Olden and Poff (2003) used in this study to assess differences in flow regime (e.g. magnitude, frequency, duration, timing, and rate of change) among study sites.

Flow metric	**Code**	**Definition**
Magnitude of flow:		
Average flow	MA1	Mean of daily flow
Stream flashiness	MA6, MA7, MA8	Ratio of 10%:90%, 20%:80%, 25:75% exceedance
Minimum annual flow	ML14	Ratio of min.to median annual flow
Baseflow index	†	Ratio of baseflow to total streamflow
High flow index	MH16	10% exceedence value / median flow
Frequency of high/low flow:		
Low flood pulse count	FL1	Mean no. of flow events < 25th percentile
Freq. of low pulse spells	FL3	Mean no. of flow events < 5th percentile
High flood pulse count	FH1	Mean no. of flow events > 75th percentile
Flood frequency	FH6	Mean no. of flow events 3x median flow
Duration of high/low flow:		
Low flow duration	DL16	Mean pulse duration for flow < 25th percentile
Number of zero-flow days	DL18	Mean annual zero-flow days
High pulse duration	DH15	Mean duration of flow >75th percentile
Timing		
Constancy of flow	TA1	(see Colwell, 1974)
Rate of Change		
Rise rate	RA1	Mean change in flow days in which change is positive

†Baseflow calculated using 'lfstat' R package.

Table 3: Trends of annual hydrological metrics for unregulated streams for 50-year (1967-2016) and 30-year (1987-2016) periods. Trend magnitude computed using Sen's Slope for linear change expressed as % per decade of the 1978-2007 reference period. The percentage of streams (leeward *n*=6; windward *n*=17; combined *n*=23) with significant trends ($p < 0.05$) are shown (in brackets). The wet season is from Nov.–Apr., and the dry season is from May–Oct.

	50-year trend in Sen's Slope (%) (1967-2016)			30-year trend in Sen's Slope (%) (1987-2016)		
	Leeward	**Windward**	**Combined**	**Leeward**	**Windward**	**Combined**
Annual baseflow	-3.64 (33)	-3.05 (29)	-3.20 (30)	-9.71 (33)	-11.32 (65)	-10.90 (57)
Annual runoff	-3.22 (17)	-2.79 (12)	-2.90 (13)	-4.77 (0)	-9.51 (29)	-8.28 (22)
Wet season baseflow	-6.59 (33)	-5.18 (35)	-5.55 (35)	-11.46 (50)	-11.96 (59)	-11.83 (57)
Wet season runoff	-6.75 (17)	-5.7 (29)	-5.95(26)	-9.21 (0)	-10.75 (18)	-10.35 (13)
Dry season baseflow	-2.09 (0)	-0.94 (29)	-1.24 (22)	-9.88 (33)	-12.03 (53)	-11.47 (48)
Dry season runoff	0.24 (0)	2.06 (12)	-1.58 (9)	-8.82 (17)	-11.29 (29)	-10.65 (26)
Instantaneous peak flow	-5.21 (0)	-0.85 (18)	-1.98 (13)	-5.45 (0)	-4.25 (18)	-4.56 (13)
High flows (Q10)	-4.02 (33)	-3.60 (24)	-3.71 (26)	-9.59 (33)	-11.28 (35)	-10.84 (35)
Low flows (Q90)	-0.77 (33)	-1.41 (24)	-1.24 (26)	-13.28 (33)	-12.35 (41)	-12.59 (39)

Table 4: Eigenvalues and cumulative percentage variance for each Principle Components Analysis (PCA) axis of streamflow variables for 23 streams.

Method: PCA				
Summary Table:	Total variation is 96.00000			
Statistic	**Axis 1**	**Axis 2**	**Axis 3**	**Axis 4**
Eigenvalues	0.48	0.30	0.1848	0.02
Explained variation (cumulative)	48.16	78.54	97.02	98.57

Table 5: Presence (X) and absence (blank) of native stream species (*Lentipes concolor*; *Awaous stamineus*; *Sicyopterus stimpsoni*; *Eleotris sandwicensis*; *Atyoida bisulcata*; *Neritina granosa*) for 11 of the study sites.

	FISHES				***CRUSTACEA***	***MOLLUSCA***	
Stream	***Lent. conc.***	***Awao. stam.***	***Sicy. stim.***	***Elect. sand.***	***Atyo. bisu.***	***Neri. gran.***	**No. sp. present**
KAUAʻI:							
Halaulani							**0**
Kawaikōï		X					**1**
EB, NF Wailua		X					**1**
Wainiha	X		X		X		**3**
OʻAHU:							
Punaluʻu	X	X			X	X	**4**
Kaluanui	X	X	X	X		X	**5**
MAUI:							
Honopou	X						**1**
W Wailuaiki					X		**1**
Honokōhau	X				X		**2**
HAWAIʻI:							
Wailuku					X		**1**
Honoliʻi	X				X		**2**
Frequency Presence %	**55**	**36**	**18**	**9**	**55**	**18**	

