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Forest cover lessens hurricane impacts on peak streamflow

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Abstract

Cyclonic storms (i.e., hurricanes) are powerful disturbance events that often cause widespread forest damage. Storm-related canopy damage reduces rainfall interception and evapotranspiration, but impacts on streamflow regimes are poorly understood. We quantify streamflow changes in Puerto Rico following Hurricane Maria in September 2017, and evaluate whether forest cover and storm-related canopy damage account for the differences. Streams are particularly vulnerable to flooding in early post-disturbance stages during hurricane season, so we focus on 3 months (Oct–Dec) following the hurricane. To discern changes in rainfall responses, we partitioned streamflow into baseflow and quickflow using a digital filter. We collected 2010–2017 streamflow and rainfall data from 18 watersheds and compared the relative magnitude of post- to pre-hurricane double mass curve slopes of baseflow and quickflow volumes against rainfall. Several watersheds displayed higher post-hurricane quickflow and baseflow, however, the response was variable. The magnitude of quickflow increase was greater in watersheds with high forest damage. Under the same level of relative damage, watersheds with low initial forest cover had greater quickflow increases than highly forested ones. Conversely, baseflow generally increased, but increases were greater in highly forested watersheds and smaller in highly damaged watersheds. These results suggest that post-storm baseflow increases were due to recharge of hurricane-related rainfall, as well as forest transpiration interruption and soil disturbance enhancing recharge of post-hurricane rainfall, while increases to quickflow are related to loss of canopy rainfall interception and higher soil saturation decreasing infiltration. Our research demonstrates that forest damage from disturbance lowers quickflow and elevates baseflow in highly forested watersheds, and elevates quickflow and lowers baseflow in less-forested watersheds. Less-forested watersheds may be closer to the forest cover loss threshold needed to elicit a streamflow response following disturbance, suggesting higher flooding potential downstream, and a lower storm-related forest disturbance threshold than in heavily forested watersheds.

KEYWORDS

double mass curves, hurricanes, lidar, Puerto Rico, streamflow, tropical forest hydrology

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1 | INTRODUCTION

Globally, forests are facing widespread threats such as deforestation, climate change and natural disturbances. Cyclonic storms are the prevalent natural disturbance events in many coastal forests of the tropics (Lugo, 2008) and atmospheric and sea surface warming are projected to lead to more frequent severe tropical cyclones, with rapid intensification and higher wind speeds (Knutson et al., 2015). Higher tropical cyclone rainfall rates are also expected as a result of increases in atmospheric moisture content (Knutson et al., 2015; Kossin, 2018). Increases in tropical cyclone wind speeds and rainfall may lead to higher disturbance-related damage to forests, with potential consequences for the hydrological services these ecosystems provide (Hall et al., 2020; Kossin, 2018). Forests provide food and water resources, harbour biodiversity, and regulate global temperatures (Brauman et al., 2007). Water provision is arguably the most immediately critical ecosystem service for human survival, and it is often directly linked to forest cover (Vose et al., 2011). Streamflow is a crucial component of global water provision, and forests act as natural buffers and reservoirs by regulating the timing, stability, and quality of streamflow (Brauman et al., 2007; Zhang et al., 2017; Zhang & Wei, 2021). To manage watersheds in preparation for future disturbances, it is imperative to gain better understanding of forest damage resulting from climate-induced disturbance events and the hydrological consequences of such damage.

There have been numerous studies on the effects of forest loss and degradation on streamflow, with some emergent patterns. Deforestation generally increases surface water flow, while afforestation decreases it (Bosch & Hewlett, 1982; Brown et al., 2013; Zhang et al., 2017). Total annual streamflow also increases after forest damage from fire (Hallema et al., 2018; Williams et al., 2022), selective logging (Bruijnzeel, 2004), and cyclones (Jayakaran et al., 2014). However, relationships between forests and streamflow may depend on rainfall regimes. In many tropical areas, precipitation is highly variable and includes frequent intense rainfall events, defined as large quantities of rainfall falling within a short time interval (Biasutti et al., 2012), that increase sediment runoff into reservoirs and flooding risk. This variability affects human water delivery systems that often rely on local channel withdrawals and surface reservoirs with limited water storage (Taylor, 2009). In such tropical regions with high but variable rainfall that is prone to extremes, total annual stream output matters less for consistent water supply than the timing of delivery occurring at finer temporal scales (Hall et al., 2022). Characterisation of the effects of disturbance on baseline inputs to streams (i.e., baseflow) and rapid stream response to rainfall from infiltration raising the potentiometric surface, shallow-soil interflow, overland flow, or a combination of these (i.e., stormflow, quickflow) may be more relevant to water provision in these regions. Quickflow and baseflow reflect rainfall responses at different temporal scales (Harman et al., 2011; Lyne & Hollick, 1979; Pelletier & Andréassian, 2020; Stewart, 2014; Stoelzle et al., 2020), making partitioning streamflow into these components useful for evaluating watershed response to disturbance.

Study results of the effects of forest cover on streamflow components are mixed, possibly due to interactions between forest integrity, soil structure and dominant flow paths. In many cases, forest cover increases baseflow and reduces quickflow (Addor et al., 2018), particularly in the tropics (Filoso et al., 2017; Peña-Arancibia et al., 2019). Roots and litter inputs in forest ecosystems develop soil structure and increase soil water storage, infiltration capacity and groundwater recharge (Bruijnzeel, 2004; Ilstedt et al., 2007), leading to higher stream levels during dry conditions (Hamilton & King, 1983; Scott et al., 2005), and lower quickflow during intense rainfall events (Bradshaw et al., 2007). In contrast, overland flow may dominate in degraded forest systems (Birch et al., 2021; Krishnaswamy et al., 2012), leading to higher quickflow and reduced dry season baseflow relative to intact forests.

Watershed forest cover may also impact the sensitivity of streamflow regimes to forest damage (Buma & Livneh, 2017). Hibbert (1967) showed that the magnitude of streamflow change after deforestation or damage from disturbance was proportionally related to the magnitude of forest loss, and subsequent studies attributed this effect to reduced transpiration driven by tree mortality and damage (Andréassian, 2004; Dai et al., 2013). However, a threshold of forest cover loss must be met before hydrological impacts are seen (Wei et al., 2021). A 20% loss of forest cover is generally used as the threshold for forest management (Bosch & Hewlett, 1982; Wine et al., 2018), but recent research has highlighted the need to develop thresholds that reflect location-specific hydrological sensitivities (Wei et al., 2021; Zhang et al., 2017). Identifying thresholds for events that do not completely remove forest cover and instead, cause widespread forest degradation (i.e., wind damage, insect outbreaks, multi-year drought) will likely require consideration of interactions between pre-existing forest cover and the degree of forest damage. We hypothesize that damaged canopies in watersheds with less forest cover may result in greater hydrological responses to disturbance than in highly forested watersheds with the same degree of canopy damage.

Despite the extensive literature examining the effects of deforestation and forest degradation from fire and other disturbances on streamflow, no studies have quantified spatial and temporal effects of forest damage resulting from cyclonic storms. Hydrological dynamics relating to cyclonic storms differ significantly from the existing forest degradation literature, as cyclones simultaneously damage forests (Chambers et al., 2007; Hall et al., 2020; Uriarte et al., 2019; Xi et al., 2008; Xi & Peet, 2008) and often bring extreme rainfall (Keellings & Hernández Ayala, 2019; Kossin, 2018). We hypothesize that streams are most affected on timescales of a few months following cyclonic storms because the combined effects of soil saturation and declines in vegetation water demand can lead to short-term increase in quickflow, runoff ratios (i.e., streamflow/rainfall) and baseflows (Chen et al., 2015; Jayakaran et al., 2014; Musser et al., 2017; Vidon et al., 2018; Zhang et al., 2018). Intense rainfall events may also lead to higher flooding, turbidity and increased strain on downstream water infrastructure, particularly if further storms or intense rainfall events occur during the remainder of the hurricane season. As more frequent and intense storms are expected to place increasing pressure

on forests in many areas of the coastal tropics (Hall et al., 2020; Knutson et al., 2010; Kossin, 2018), it is imperative not only to evaluate the impacts of forest damage on streamflow, but also to use this knowledge to increase efficacy of forest management for protecting water resources.