(Not present: *Stenogobius hawaiiensis; Kuhlia sp; Macrobrachium grandimanus).*

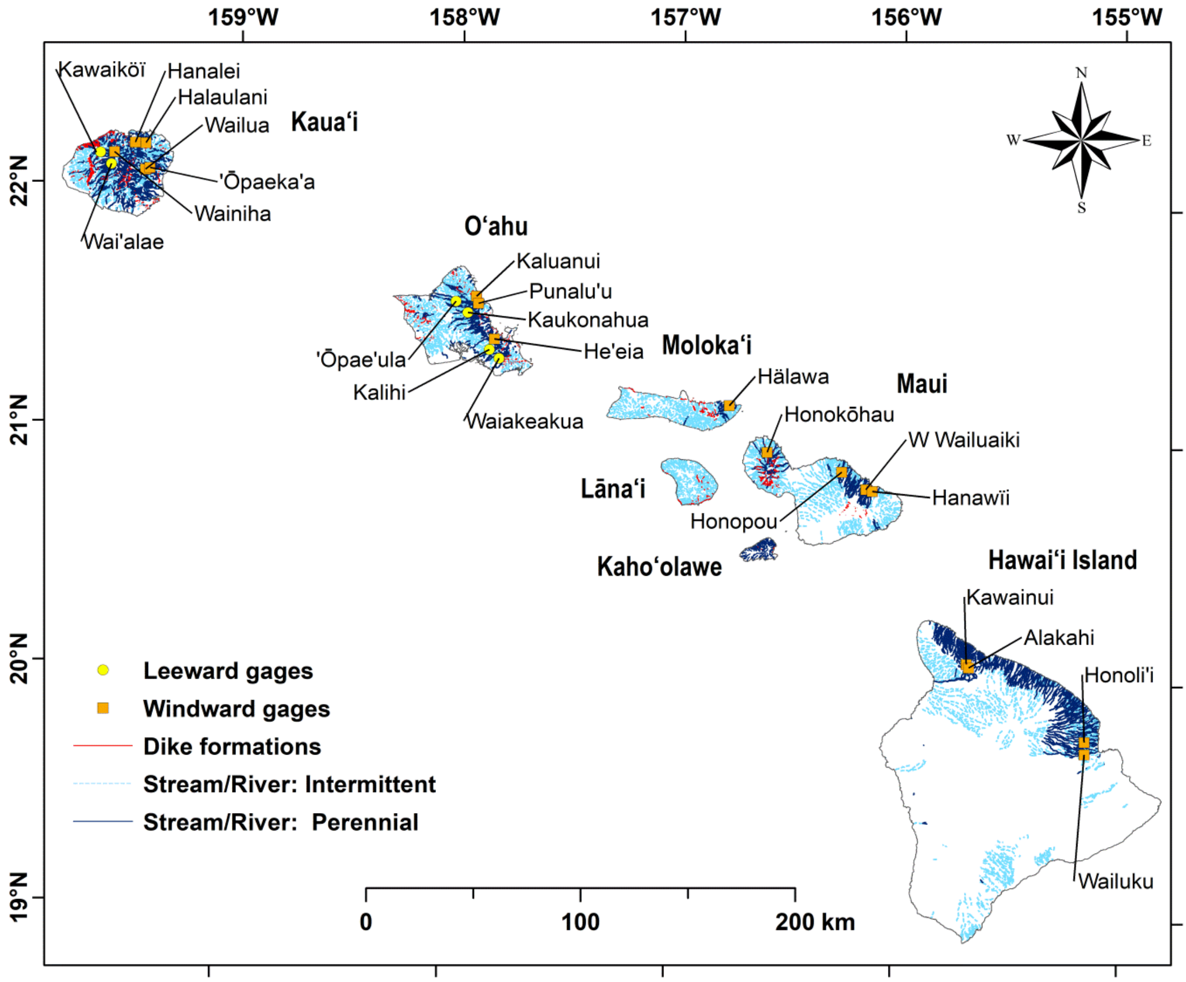


Figure 1: Location of USGS stream gages for streams with unregulated flow† and intermittent vs. perennial stream reaches (National Hydrography Dataset layer, last modified 2016-2017) across the Hawaiian Islands. USGS gage numbers provided in Table 1.

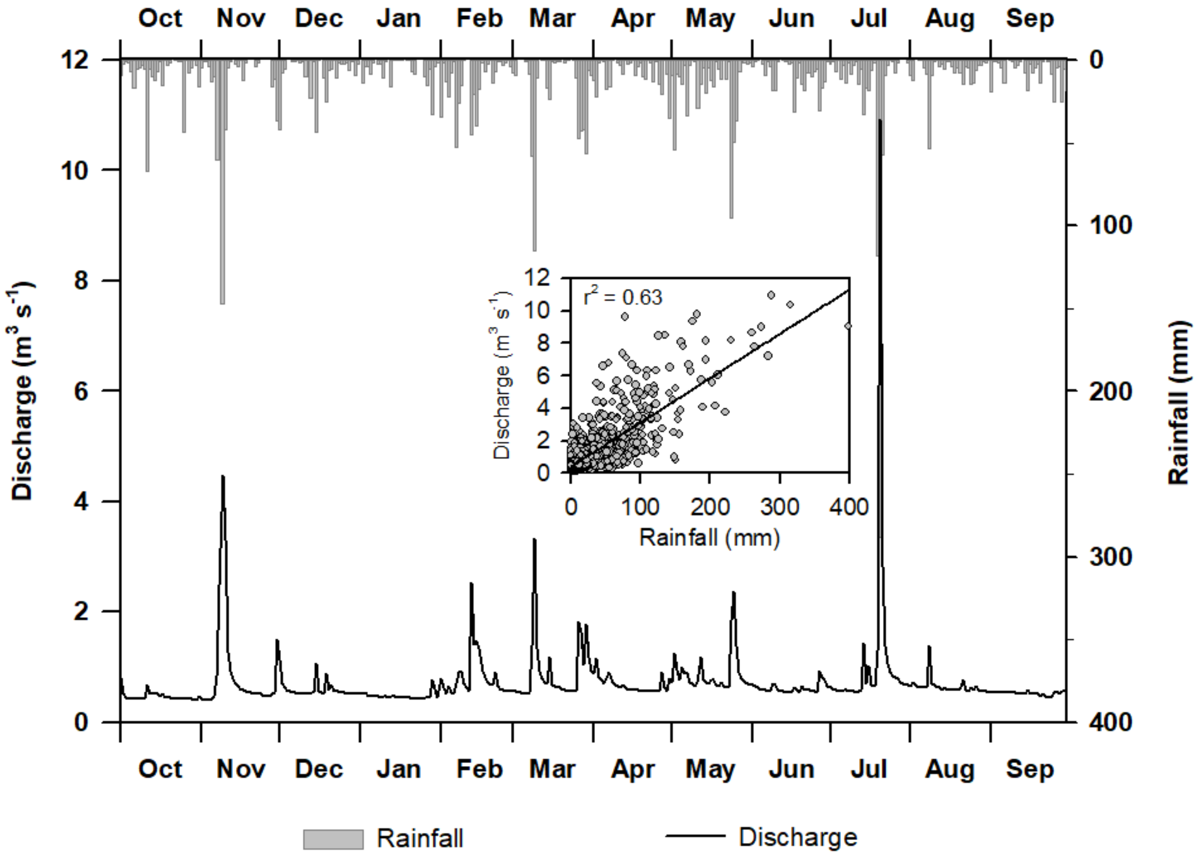


Figure 2: Time series of mean daily streamflow and total daily rainfall for Punaluʻu Stream, Oʻahu for water year 2014; inset the relationship between daily rainfall and streamflow from 1990 – 2014. Discharge data are from the USGS gaging station (#16301050). Rainfall data represent average total rainfall for Punaluʻu catchment, upstream of the gaging station (Longman et al., in review).

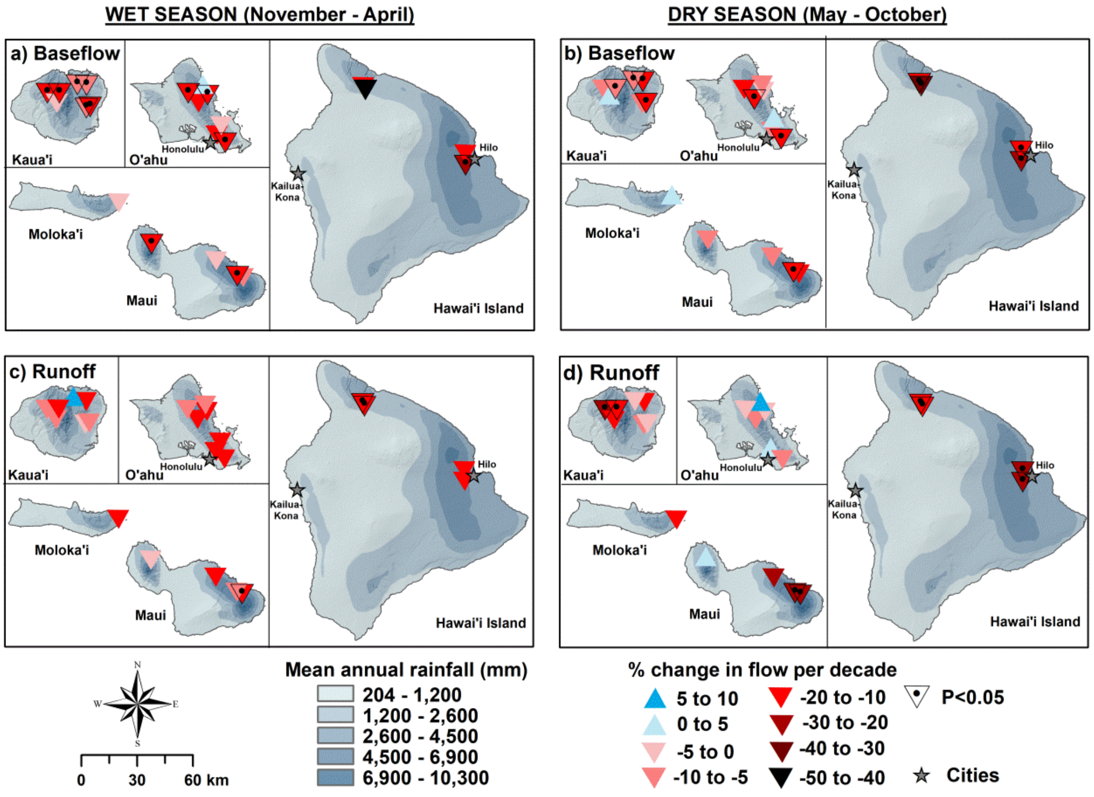


Figure 3: Mean annual baseflow trends (top panels) and runoff trends (bottom panels) from 1987-2016 for wet season (Nov.–Apr.) (left panels) and dry season (May–Oct.) (right panels), superimposed on mean annual precipitation (from Rainfall Atlas, Giambelluca et al. (2013)). Trend magnitudes computed using the Sen's estimator of trend slope expressed as a percentage of the 1978-2007 reference period. Significant trends ($p < 0.05$) are highlighted with •.