On 20 September 2017, Hurricane Maria made landfall in Puerto Rico as a category 4 storm, causing widespread forest damage (Hall et al., 2020; Uriarte et al., 2019). Wind speeds reached up to 250 km hr^{-1} (Pasch et al., 2019) and over a metre of rainfall fell in some areas (Keellings & Hernández Ayala, 2019). With a 115–152 year return interval, rainfall from Hurricane Maria was much higher than that of previous storms (Pokhrel et al., 2021). This resulted in an 85% increase in streamflow for the first 6 weeks after storm landfall relative to the months before in a period with a 35% reduction in rainfall compared with the month before (Miller et al., 2019). Mass damage and defoliation reduced forest greenness across much of the island for 1–3 months (Van Beusekom et al., 2018), and temperature and water vapour anomalies did not recover for at least 12 months after Hurricane Maria (Miller et al., 2019; Scholl et al., 2021), indicating that forests did not recover the evapotranspiration regimes (i.e., energy balance) of intact forests for some time. This suggests that the storm had important effects on the island's hydrological cycle, which may have significant implications for water provision.

A large proportion (84%) of the total water used for human consumption in Puerto Rico comes from surface streamflow (Molina-Rivera, 2014) and Puerto Rican streams are notoriously flashy (Jones et al., 2012). High elevation forested watersheds release up to 36% of storm rainfall from overland and shallow groundwater flow within hours (Schellekens et al., 2004; Scholl et al., 2015), and much of this runoff is lost as reservoir evaporation or as surface flow to the ocean before it can be used (Larsen, 2000; Molina-Rivera, 2014). These characteristics as well as recent calls to re-evaluate Puerto Rican water management systems (Murry et al., 2019) highlight the need to understand the influence of forest disturbance on the partitioning of rainfall into quickflow and baseflow, rather than looking at total streamflow.

Here, we link observed post-hurricane changes in stream response to spatially explicit estimates of forest damage across multiple watersheds with varying forest cover. We quantify short-term (within 3 months post-storm) stream response to rainfall in Puerto Rico after Hurricane Maria, the strongest hurricane to make direct landfall on the island since Hurricane San Felipe in 1928 (Boose et al., 2004; Pasch et al., 2019). We separate streamflow into quickflow and baseflow components using a digital filter method (Ladson et al., 2013; Lyne & Hollick, 1979). This approach does not represent flow pathways, however it captures stream response to rainfall at quick and slow timescales in a uniform way before and after land cover changes, as it depends only on streamflow measurements. To determine the magnitude and direction of stream response to the storm, we examined the slopes of modified double mass curves (DMC) (Searcy et al., 1960) generated by regressing cumulative daily quickflow or baseflow against cumulative daily rainfall estimates. We hypothesized that both quickflow and baseflow components, and

therefore total flow, produced for a particular rainfall amount were greater after than before the storm. Increase in quickflow would result from a combination of storm-related soil saturation increasing overland and shallow subsurface flow in addition to reductions in canopy interception of rainfall. In contrast, baseflow would increase from increased groundwater levels and decreased vegetation water demand. Increases in both quickflow runoff and baseflow storage would be consistent with widespread vegetation changes leading to a decrease in evapotranspiration within the water balance post-hurricane.

After evaluating streamflow response to Hurricane Maria, we also tested whether estimates of forest cover and canopy damage can explain the magnitude and direction of changes to quickflow and baseflow. Quickflow and baseflow are both hypothesized to be higher in highly damaged watersheds, however, this effect may be modulated by forest cover percentage. When watershed forest cover is high, storm-related forest damage may still fall below the critical forest disturbance threshold required to have an impact on streamflow. Under the same level of proportional canopy damage, we expect less-forested watersheds to display a greater streamflow response than highly forested watersheds.

2 | DATA AND METHODS

2.1 | Study area

Puerto Rico ($\sim 9000 \text{ km}^2$) is a heavily forested (57%) island in the Caribbean Greater Antilles (Figure 1). There is large variation in rainfall across the island ($700\text{--}4600 \text{ mm year}^{-1}$) (Daly et al., 2003) resulting from complex topography ($0\text{--}1331 \text{ m asl}$) (Carswell, 2016; Kennaway & Helmer, 2007) and prevailing trade winds. Puerto Rico experiences a characteristic bimodal wet season, with an early wet season from May to July and a late wet season from August to November (Karmalkar et al., 2013). Much of the weather occurs within the framework of the easterly trade winds, and approximately 70% of the yearly rainfall comes from hurricanes and other large storms at an average of nine times a year (Murphy & Stallard, 2012a).

2.2 | Data

All data retrieval and analysis was conducted using R statistical software.

2.2.1 | Streamflow

To observe streamflow response to disturbance, we selected 18 U.S. Geological Survey (USGS) stream gages based on watershed characteristics and post-storm data availability. To determine watershed characteristics, we delineated contributing watershed areas for each stream gage using the “delineateWatershed” function in the

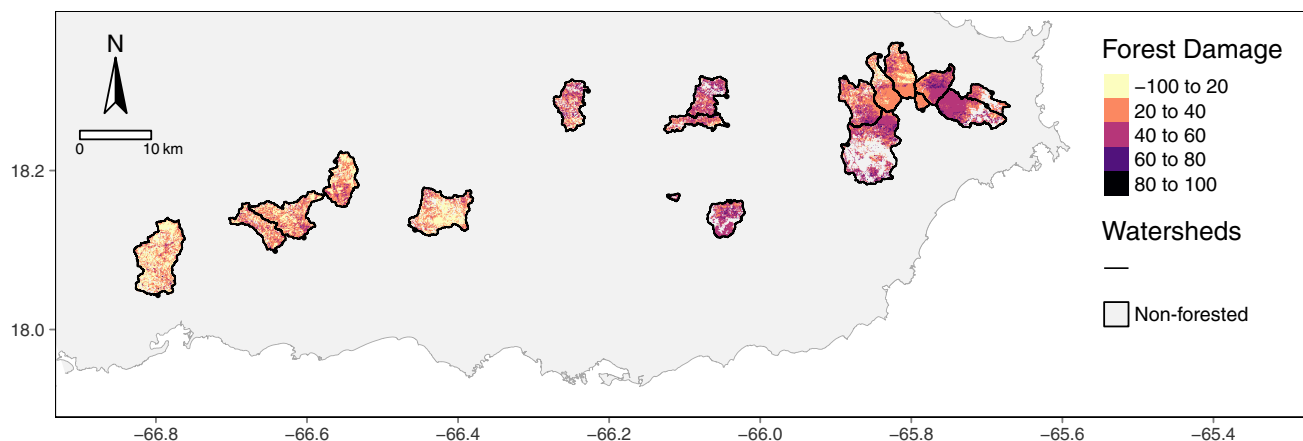


FIGURE 1 Selected stream gage locations and contributing watershed areas. Colours indicate the magnitude of forest damage (i.e., percent canopy height loss after the storm).

“streamstats” package (Hagemann, 2021). Using the National Hydrography Dataset (USGS, 2020) and StreamStats station information (USGS, 2021), we identified and excluded watersheds containing pipelines, large lakes, karst topography, or dams and only considered those with a majority of contributing area on volcanoclastic substrate, the most common substrate by area in Puerto Rico, which is characterized by fine grained soils, low infiltration rates and high water storage potential at depth (Reed Jr. & Bush, 2005; Thomas et al., 2020) (Table S1). Additionally, Hurricane Maria damaged or destroyed many stream gages, leaving widespread data gaps during the study period. To reduce uncertainty in our estimates, we excluded stations that had <50% of 15-minute streamflow observations for the first 3 months after the storm (October to December, 2017), as well as stations with >50% estimated flow values during the same period. We also excluded watersheds affected by human activities and limited our analysis to watersheds with similar geology using methods detailed in a previous study (Hall et al., 2022) (see [Supporting Information](#) for detailed site selection and processing methods).

Instantaneous streamflow records collected at approximately 15-minute intervals over the study period (October through December 2010–2017) were obtained for 18 selected USGS stream gages (Figure 1; Table 1) (USGS, 2019). We excluded September 2017 from analysis to remove the immediate stream response to rainfall from Hurricane Maria (20 September 2017), as well as Hurricane Irma, a category 5 storm that passed near Puerto Rico 14 days before Hurricane Maria (6 September 2017).

2.2.2 | Rainfall

We obtained global rasters of Multi-Source Weighted-Ensemble Precipitation (MSWEP) 3-h rainfall (0.1-degree spatial resolution) from 2013 to 2020 (Beck et al., 2019) and extracted the spatially-weighted average rainfall values for each watershed contributing area. The use of MSWEP (a gridded product combining radar and gauge rainfall data) results in uncertainty in rainfall-streamflow relationships. Rainfall in Puerto Rico and elsewhere in the tropics has been difficult

to properly characterize (Murphy et al., 2017) due to the complex topography of the island paired with limited high-elevation rain gages (Murphy & Stallard, 2012b), as well as light orographic rain and cloud water deposition on the north-eastern portion of Puerto Rico that current rainfall data sets are unable to capture (Scholl et al., 2021). As rainfall at high elevations is difficult to measure (Beck et al., 2019; Murphy et al., 2017), the MSWEP data may underestimate high elevation watershed rainfall and increase uncertainty in rainfall-streamflow relationships. However, comparing streamflow-rainfall regression slopes for the same watersheds before and after the storm (Hurricane Maria) should partially account for errors in rainfall estimates if we assume that chronic underestimation of rainfall persists after the storm.

2.2.3 | Forest cover and watershed forest damage

Watershed-level forest cover proportion was determined using the 2010 Puerto Rico C-CAP Land Cover dataset (NOAA, 2010). Estimates of forest cover loss derived using the Global Forest Watch data viewer (Hansen et al., 2013) showed that Puerto Rico lost less than 1% of the primary forest cover between 2010 and 2017, the period with best spatial distribution of streamflow data prior to Hurricane Maria. Percent forest cover was extracted using the R packages “raster” (Hijmans et al., 2011), “sf” (Pebesma, 2021) and “sp” (Pebesma et al., 2013) (Table 1) for each watershed contributing area.

Watershed-level forest damage was calculated using a canopy height model derived from the USGS 3D Elevation Program (3DEP) (Carswell, 2016) lidar point clouds from separate campaigns in 2015 and in 2018. For each campaign, we created a digital elevation model (DEM) using last returns and normalized point clouds to height above land surface. We removed points classified as low or high noise, and implemented an island-wide maximum height of 100 m; the approximate height of the tallest tree in the tropics (Shenkin et al., 2019), and estimated canopy height using LASTools (Isenberg, 2014). Forest damage for each watershed was calculated as the pixel-level relative loss in forest canopy height in forested areas in each watershed after

TABLE 1 Watershed characteristics and double mass curves (DMC) slope summary values for selected streamflow monitoring stations.

USGS stream gage site no.	Catchment area (ha)	% Forest cover	2016 Mean canopy height (m)	Canopy height loss (m)	% Canopy height loss	Relative % canopy height loss	Baseflow			Quickflow		
							Pre-storm DMC slope	Post-storm DMC slope	Signal direction	Pre-storm DMC slope	Post-storm DMC slope	Signal direction
50025155	2296	93	13.96	3.77	0.25	0.27	0.32 (0.15, 0.48)	0.57 (0.55, 0.58)	+	0.34 (0.14, 0.6)	0.29 (0.27, 0.31)	No change
50044810	2100	65	10.81	4.37	0.35	0.54	0.24 (0.11, 0.4)	0.31 (0.3, 0.32)	No change	0.24 (0.15, 0.36)	0.17 (0.17, 0.18)	No change
50047535	108	55	11.7	5.52	0.46	0.84	0.15 (0.06, 0.5)	0.14 (0.13, 0.14)	No change	0.34 (0.19, 0.61)	0.79 (0.71, 0.87)	+
50053025	1887	75	13.86	7.03	0.47	0.62	0.26 (0.06, 0.43)	0.52 (0.51, 0.54)	+	0.43 (0.32, 0.64)	0.5 (0.46, 0.55)	No change
50055380	1249	71	13.49	5.55	0.39	0.54	0.23 (0.05, 0.52)	0.35 (0.32, 0.38)	No change	0.26 (0.15, 0.64)	0.61 (0.49, 0.72)	No change
50055750	5724	50	11.44	5.37	0.44	0.89	0.15 (0.08, 0.26)	0.2 (0.18, 0.23)	No change	0.23 (0.06, 0.43)	0.79 (0.77, 0.81)	+
50058350	1955	69	13.5	6.35	0.45	0.65	0.18 (0.04, 0.38)	0.24 (0.22, 0.26)	No change	0.23 (0.15, 0.31)	0.55 (0.48, 0.61)	+
50061800	2646	81	12.74	5.18	0.39	0.48	0.25 (0.06, 0.43)	0.43 (0.41, 0.45)	No change	0.18 (0.05, 0.28)	0.34 (0.3, 0.37)	+
50063800	2243	94	14.55	4.54	0.3	0.32	0.38 (0.25, 0.51)	0.6 (0.56, 0.65)	+	0.71 (0.37, 1.05)	0.56 (0.54, 0.58)	No change
50064200	1887	85	12.63	4.1	0.3	0.36	0.32 (0.14, 0.51)	0.69 (0.67, 0.71)	+	0.64 (0.3, 0.9)	0.58 (0.55, 0.62)	No change
50065500	1755	99	17.9	8.26	0.44	0.44	0.53 (0.42, 0.71)	0.62 (0.59, 0.65)	No change	0.71 (0.46, 1.03)	1.05 (1, 1.09)	No change
50070900	2839	79	14.75	7.2	0.46	0.59	0.18 (0.05, 0.25)	0.33 (0.31, 0.34)	+	0.27 (0.10, 0.59)	0.72 (0.7, 0.75)	+
50071000	3861	78	14.31	6.9	0.45	0.57	0.25 (0.06, 0.45)	0.35 (0.32, 0.38)	No change	0.6 (0.28, 1.01)	0.84 (0.82, 0.86)	No change
50075000	321	99	11.64	4.06	0.34	0.35	0.99 (0.72, 1.79)	1.38 (1.34, 1.42)	No change	0.84 (0.59, 1.06)	0.84 (0.81, 0.87)	No change
50110900	3725	72	10.84	2.48	0.21	0.29	0.12 (0.01, 0.24)	0.36 (0.35, 0.37)	+	0.16 (0.07, 0.27)	0.39 (0.37, 0.42)	+
50113800	3073	89	15.04	4.22	0.27	0.31	0.31 (0.23, 0.41)	0.72 (0.69, 0.76)	+	0.38 (0.15, 0.68)	0.45 (0.44, 0.46)	No change
50114900	1907	84	15.15	4.51	0.29	0.34	0.28 (0.13, 0.38)	0.6 (0.57, 0.62)	+	0.2 (0.03, 0.39)	0.4 (0.36, 0.43)	No change
50124200	4876	79	12.01	2.36	0.18	0.23	0.16 (0.06, 0.25)	0.22 (0.21, 0.24)	No change	0.15 (0.04, 0.25)	0.13 (0.12, 0.13)	No change

Note: Relative canopy height loss for forested areas was calculated on the pixel level and then aggregated to mean watershed levels to increase accuracy. Non-significant flow changes are expressed as “No change” (i.e. when disturbance period DMC slopes and 95% confidence intervals fell within the range of historical variability). The + symbol indicates watersheds with significant slope increases after Hurricane Maria.

the storm. Canopy height values used to estimate forest damage were resampled to match the resolution of the CCAP forest cover layer (~ 32 m). Positive values indicate a loss in forest cover, and higher values represent greater damage extent.