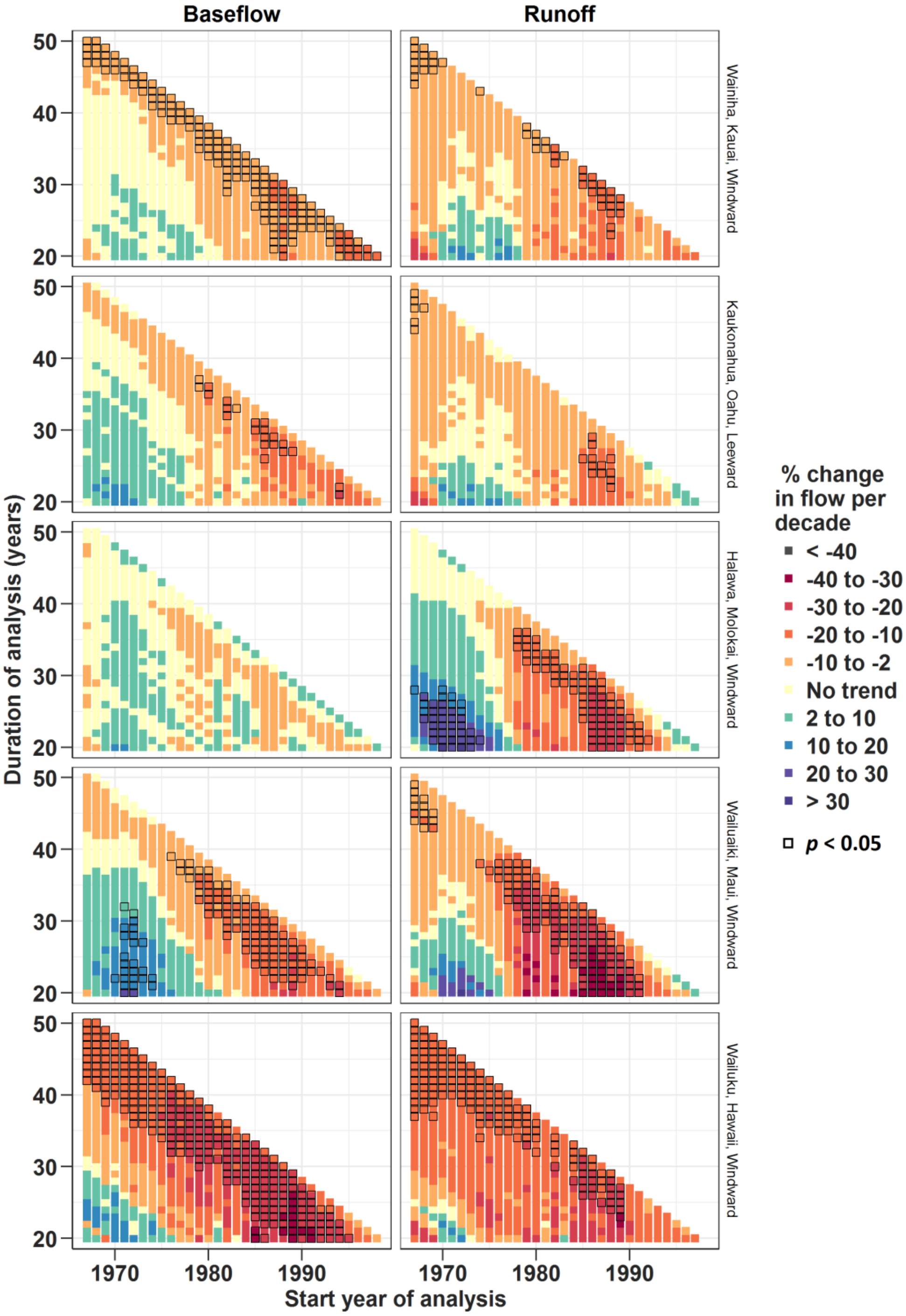


Figure 4: Running trend analysis for mean annual baseflow (left panel) and runoff (right panel) from 1967-2016 for five representative streams, on Kauaʻi, Oʻahu, Molokaʻi, Maui, and Hawaiʻi, consecutively from top to bottom panels. Trend magnitudes computed using the Sen's estimator of trend slope expressed as a percentage of the 1978-2007 reference period. The open boxes represent trends that are significant at $p < 0.05$.

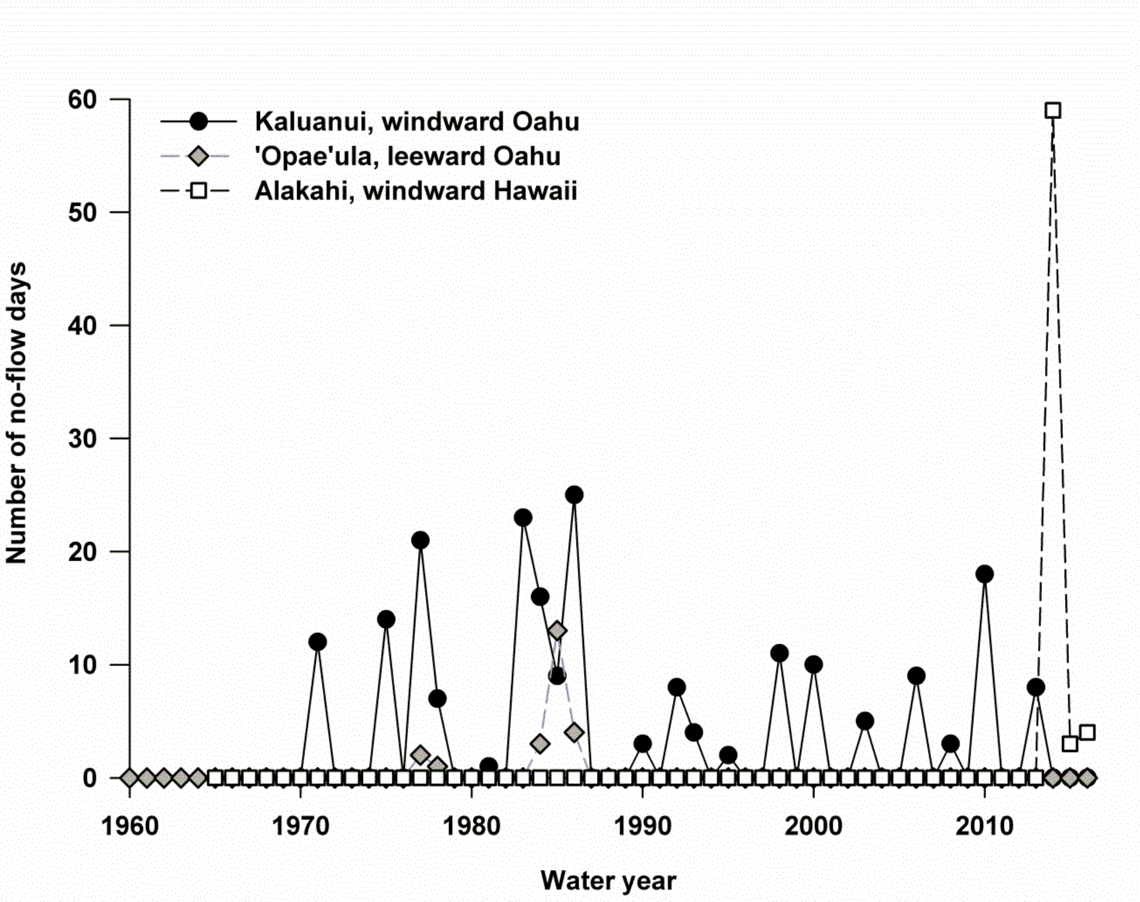


Figure 5: Time series of the number of no-flow days for three streams that exhibited intermittent flow for unregulated streams.