There were gaps in 2018 lidar point cloud coverage (Figure S1), leading to gaps in our estimates of canopy height loss in some watershed contributing areas. To approximate watershed contributing area damage in areas containing gaps, we trained random forest models (Breiman, 2001) to predict canopy height loss as a function of a number of covariates known to influence forest damage from Hurricane Maria using the “randomForest” package in R (Liaw & Wiener, 2002). We included a series of meteorological, topographic, soil and stand-level spatial predictors in the random forest models, including those used in Hall et al. (2020). Predictors included Hurricane Maria-related maximum sustained wind speeds and rainfall, antecedent rainfall, distance to the Hurricane Maria storm track, elevation, slope, aspect, topographic position index (TPI), available water storage and 2016 canopy height (Figure S2). We obtained 1-km RMS[®] HWind maximum 1-minute sustained wind speeds (km hr^{-1}) for Hurricane Maria (<https://www.rms.com/models/hwind>). We included downscaled estimates of 5-km storm-related NOAA gridded Hurricane Maria-related rainfall (20–21 September 2017) as well as antecedent rainfall including that which fell during Hurricane Irma, which passed Puerto Rico weeks before Hurricane Maria hit (6–19 September 2017) (<https://water.weather.gov/precip/download.php>). Distance to the storm path was determined using the Hurricane Maria best fit path trajectory developed by NOAA (Pasch et al., 2019). We calculated elevation, slope and TPI from the 5 m 2016 USGS 3DEP DEM. We used water storage capacity (in cm of water) for soil horizons from 0 to 100 cm below the surface (10 m resolution) from the Gridded Soil Survey Geographic database (Soil Survey Staff, Natural Resources Conservation Service, U.S. Department of Agriculture, n.d.). Finally, canopy height was derived from the canopy height model derived from the 2015 USGS 3DEP point cloud (Carswell, 2016). All predictors were aggregated to the spatial scale of the forest cover layer (~ 30 m) before processing. Pre-processing the predictors for the random forest models was conducted using the sf (Pebesma, 2021), raster (Hijmans et al., 2011) and terra (Hijmans, 2021) packages.

We ran 50 iterations of random forest models with 500 trees each, using separate sets of 10 000 sample locations for each iteration. We predicted canopy height loss across all forested areas, and used the mean predicted values from the 50 random forest models to fill gaps in the lidar-derived estimates of watershed damage. To evaluate prediction accuracy, we sampled an additional 1000 locations from the forested areas in the study area without gaps and regressed observed against predicted values for the sample locations.

2.3 | Statistical analysis

2.3.1 | Hydrograph separation

To match the temporal resolution of the MSWEP rainfall data, we aggregated streamflow to mean 3-h values. All streamflow was

converted to specific discharge in millimetres per second (mm s^{-1}) by dividing by the contributing watershed area for each gage to account for variation in drainage area and facilitate cross-watershed comparisons. The term ‘streamflow’ in this document refers to specific discharge.

Using the 3-h mean streamflow time series for each watershed, we performed hydrograph separation into instantaneous quickflow and baseflow components using the Ladson et al. (2013) modified Lyne and Hollick digital filter (Ladson et al., 2013; Lyne & Hollick, 1979). We chose this method because the Lyne and Hollick filter outperformed both the Boughton and Eckhardt filters across a range of watershed characteristics and rainfall regimes as reported by Li et al. (2014). Ladson et al. (2013) further developed the method by suggesting standard methods that would enable easier comparison of results between studies. Using the guidelines set by Ladson et al. (2013), we chose to estimate baseflow using 9 passes and 30 reflection values. To ensure that we could compare results across multiple catchments (Duncan, 2019; Li et al., 2014), we employed a standard α parameter value of 0.925 as suggested by (Nathan & McMahon, 1990) (Figure 2). We approximated total baseflow and quickflow for each 3-h period (mm 3-h^{-1}) from instantaneous values by assuming a constant mean instantaneous value between measurement intervals. We conducted all analyses (see below) for baseflow and quickflow separately but referred to “flow” to reference methods examining both metrics independently.

2.3.2 | Short-term impacts of Hurricane Maria on streamflow

We used a DMC approach to evaluate whether forest damage from Hurricane Maria altered flow (Searcy et al., 1960). In this context, a DMC is a graphical technique that represents hydrological regimes within a given watershed by plotting cumulative values of a response variable (i.e., streamflow) against its driver (i.e., rainfall). The main assumptions of the DMC are that (1) a linear relationship exists between cumulative values of streamflow and rainfall if the ratio between the two remains constant, (2) a significant change in the slope of the DMC (i.e., break point) breaks the time series into a reference period and a disturbance period, (3) the time of the slope break point is representative of the time of the change in the ratios between the two variables when factors not related to rainfall significantly change flow (Gao et al., 2017; Searcy et al., 1960). DMCs are a useful visual tool for determining slope break points in time series, but must be statistically evaluated (Gao et al., 2017; Searcy et al., 1960; Zhang et al., 2012).

DMCs are generally conducted on streamflow data aggregated to monthly or annual scales to avoid noise and outliers in the slope time series, but aggregating to monthly time scales may mean that the immediate impacts of the storm are indiscernible. Streams in Puerto Rico are extremely responsive to rainfall (Schellekens et al., 2004) and recovered from the effects of a previous category 4 hurricane (Hugo) within 12–24 h (Scatena & Larsen, 1991), but as Hurricane Maria caused record-breaking rainfall in addition to more severe forest

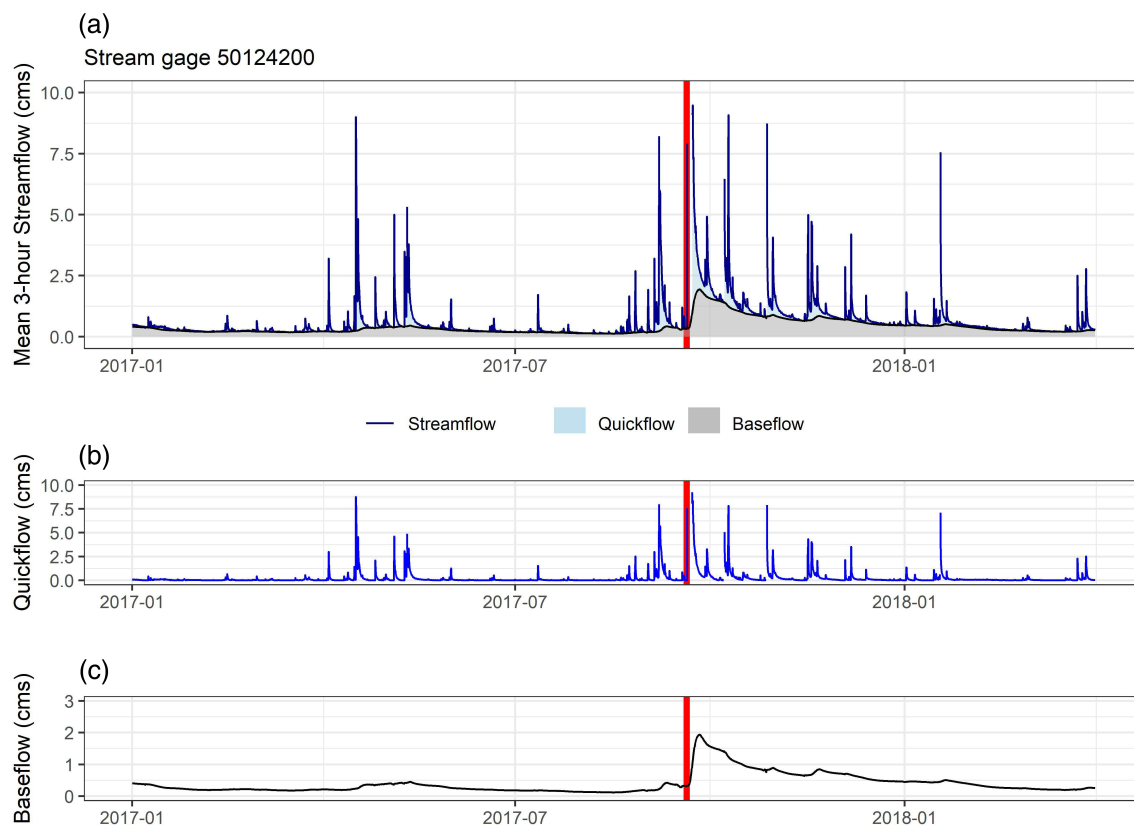


FIGURE 2 Mean 3-h streamflow time series for sample watershed (a) and the separated quickflows (b) and baseflows (c). Hurricane Maria is displayed as the vertical red line. Note this figure includes September 2017 for better visualisation of the change in streamflow after Hurricane Maria, and the y-axis has been truncated as streamflow in the days post-Maria was significantly higher than all other flow values.

damage than previous storms (Miller et al., 2019; Uriarte et al., 2019), we expected the effects from this hurricane to persist for longer than previously seen. Due to the flashy nature of the streams paired with rapid understorey regrowth (Leitold et al., 2021; Van Beusekom et al., 2018), we expected the streams to recover on finer timescales (i.e., months) than is generally evaluated with DMCs.

To balance the need for evaluating streamflow changes on finer timescales with the need for aggregating values for meaningful interpretations, we summed 3-h quickflow and baseflow for each day and estimated the cumulative values from 30-day moving average rainfall and flow values from October to November for each year of the study period (2010–2017). Cumulative values were calculated separately for each year. We centred the moving window on each day and used 15 days on either side of the day (e.g., values from November 30 are the mean of all values from November 15–December 14). By separating flow components at a fine temporal scale before aggregating to daily values and estimating the moving average values, we could account for fine-scale variation while considering monthly aggregations.

To evaluate the short-term impacts of Hurricane Maria on streamflow, we divided the 30-day moving average values into reference (before Hurricane Maria, October–November from 2010 to 2016) and disturbed (after Hurricane Maria, October–November 2017). By only using October–November flow values, we also controlled for rainfall seasonality. We quantified annual DMC slopes for

each watershed by regressing cumulative flow against cumulative rainfall using the “glS” function in the nlme package (Pinheiro et al., 2020) and accounted for temporal autocorrelation using a first order correlation term. For each watershed, we characterized pre-storm average slope and historical variability as the mean and range of annual DMC slopes during the reference period, respectively. We classified watersheds as having a significant change in stream response to rainfall after Hurricane Maria when disturbance period DMC slopes and 95% confidence intervals did not fall within the range of historical variability. We evaluated statistical significance of stream response separately for each streamflow component.

2.3.3 | Relationships between forest cover, forest damage and stream response

We used linear regressions to test whether estimates of forest cover and canopy damage explain the magnitude and direction of changes to quickflow and baseflow. Using separate models, we regressed relative change in stream response against forest cover and canopy damage. We determined whether forest cover and forest damage had a significant relationship with each streamflow component using regression model fit (R^2) and significance (p value) estimates. We assessed the direction of the relationships using regression line slopes.

To ensure that results were comparable across watersheds and to assess the relationship between forest damage and short-term streamflow response, we calculated the relative change in stream response to rainfall (i.e., the slope of the relationship) after the storm for each watershed as follows:

$$\text{Relative Change} = \frac{(\text{Slope}_{\text{After}} - \text{Slope}_{\text{Before}})}{\text{Slope}_{\text{Before}}}, \quad (1)$$

where slopes are DMC slopes for each watershed before and after the storm. We conducted separate analyses for watershed slopes from the DMCs of cumulative daily quickflow and baseflow to rainfall.

We also tested whether creating a relative estimate of forest damage that considers pre-storm watershed forest cover increased model fit (R^2) relative to a model that only considered canopy damage. To relate forest damage to forest cover, we used the following equation:

$$\text{Relative Forest Damage}_i = \frac{\text{Forest Damage}_i}{\text{Forest cover}_i}, \quad (2)$$

where for each watershed i , Forest Damage represents the percent canopy height loss across all forested areas of the watershed, and Forest Cover represents the forest cover of each watershed. By creating an estimate of forest damage relative to forest cover, we could evaluate whether damaged canopies in less-forested watersheds lead to a greater stream response to Hurricane Maria than those in heavily forested watersheds.

3 | RESULTS

3.1 | Short-term impacts of Hurricane Maria on streamflow

We fit linear regressions to DMCs of cumulative October–December quickflow and rainfall to determine changes in quickflow in the months after the storm (2017) compared with the same months in previous years (2010–2016). DMCs created from regressing cumulative quickflow (Figure 3) and baseflow (Figure 4) against cumulative rainfall indicate strong linear relationships between flow and rainfall before the storm.

In the 3 months following Hurricane Maria, we found quickflow DMC slopes increased in a third (6) of 18 watersheds, while 12 watersheds did not exhibit a significant change (Figure 3; Table 1). Of the 12 watersheds with no statistically significant change in quickflow, two appeared to have initial higher post-storm DMC slopes than had occurred within the historical range of variability, but midway through the post-storm study period the DMC slopes abruptly declined and were back in the historical range (Figure 3). This result suggests that factors influencing quickflow were rapidly re-established in the period after Hurricane Maria, however, the response was variable, and six watersheds saw an increase in quickflow relative to rainfall after the

storm that persisted for the entirety of our study period. In contrast, nearly half (8) of all 18 watersheds had significantly higher cumulative baseflow values relative to cumulative rainfall (Figure 4; Table 1), and all but one watershed had higher post-storm DMC slopes compared with pre-storm DMC average annual slopes (Table 1). This suggests that baseflow generally increased in the months after Hurricane Maria.

Two thirds (12) of all watersheds surveyed experienced post-storm increases in either baseflow or quickflow relative to rainfall volumes. Of these, two watersheds exhibited increases in both quickflow and baseflow, indicating increased total flow in the 3 months after Hurricane Maria relative to the same months in the years before the storm.

3.2 | Relationships between forest cover, forest damage and stream response

The random forest model predicted canopy height loss for 1000 sample point locations with 83% accuracy ($p < 0.01$) (Figure S3), indicating that the predicted canopy height loss values for areas without lidar coverage are reasonable. Residuals from the regression between observed and predicted values increase with increased observed canopy height loss (Figure S3), which suggests that there is a higher degree of uncertainty in our estimates of forest damage in highly damaged areas.