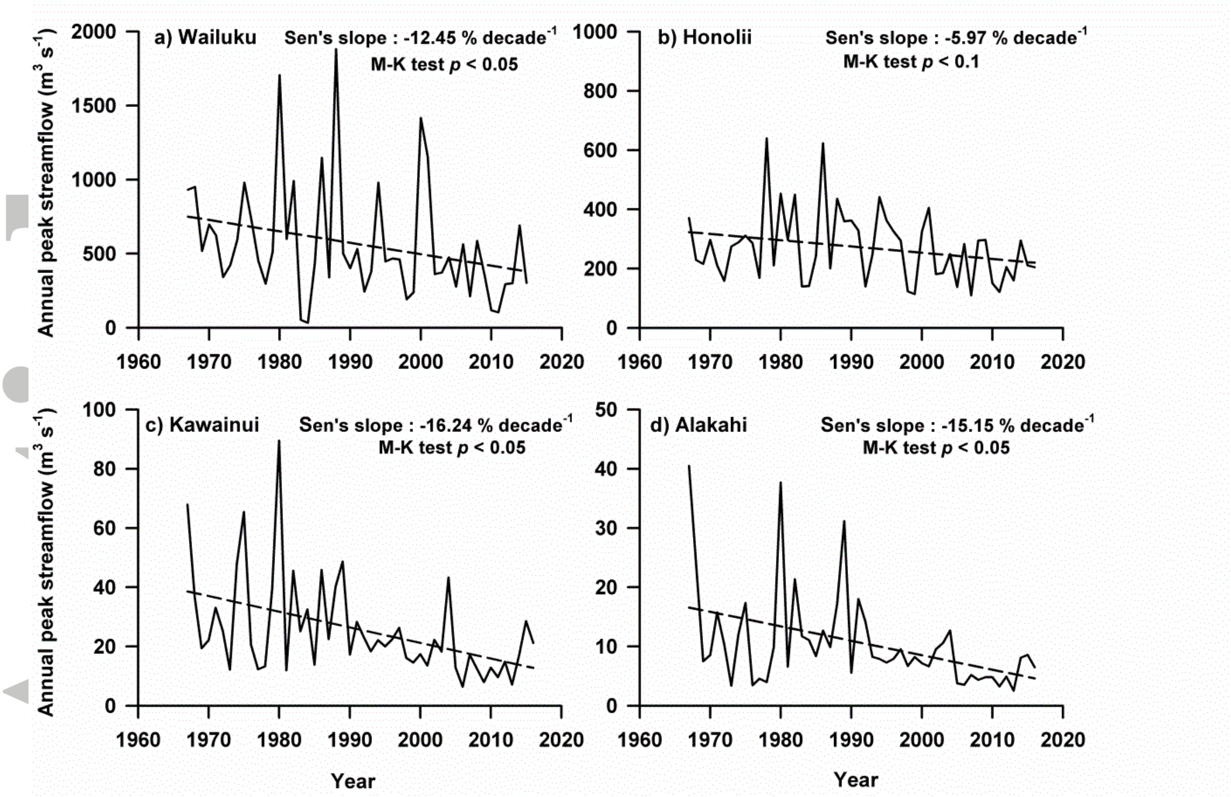


Figure 6: Declining annual peak instantaneous streamflow on windward Hawai‘i from 1967-2016. Percent per decade trends (Sen’s slope), expressed as a percentage of the 1978-2007 reference period, and statistical significance from Mann-Kendall tests are shown.

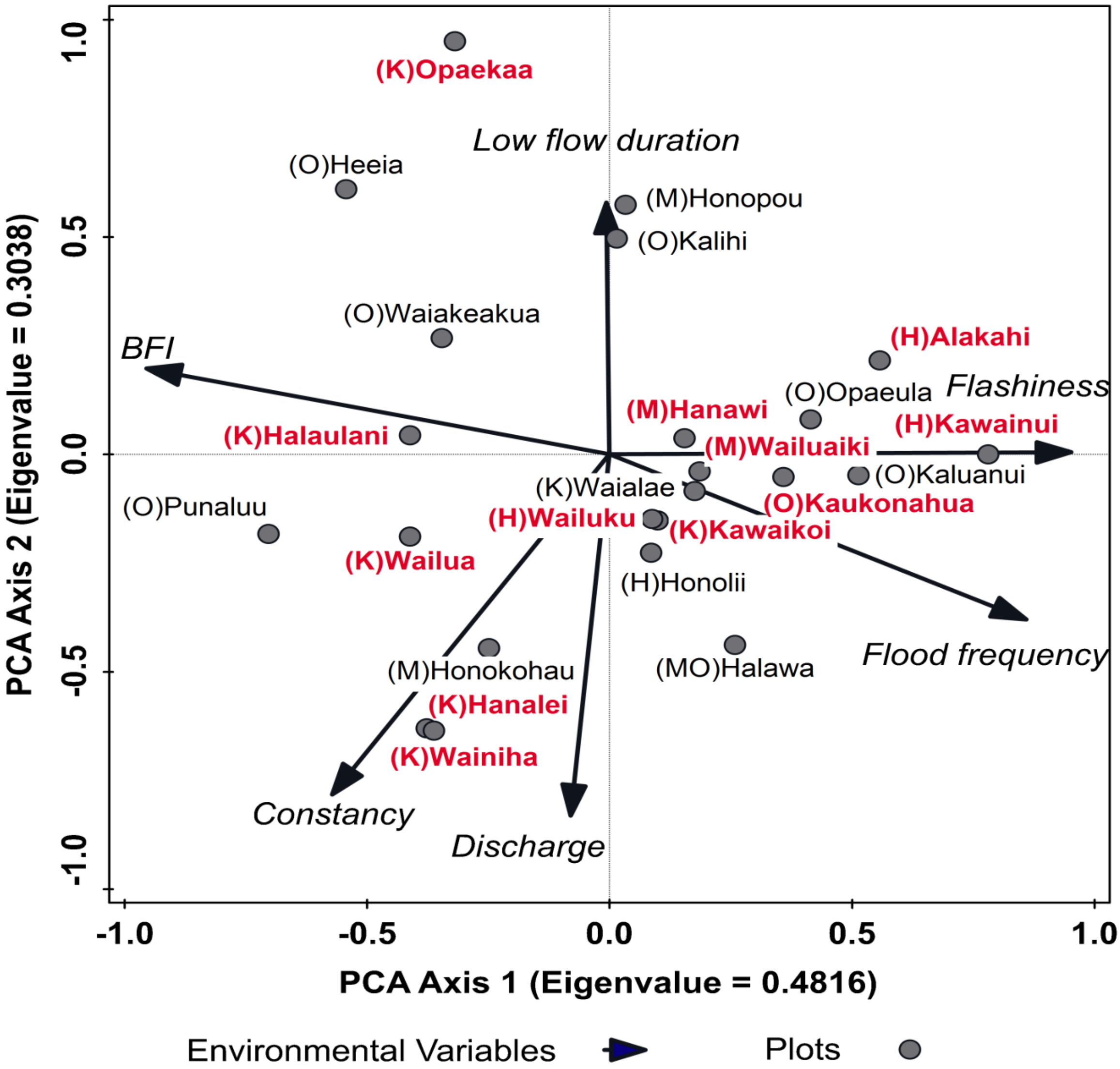


Figure 7: Principal components analysis of streamflow regime (i.e. mean annual discharge, flood frequency, Baseflow Index (BFI), low flow duration, flashiness (ratio of 25:75% exceedance), and constancy (temporal invariance) for streams (n=23) across five of the main Hawaiian Islands. The stream names relate to plot locations, and the islands are given by the following text in parentheses: K=Kaua‘i; O=O‘ahu; MO=Moloka‘i; M=Maui; H=Hawai‘i. Each arrow points in the direction of the steepest increase of the values for the corresponding environmental variable. The relative distance between the plots represents the similarity or dissimilarity of environmental parameters across the streams. Plot names highlighted in bold red indicate streams that exhibit a significant ($p < 0.05$) decline in baseflow from 1987-2016.