Watershed-level estimates of forest damage as mean percent canopy height loss in forested areas (Figure 1) ranged from 18.18% to 46.70%, and mean forest damage across the watersheds was 35.81% (Table 1). To assess how forest cover and forest damage affected short-term stream response to Hurricane Maria, we evaluated the relationships between each and the relative DMC slope change of cumulative quickflow (Figure 5a,b) and cumulative baseflow (Figure 5d,e) in the 3 months following the storm. In watersheds with high forest cover, quickflow relative slope change was lower ($R^2 = 0.40$, $p < 0.01$) (Figure 5a), and in watersheds that experienced greater forest damage, quickflow relative slope change was higher (Figure 5b) ($R^2 = 0.19$, $p < 0.01$). Inversely, we found that baseflow relative slope increase was greater in watersheds with high forest cover, although the proportion of variance explained by the model was low ($R^2 = 0.05$, $p < 0.01$) (Figure 5d). In watersheds with high forest damage, we found that baseflow relative slope increase was less pronounced ($R^2 = 0.27$, $p < 0.01$) (Figure 5e).

We hypothesized that damage to forested areas in less-forested watersheds would result in greater hydrological changes than in more forested watersheds, and tested this premise by examining whether weighting estimates of forest damage by watershed forest cover improved the relationships between forest damage and relative DMC slope changes in streamflow metrics (Figure 5c,f). Although the direction of the relationships did not change, we found that weighting estimates of forest damage by forest cover improved R^2 values for quickflow from 0.19 to 0.40 but did not improve the regressions between baseflow and forest damage (Figure 5b,c).

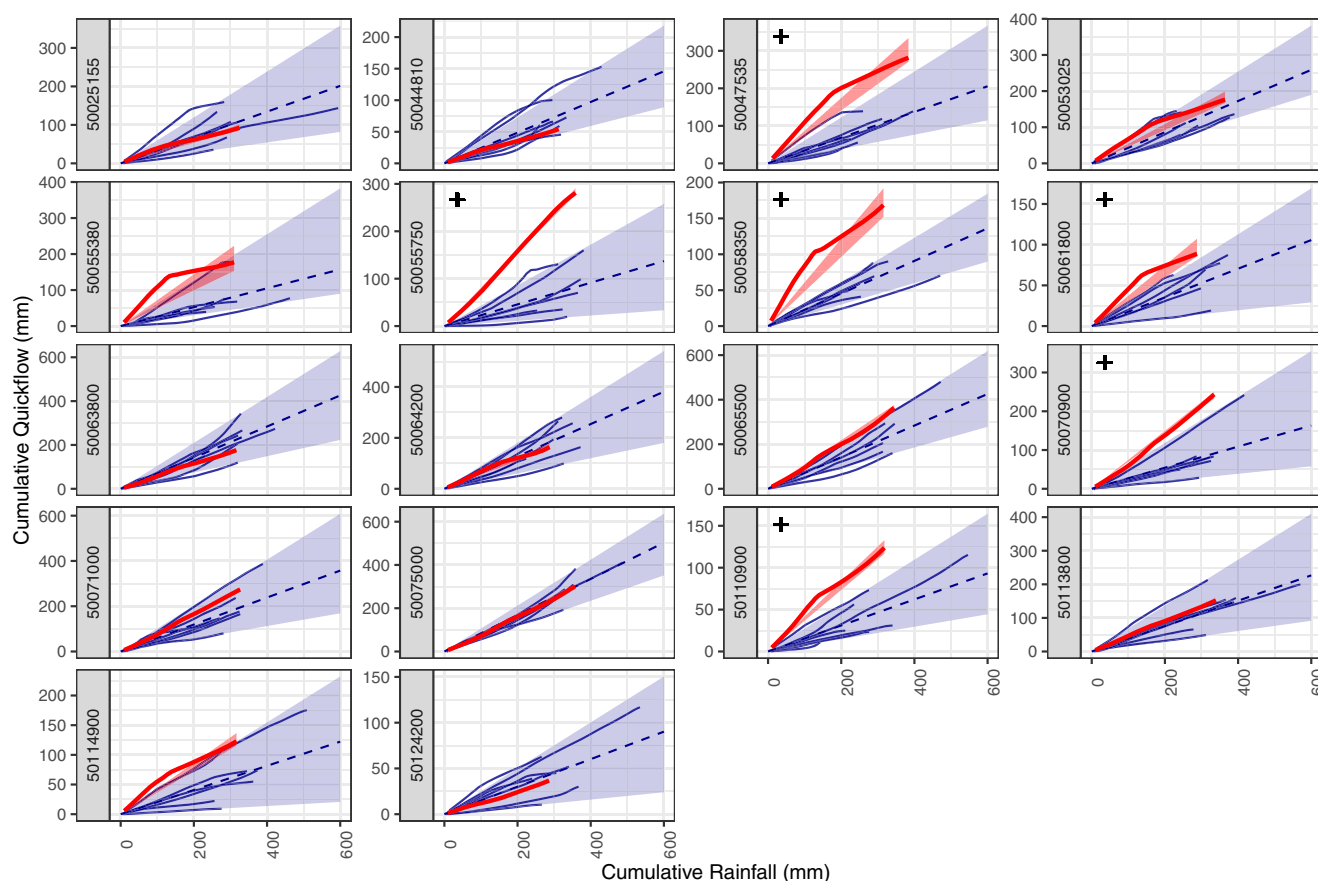


FIGURE 3 Daily double mass curves showing annual relationships between quickflow and rainfall at each of the 18 watersheds for pre- (blue, October–November 2010–2016) and post- (red, October–November 2017) Hurricane Maria. Dotted lines indicate predicted values using coefficients from linear regressions of average pre-storm values, and blue shaded areas represent the historical range of variation taken from the minimum and maximum pre-storm slopes for each watershed. Red shaded areas represent 95% confidence intervals of post-storm slopes and + symbols indicate watersheds with significant slope increases after Hurricane Maria.

4 | DISCUSSION

The primary goal of this study was to examine streamflow response to rainfall in a tropical forest system in the 3 months following hurricane disturbance, and to evaluate whether the magnitude of watershed-scale forest damage from the storm explains observed changes. A novel aspect of this analysis was our attempt to distinguish the influence of pre-existing forest cover and forest damage from a major hurricane on streamflow response, and to elucidate interactions between the two. This is crucial for identifying forest cover loss thresholds for hydrological impacts under expected changes in natural disturbance regimes. In the 3 months after Hurricane Maria, we found higher baseflow relative to rainfall for nearly half surveyed watersheds compared with the same months in previous years, and higher quickflow relative to rainfall for one third of watersheds. The magnitude of change in quickflow was positively correlated with the degree of forest damage from the storm and negatively correlated with percent forest cover. Compared with quickflow, we found inverted relationships between changes to baseflow and forest cover or damage, with greater baseflow increases in watersheds with high forest cover and low forest damage. Our findings are consistent with previous studies

evaluating the role of tropical cyclone-related forest degradation on changes to streamflow regimes (Chen et al., 2015; Jayakaran et al., 2014; Musser et al., 2017; Zhang et al., 2019) and point to a significant reduction in canopy rainfall interception and transpiration following the storm. By evaluating the effects of disturbance across watersheds with different pre-existing forest cover, we were also able to separate the effects of forest damage and forest cover which were only modestly correlated ($r = 0.36$) and discern how interactions between the two influence hydrological response thresholds. We found forest damage subdued post-disturbance increases in quickflow in highly forested watersheds and magnified them in less-forested watersheds. Our results indicate that less-forested watersheds are more vulnerable to subsequent flooding in the months following forest disturbance than heavily forested watersheds.