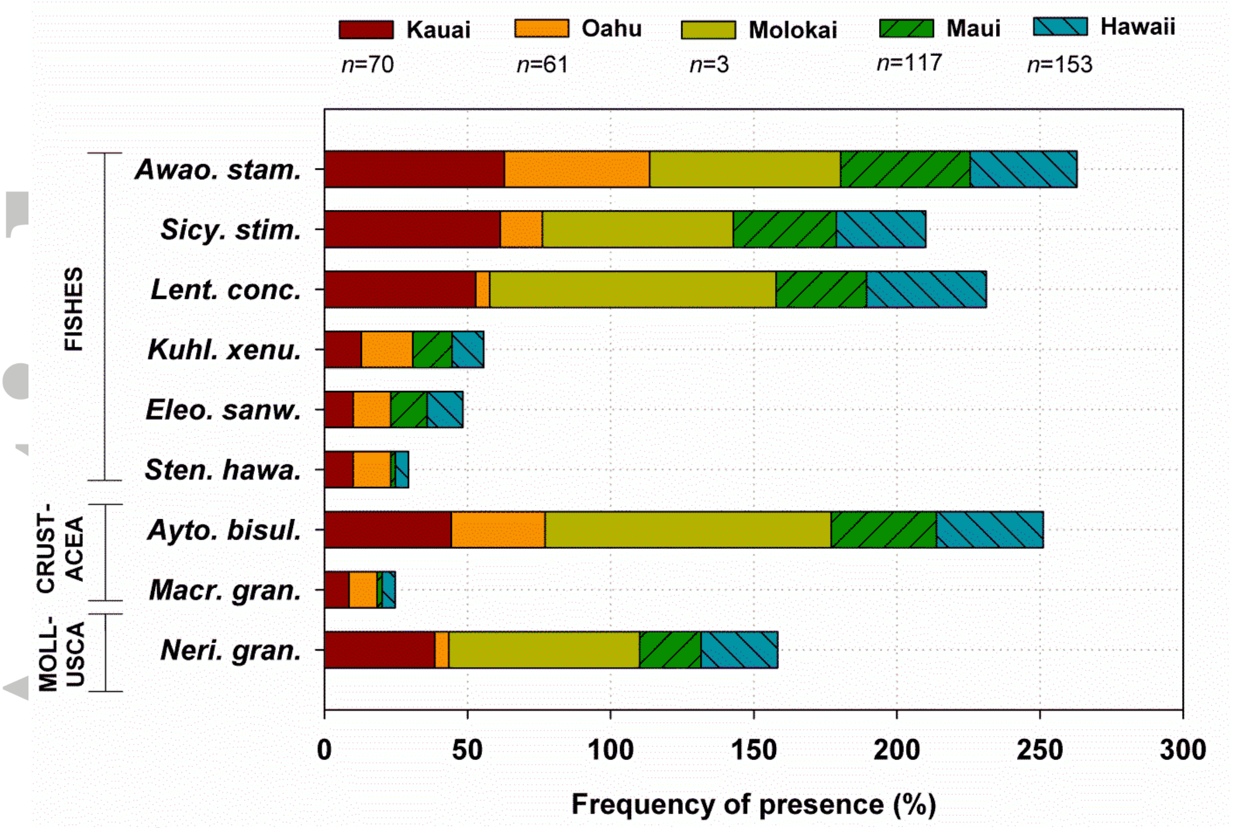
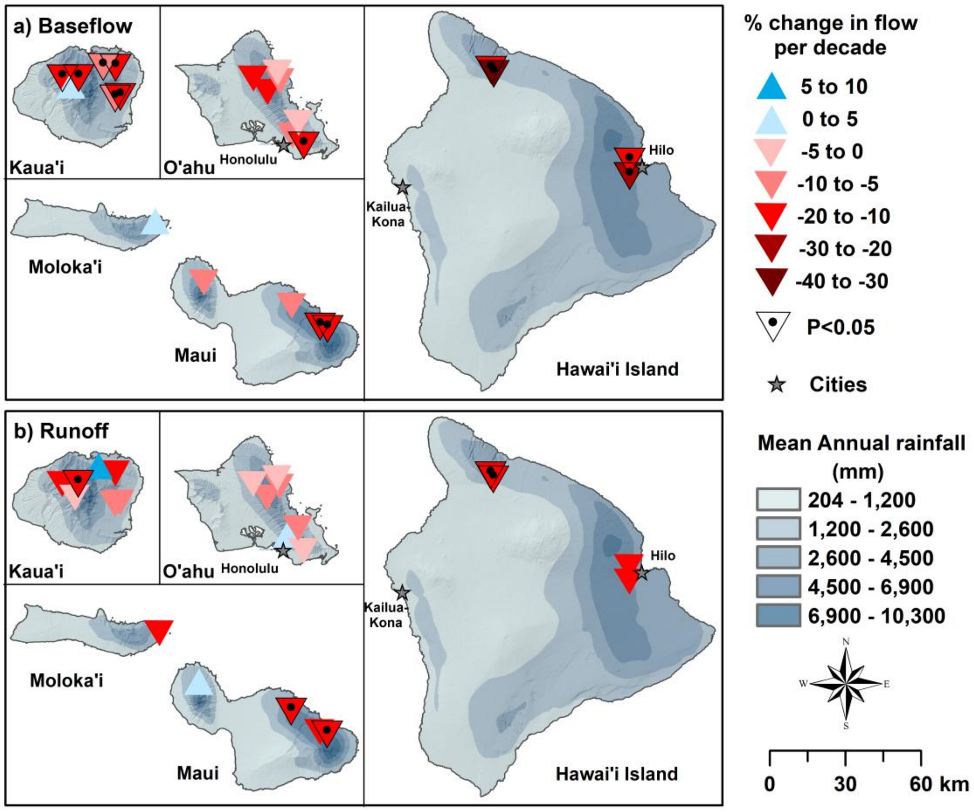
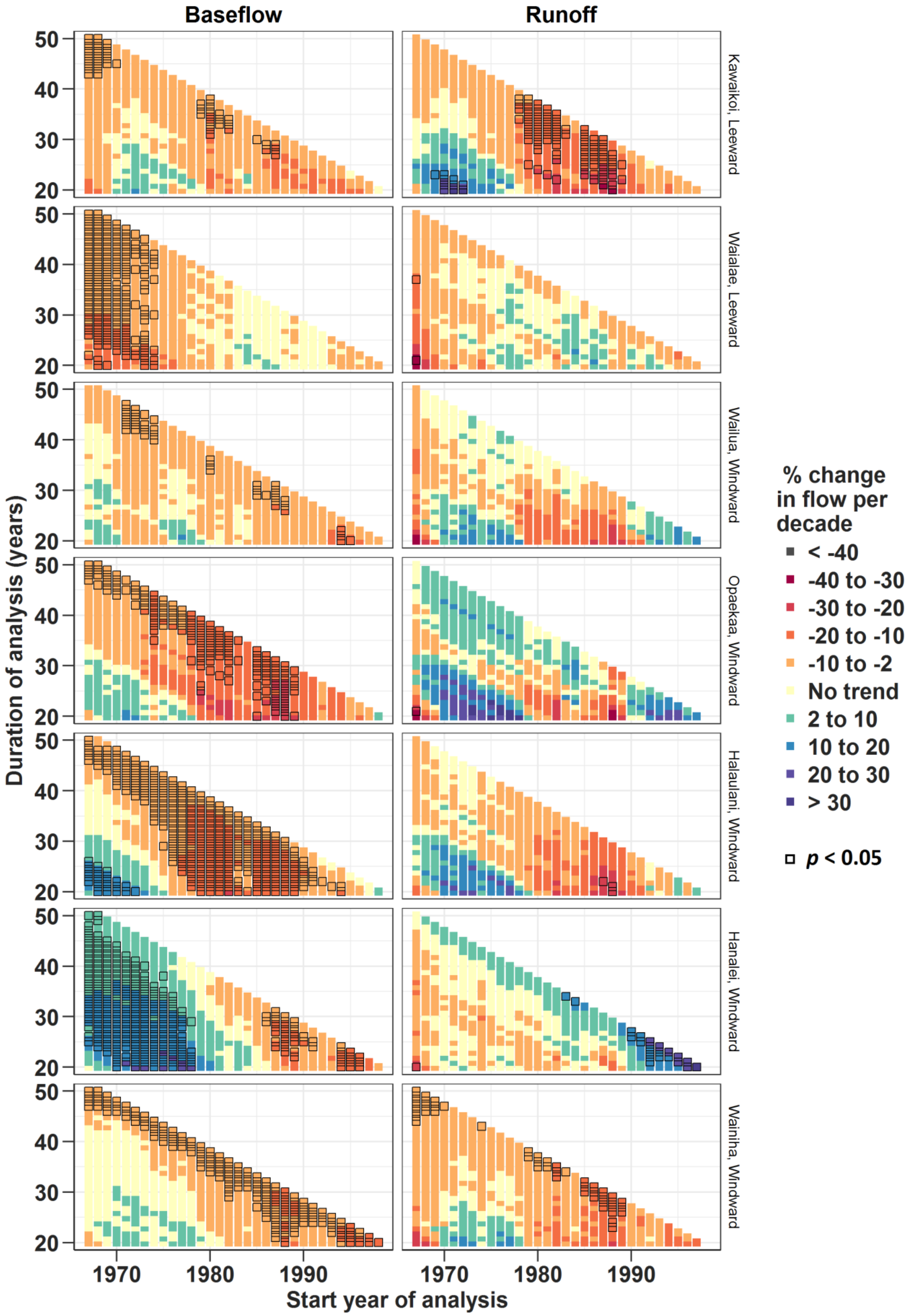