In our study, we found higher post-storm quickflow in some watersheds given the same rainfall amounts, suggesting that buffering of intense rainfall by canopy interception is a major factor in maintenance of stream ecosystem services in forested tropical watersheds. Rainfall intensities during periods of high rainfall likely surpass infiltration rates in Puerto Rico, even in highly forested areas (Clark et al., 2017; Larsen & Simon, 1993). Previous studies conducted in

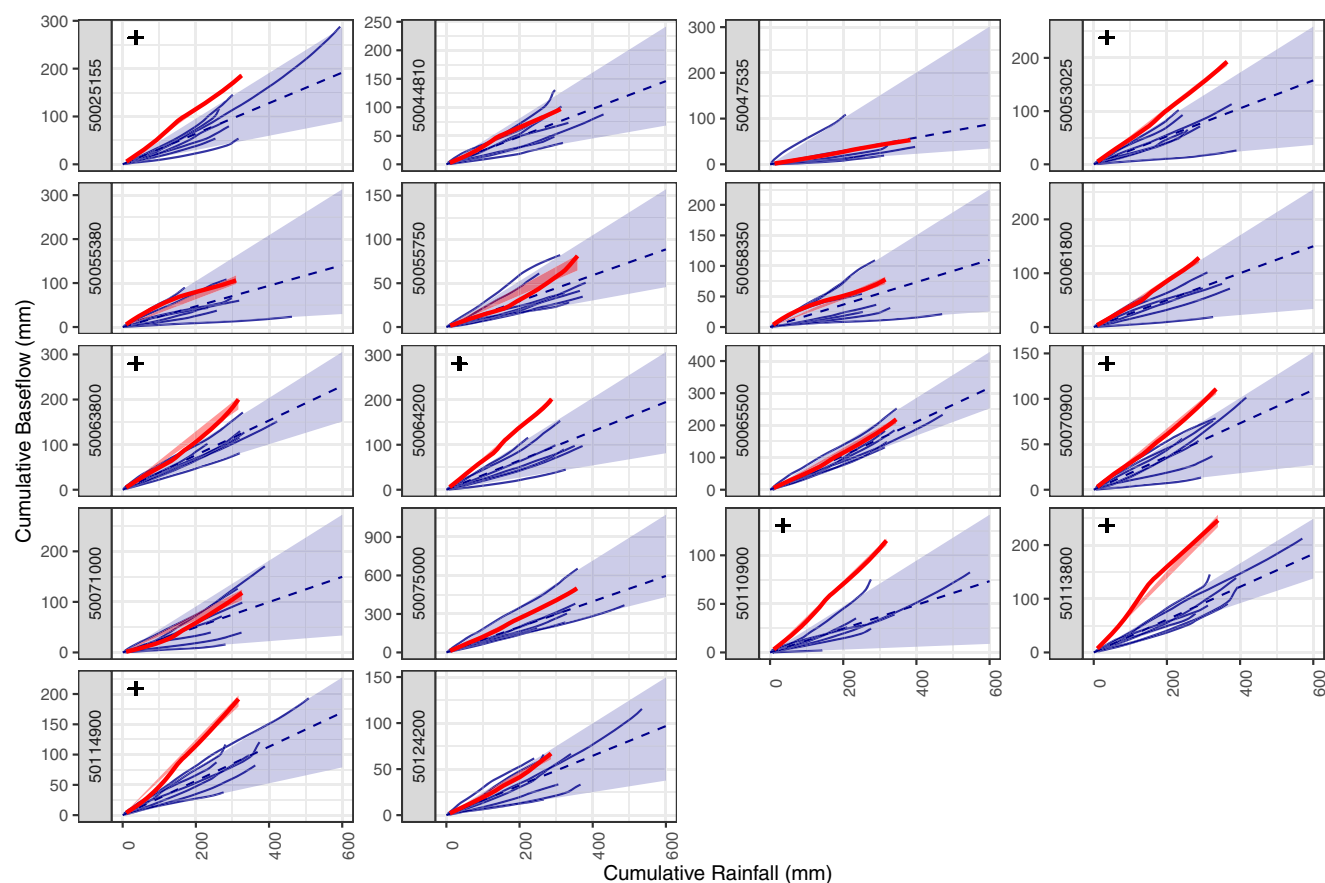


FIGURE 4 Daily double mass curves showing watershed-level relationships between baseflow and rainfall pre- (blue, October–November 2010–2016) and post- (red, October–November 2017) Hurricane Maria. Dotted lines indicate predicted values using coefficients from linear regressions of average pre-storm values, and blue shaded areas represent the historical range of variation taken from the minimum and maximum pre-storm slopes for each watershed. Red shaded areas represent 95% confidence intervals of post-storm slopes and + symbols indicate watersheds with significant slope increases after Hurricane Maria.

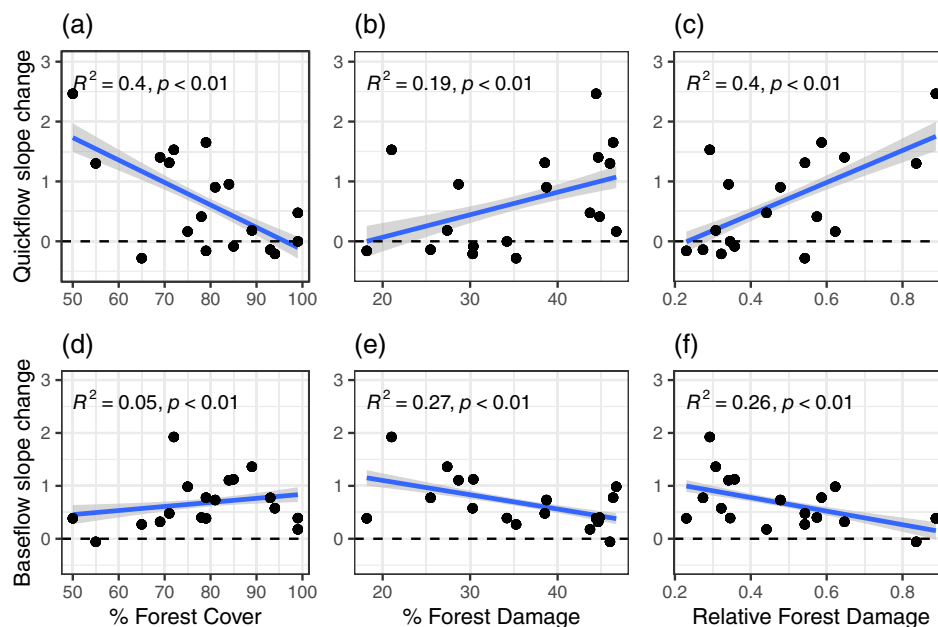
Puerto Rico (Beck et al., 2013; Clark et al., 2017; Hall et al., 2022; Ramírez et al., 2009) have characterized peak flow as a rapid response to rainfall regardless of forest cover or rainfall conditions. That we found evidence of an increase in quickflow-rainfall relationships indicates that presence of intact forest canopy in this system reduced overland and shallow subsurface flow before disturbance. This is consistent with previous studies evaluating post-storm quickflow and suggests that watersheds with less forest cover are more vulnerable to increases in quickflow after forest disturbance than highly forested watersheds, confirming the role of forest cover in lessening the effects of rainfall extremes on streamflow (Krishnaswamy et al., 2012; Zhang et al., 2018).