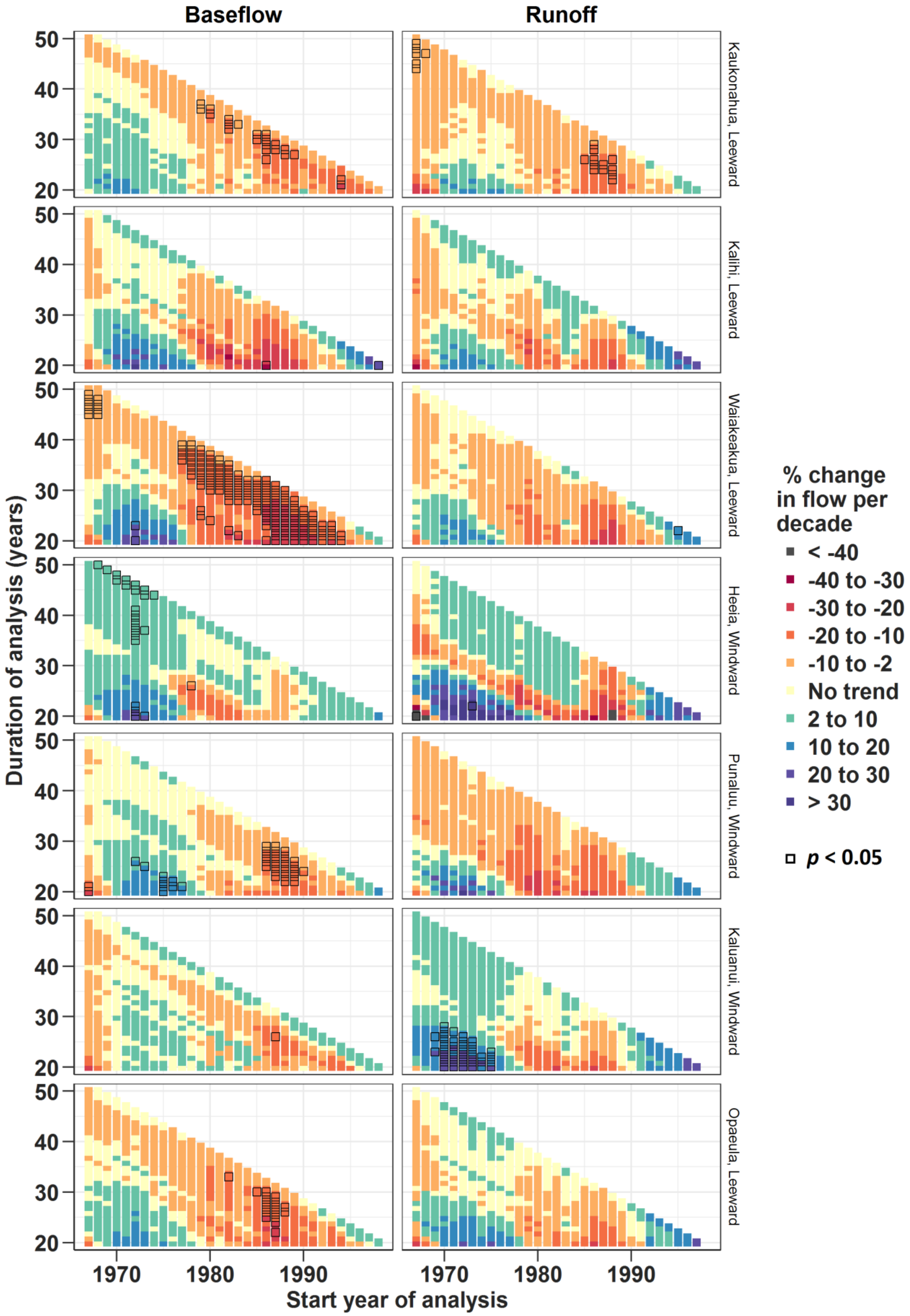
Figure 8: Presence of native freshwater species (*Awaous stamineus*; *Sicyopterus stimpsoni*; *Lentipes concolor*; *Kuhlia sp.*; *Eleotris sandwicensis*; *Stenogobius hawaiiensis*; *Atyoida bisulcata*; *Macrobrachium grandimanus*; *Neritina granosa*) for each of the main Hawaiian Islands: Kauai (circle, *n*=70); Oahu (triangle, *n*=61); Molokai (square, *n*=3); Maui (diamond, *n*=117); and Hawaii (hexagon, *n*=153), superimposed on frequency of presence of species in all samples (*n*=404) (grey bars) across the five islands. Note the small sample size on Molokai. Data provided by the Hawaii Division of Aquatic Resources. This dataset represents a total of 404 stream reaches, and includes 11 out of our 23 focal streams.



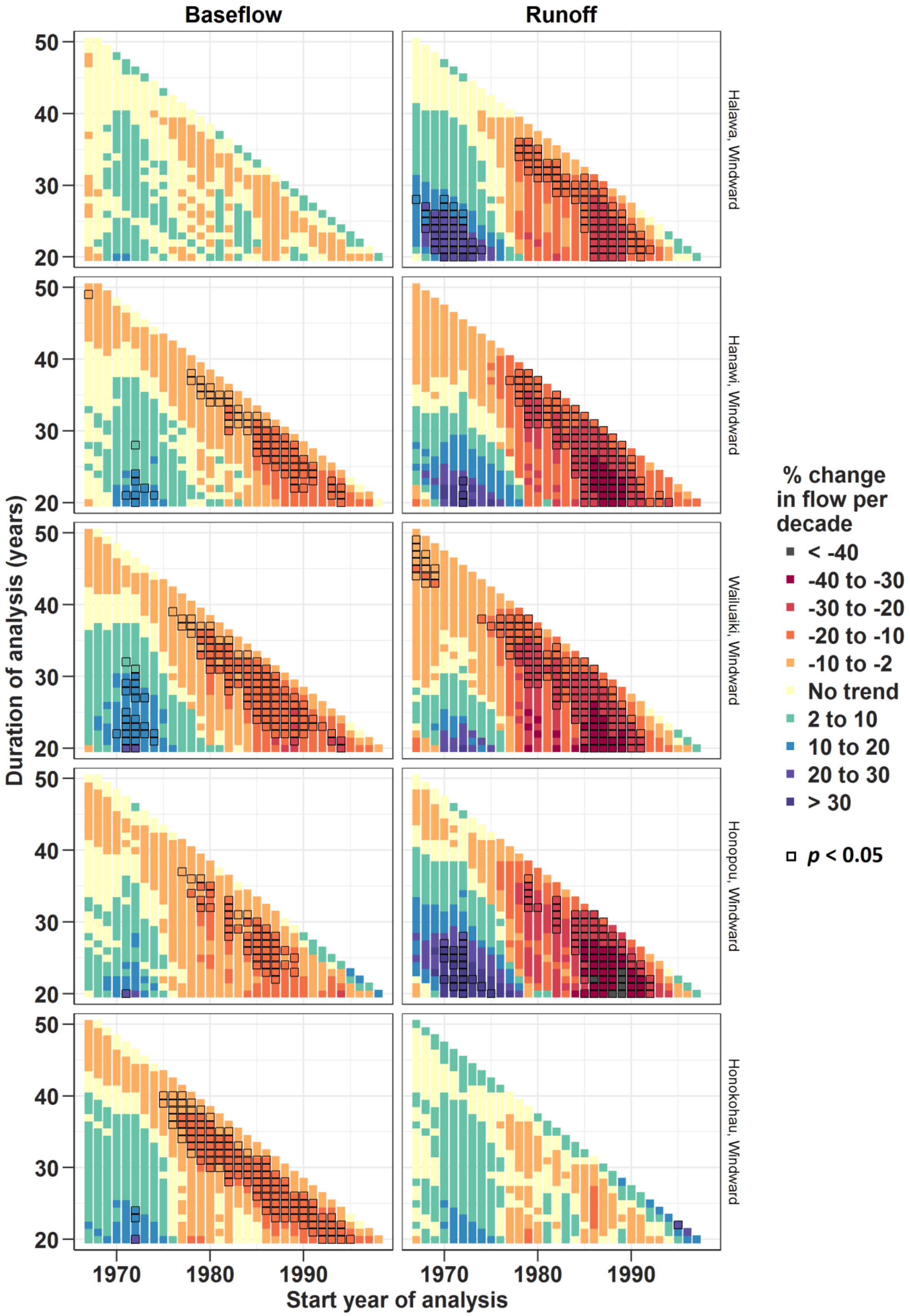
Appendix 1: (a) Mean annual baseflow and (b) runoff trends from 1987-2016, superimposed on mean annual precipitation (from the Rainfall Atlas of Hawai‘i, Giambelluca et al. (2013)). Trend magnitudes computed using the Sen’s estimator of trend slope expressed as a percentage of the 1978-2007 reference period. Significant trends ($p < 0.05$) are highlighted with •.


Baseflow
Runoff
Kawaikoi, Leeward
Waialae, Leeward
Wailua, Windward
Opaekaa, Windward
Halaulani, Windward
Hanalei, Windward
Wainiha, Windward
Duration of analysis (years)
20
30
40
50
1970
1980
1990
Start year of analysis
% change in flow per decade
< -40
-40 to -30
-30 to -20
-20 to -10
-10 to -2
No trend
2 to 10
10 to 20
20 to 30
> 30
p < 0.05

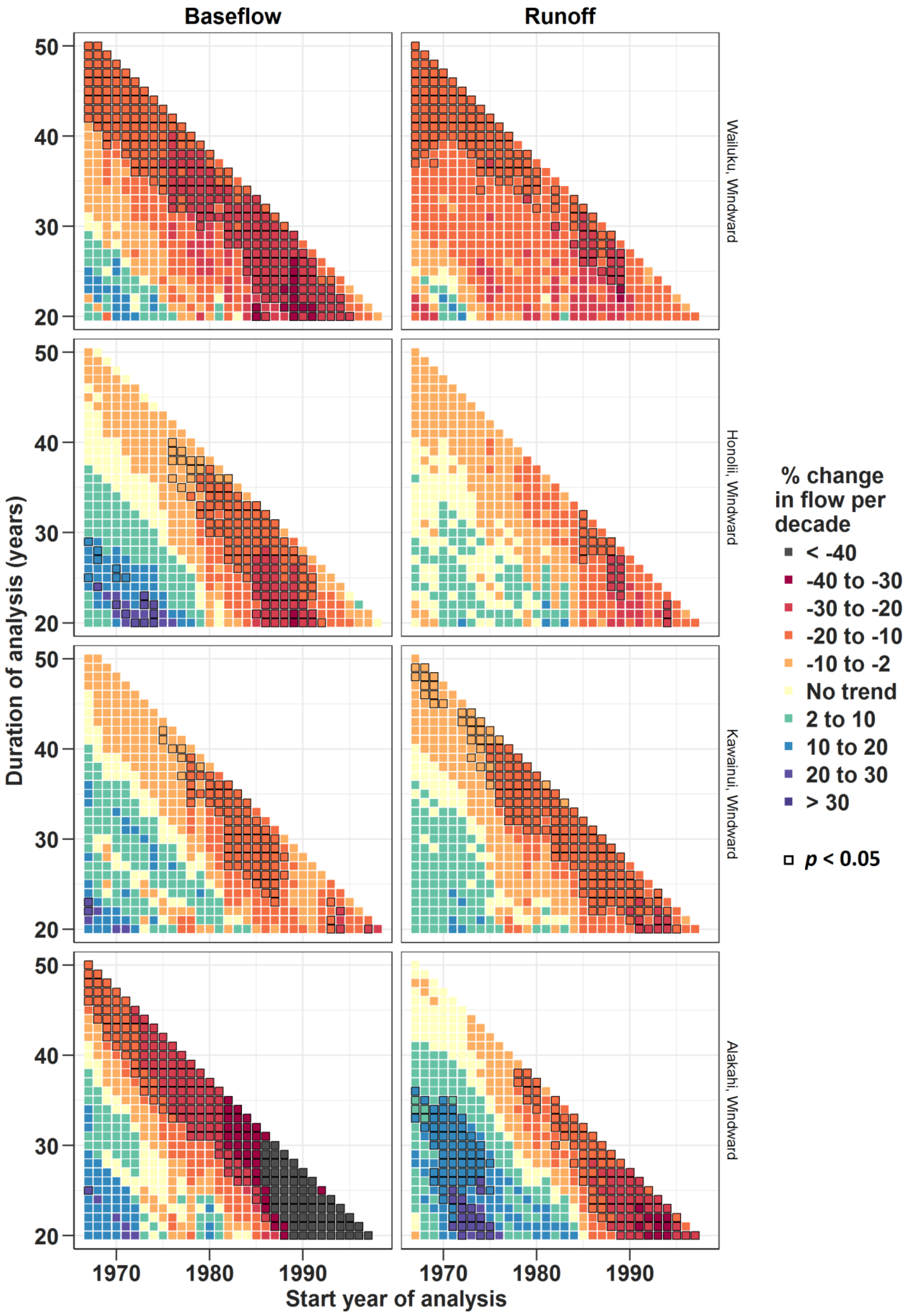
Appendix 2: Running trend analysis for mean annual baseflow (left panel) and runoff (right panel) for unregulated streams on Kaua‘i. Trend magnitudes computed using the Sen’s estimator of trend slope expressed as a percentage of the 1978 to 2007 reference period. The open boxes represent trends that are significant at $p < 0.05$.