Twelve of the watersheds experienced no significant changes in quickflow relative to rainfall after Hurricane Maria. A lack of persistent post-hurricane quickflow response generally reflected low levels of damage as vegetation in these watersheds may have recovered quickly, increasing vegetation water use faster than more heavily damaged watersheds. One of these watersheds was the least damaged of all watersheds surveyed (18% canopy loss) and the farthest from the hurricane storm path, while all but three had lower damage values than the majority of the watersheds that displayed higher

quickflow after disturbance (25th quantile = 40%). Additionally, many watersheds that exhibited no change in quickflow after the storm had high forest cover (>85%), suggesting that remaining canopy structure in damaged canopies continued to intercept rainfall even when the majority of biomass had been moved from the canopy to the understorey. Finally, watersheds experiencing non-significant quickflow changes did not differ in drainage area from those experiencing positive changes, suggesting that scaling effects are not a contributing factor.

We found statistically significant baseflow increases in approximately half of all watersheds in the 3 months after the storm. We also found higher, if insignificant, post-storm DMC slopes than the average pre-storm DMC slopes in all but one watershed. This suggests that hurricane-related rainfall recharge in addition to a reduction in transpiration led to an increase in groundwater contribution to streams or augmented additional streamflow generating processes relating to slow stream response to rainfall (Chen et al., 2015). It is possible that the observed increase in baseflow reflected the continued release of the record-breaking rainfall volume from the storm (Keellings & Hernández Ayala, 2019) rather than a reduction of transpiration. However, we partially accounted for this possibility by removing the

FIGURE 5 Relationships between relative change in slope of baseflow and quickflow after Hurricane Maria and watershed forest cover, percent canopy height loss in forested areas within the watershed, and percent canopy height loss normalized by forest cover. Relative proportional changes in slopes after Hurricane Maria are shown on the y-axis, and watershed forest cover (a, d), percent canopy height loss in forested areas within the watershed (b, e), and percent canopy height loss relative to forest cover (c, f) are shown on the x-axis for quickflow, and baseflow, respectively.



month Hurricane Maria hit Puerto Rico (September 2017) from all analyses, so the first estimates of baseflow were 10 days following the storm. High elevation forested watersheds in the north-eastern Luquillo Experimental Forest in Puerto Rico transit storm rainfall from overland and shallow groundwater flow within hours (Schellekens et al., 2004; Scholl et al., 2015), and streamflow in the Luquillo Experimental Forest returned to normal conditions (pre-storm values) within 1 day of the previous major hurricane (Scatena & Larsen, 1991). Our finding of increased baseflow in the months following Hurricane Maria is likely a combination of gradual drainage of extreme storm-related rainfall paired with increased recharge through soil reservoirs following unprecedented canopy damage and defoliation. Our results are also more representative of stream response to disturbance across the island, as many studies evaluating the impacts from previous hurricanes have focused on the small catchments in the Luquillo Experimental Forest.

Because we separated streamflow into responses to rainfall at short (quickflow) and long (baseflow) timescales, we were able to evaluate whether forest damage influenced one or both independently. We found that forest damage inversely affected the magnitude and direction of quickflow and baseflow response to Hurricane Maria. This result supports our initial hypothesis that changes to quickflow were caused from a combination of the increase in rainfall reaching the surface through defoliated canopies and reduced forest water demand, but our result that watersheds with high forest damage had no significant increase in baseflow came as a surprise. It is possible that this result is due to many of the most highly damaged watersheds also being some of the wettest and most resilient to change. Half of the watersheds with no significant change to baseflow were completely or partially located in El Yunque National Forest, a tropical rainforest with mean annual rainfall of up to 4600–5000 mm year⁻¹ (Murphy et al., 2017). The Luquillo Experimental Forest, located within the El Yunque National Forest, has been shown to have deep soil profiles

(up to 9 m) with high soil water storage potential (Post & Jones, 2001). This combination of high rainfall and deep soils has led previous studies to find a gradual baseflow release to streams with little monthly response to changes in rainfall (Hall et al., 2022; Post & Jones, 2001). However, the increases in baseflow that we found in many watersheds throughout Puerto Rico support our initial hypothesis that baseflow increases were caused by greater infiltration and groundwater recharge (Chen et al., 2015; Jayakaran et al., 2014).

As vegetation regrows and forest water demand increases (Jayakaran et al., 2014), streamflow components may recover at different time scales (Buma & Livneh, 2017; Harman et al., 2011). Rapid canopy regreening after defoliation increases rainfall interception and can lead to quickflow recovery within weeks after a large forest disturbance (Ellison et al., 2012; Malmer et al., 2010), while soils may remain saturated for weeks or months after the storm, prolonging elevated baseflow levels (Zhang et al., 2018). Forests can also take up to a decade to recover lost biomass from broken, uprooted, and highly damaged trees (Heartsill-Scalley et al., 2007). If the magnitude of forest damage is high enough, recovery to pre-disturbance values may take years or decades (Post & Jones, 2001). Examining the long term effects of forest degradation resulting from cyclonic storms in subsequent studies would offer an opportunity to further understand these processes.

Although hurricane-induced forest damage generally led to increases in quickflow after the storm, the magnitude of this effect depended on watershed forest cover. After Hurricane Maria, watersheds with high pre-existing forest cover had smaller increases in quickflow than those with low forest cover, suggesting that forests stabilize streamflow dynamics. Rainfall interception and resulting canopy evaporation keep up to 50% of gross rainfall from reaching the soil surface in the dense canopies in Puerto Rico (Schellekens et al., 1999). High tree mortality through uprooting and stem breaks (Uriarte et al., 2019) reduced canopy heights and moved much of the

dense canopy branch and leaf litter closer to the ground (Hall et al., 2020). In highly forested Puerto Rican watersheds, it is possible that there was enough remaining canopy, dislodged canopy and understorey biomass to intercept and slow rainfall even after much of the canopy was damaged.

Our estimate of forest damage was also more closely related to changes in quickflow when related to watershed forest cover than when used alone. The magnitude and direction of the hydrological impacts on streams are closely related to watershed characteristics and the extent of forest damage (Buma & Livneh, 2017). An improved relationship between the change in DMC quickflow slopes and forest damage relative to forest cover means that forest damage is more likely to result in hydrological impacts in less-forested watersheds than in highly forested watersheds. Forest cover, even if damaged, likely reduces quickflow sensitivity to disturbance. The damage to forests resulting from strong storms may be substantial enough to match deforestation in severity. As less-forested watersheds are closer to the forest cover loss threshold needed to elicit a streamflow response following forest damage, they may have a lower storm-related forest disturbance threshold response following forest damage while highly forested watersheds remain protected (Wei et al., 2021). However, the nature of storm-related forest damage differs from that of deforestation; rather than losing forest cover completely, canopy height is reduced and living biomass is lost. More research is needed to determine the relationships between forest cover loss thresholds and the type and magnitude of storm-related forest damage.

5 | CONCLUSIONS

Here, we presented a spatially explicit examination of forest damage from Hurricane Maria on streamflow in Puerto Rico. We studied watersheds with 50%–99% forest cover and 18–47% forest damage (relative canopy height loss) and observed post-hurricane baseflow increases in nearly half of all cases. We also saw quickflow increases in most watersheds with greater than 39% canopy damage, while all watersheds with unchanged post-storm quickflow had over 85% pre-storm forest cover. Our results suggest that maintaining moderate levels of forest cover in areas with high rainfall amounts can greatly increase streamflow resilience to disturbance. Forest conservation and management will be critical in maintaining water provision under expected increases in the frequency of severe disturbance.

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DATA AVAILABILITY STATEMENT

All novel statistical and mathematical code used to generate results of this study will be provided in the Dryad database upon publication. See in-text citations for all publicly available datasets used in this study (e.g., streamflow, rainfall, forest cover). RMS HWind data, although not necessary to replicate the critical components of this analysis, is proprietary and cannot be provided but can be requested from RMS.

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SUPPORTING INFORMATION

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