Baseflow
Runoff
Kaukonahua, Leeward
Kalihi, Leeward
Waiakeakua, Leeward
Heeia, Windward
Punaluu, Windward
Kaluanui, Windward
Opaeula, Leeward
Duration of analysis (years)
50
40
30
20
1970
1980
1990
Start year of analysis
% change in flow per decade
■ < -40
■ -40 to -30
■ -30 to -20
■ -20 to -10
■ -10 to -2
■ No trend
■ 2 to 10
■ 10 to 20
■ 20 to 30
■ > 30
□ p < 0.05

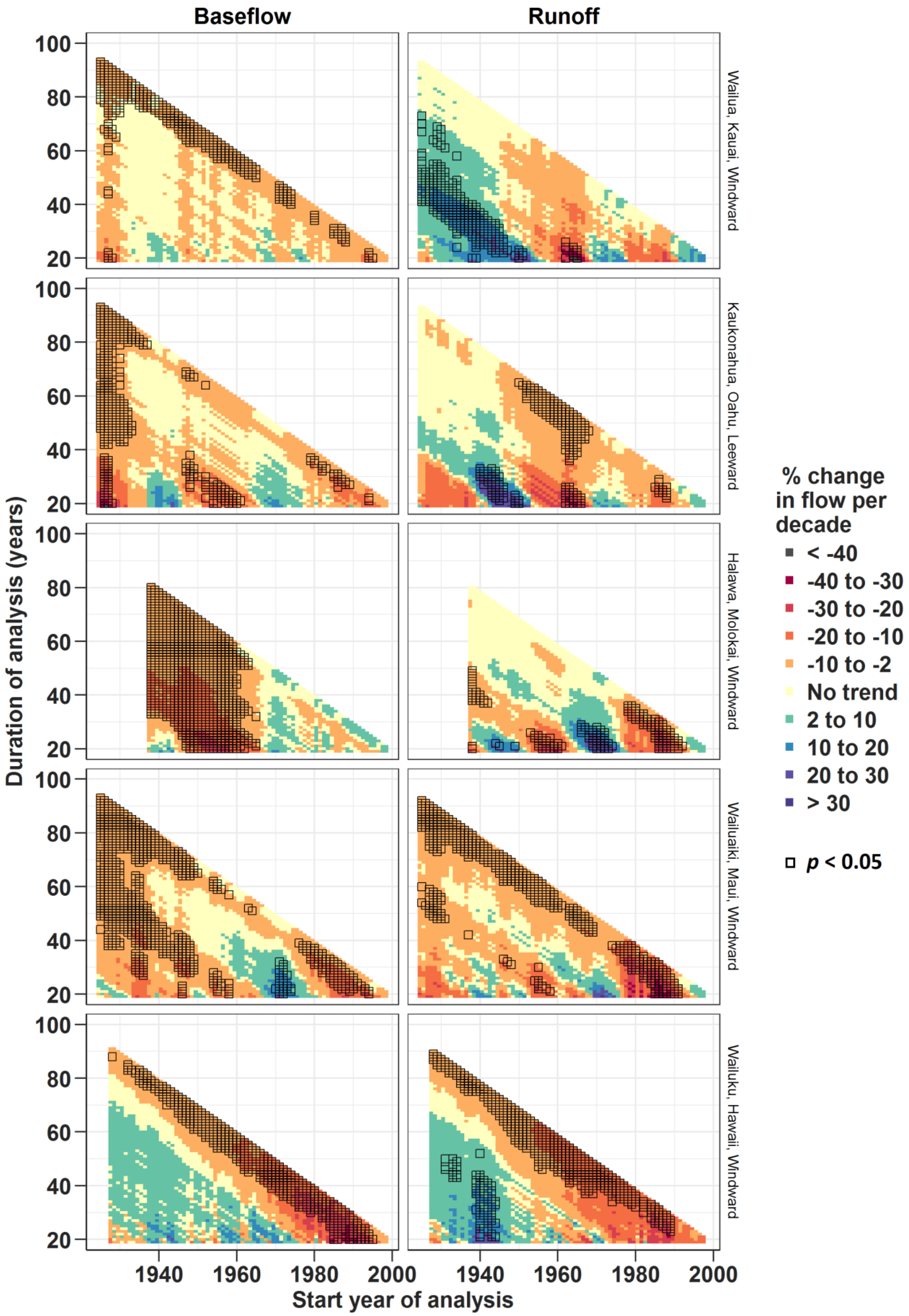
Appendix 3: Running trend analysis for mean annual baseflow (left panel) and runoff (right panel) for unregulated streams on O‘ahu. Trend magnitudes computed using the Sen’s estimator of trend slope expressed as a percentage of the 1978 to 2007 reference period. The open boxes represent trends that are significant at $p < 0.05$.


Baseflow
Runoff
Halawa, Windward
Hanawi, Windward
Wailuaiki, Windward
Honopou, Windward
Honokohau, Windward
Duration of analysis (years)
50
40
30
20
1970
1980
1990
Start year of analysis
% change in flow per decade
< -40
-40 to -30
-30 to -20
-20 to -10
-10 to -2
No trend
2 to 10
10 to 20
20 to 30
> 30
$p < 0.05$

Appendix 4: Running trend analysis for mean annual baseflow (left panel) and runoff (right panel) for unregulated streams on Moloka‘i (top panel) and Maui (remaining panels). Trend magnitudes computed using the Sen’s estimator of trend slope expressed as a percentage of the 1978 to 2007 reference period. The open boxes represent trends that are significant at $p < 0.05$.


Baseflow
Runoff
Wailuku, Windward
Honolii, Windward
Kawainui, Windward
Alakahi, Windward
Duration of analysis (years)
50
40
30
20
Start year of analysis
1970
1980
1990
% change in flow per decade
< -40
-40 to -30
-30 to -20
-20 to -10
-10 to -2
No trend
2 to 10
10 to 20
20 to 30
> 30
$p < 0.05$

Appendix 5: Running trend analysis for mean annual baseflow (left panel) and runoff (right panel) for unregulated streams on Hawai‘i. Trend magnitudes computed using the Sen’s estimator of trend slope expressed as a percentage of the 1978 to 2007 reference period. The open boxes represent trends that are significant at $p < 0.05$.



Baseflow
Runoff
Wailua, Kauai, Windward
Kaukonahua, Oahu, Leeward
Halawa, Molokai, Windward
Wailuaiki, Maui, Windward
Wailuku, Hawaii, Windward
Duration of analysis (years)
100
80
60
40
20
Start year of analysis
1940
1960
1980
2000
% change in flow per decade
< -40
-40 to -30
-30 to -20
-20 to -10
-10 to -2
No trend
2 to 10
10 to 20
20 to 30
> 30
p < 0.05

Appendix 6: Running trend analysis for mean annual baseflow (left panel) and runoff (right panel) for five streams with long flow records on Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i, consecutively from top to bottom panels. Trend magnitudes computed using the Sen’s estimator of trend slope expressed as a percentage of the 1978 to 2007 reference period. The open boxes represent trends that are significant at $p < 0.05$.