Exotic Plantations Increase Risks of Flooding in Mountainous Landscapes

Rajat Nayak[1,1], Jagdish Krishnaswamy[2,2], Srinivas Vaidyanathan[1,1], Nick Chappell[3,3], Kumaran Kesavan[1,1], Prachi Ghatwai[2,2], and Ravinder Singh Bhalla[1,1]

[1]Foundation for Ecological Research, Advocacy and Learning
[2]Ashoka Trust for Research in Ecology and the Environment
[3]Lancaster University

November 30, 2022

Abstract

We examined the effect of land cover on stream discharge in hilly catchment streams during extreme rain events. Three years of rainfall-runoff observations, between January 2014 and December 2016, were collected in eleven neighbouring catchments. Each catchment was dominated by a different land cover, namely natural shola forests, natural grasslands and wattle (Acacia mearnsii). Rain intensities between percentiles 25-90, 90-95 and over 95 were categorised as light, heavy and extreme and were used to study stream discharge responses. Land cover significantly influenced the hydrologic response to extreme rain events. During light rains (< 38 mm/day), grassland dominated catchments showed higher discharge than shola (0.01 mm/s) and wattle (0.004 mm/s). However, during extreme rain events (> 71 mm/day) discharge was significantly higher in wattle dominated catchments when compared to the natural shola (0.033 mm/s) and grasslands (0.023 mm/s). Antecedent moisture conditions played a major role in determining peak flows along with rainfall, catchment shape and drainage density.

Exotic Plantations Increase Risks of Flooding in Mountainous Landscapes

Rajat Ramakant Nayak[1], Jagdish Krishnaswamy[2], Srinivas Vaidyanathan[1], Nick A Chappell[3], Kumaran K[1], Ghatwai, Prachi[2] and R. S. Bhalla[1]

[1]Foundation for Ecological Research, Advocacy and Learning, Pondicherry, India

[2]Ashoka Trust for Research in Ecology and the Environment, Bangalore, India.

[3]Lancaster Environment Centre, Lancaster University, U.K.

Key Points:

- Stream flow is faster in wattle dominated catchments during extreme rain than native grassland or shola forest and may contribute to floods.
- Land cover, along with antecedent moisture and topographic conditions determine rain-runoff responses during extreme events.
- Hydrologic footprint of exotic invasives have consequences for ecosystems and human well being which outweigh perceived carbon benefits.

Corresponding author: R. S. Bhalla, `bhalla@feralindia.org`

Abstract

We examined the effect of land cover on stream discharge in hilly catchment streams during extreme rain events. Three years of rainfall-runoff observations, between January 2014 and December 2016, were collected in eleven neighbouring catchments. Each catchment was dominated by a different land cover, namely natural shola forests, natural grasslands and wattle (*Acacia mearnsii*). Rain intensities between percentiles 25-90, 90-95 and over 95 were categorised as light, heavy and extreme and were used to study stream discharge responses. Land cover significantly influenced the hydrologic response to extreme rain events. During light rains (< 38 mm/day), grassland dominated catchments showed higher discharge than shola (0.01 mm/s) and wattle (0.004 mm/s). However, during extreme rain events (> 71 mm/day) discharge was significantly higher in wattle dominated catchments when compared to the natural shola (0.033 mm/s) and grasslands (0.023 mm/s). Antecedent moisture conditions played a major role in determining peak flows along with rainfall, catchment shape and drainage density.

Plain Language Summary

Increasing frequency of extreme rain events is a cause of concern as they often trigger floods and consequent damage. We found that catchments dominated by wattle plantations, an invasive alien species, cause significantly quicker discharge during extreme rain events when compared with the natural grassland and montane forest (shola) mosaics. Our study, located in the Upper Nilgiris in the Western Ghats mountains of Southern India, also found that stream-flows in wattle dominated catchments were lower than those of grassland dominated catchment during the dry season. We demonstrate that invasive wattle plantations have a significant hydrologic footprint which alters the rainfall-runoff behaviour of catchments in the Western Ghats. Widespread plantations of exotic species in the region, which include Eucalyptus, various acacia and pines, could have serious hydrologic consequences and could similarly alter rain-runoff response by exacerbating floods during the monsoon and reducing stream-flow and hydro-power generation during the dry season.

1 Introduction

Global climate change scenarios often show an increased frequency of extreme events, particularly rainfall, which is a major concern worldwide (Goswami et al., 2006; Guhathakurta et al., 2011; Mason et al., 1999; Osborn et al., 2000; Zhou et al., 2013). Such extreme rain events (ERE) often lead to destructive floods causing extensive loss of lives and property (Fowler & Kilsby, 2003; Guhathakurta et al., 2011; Mishra & Shah, 2018; Ranger et al., 2011). During heavy rains, the saturated hydrologic conductivity of soils is quickly exceeded (Koutnỳ et al., 2014) and sub-surface flow pathways get activated (Chappell et al., 2017; Bonell et al., 2010), resulting in higher and quicker discharge from the basin. The problem is more serious in mountainous terrain where steep slopes accelerate the accumulation of stream water leading to a rapid discharge of rain water and sediments downstream (Serrano-Muela et al., 2015). Understanding the relationship between rainfall and discharge can help design mitigation strategies for destructive floods. Such relationships need to be studied at local scales as most water-flow enters rivers via low-order channels and is governed by catchment characteristics and micro-climate (Borga et al., 2014). A large number of local factors such as steepness of slopes, catchment shape and size, drainage networks (D'Odorico & Rigon, 2003; Rinaldo et al., 1991) and antecedent moisture (Chappell et al., 2017; Haga et al., 2005; Kim et al., 2019; Song & Wang, 2019) influence the rainfall-runoff relationship.

Vegetative cover is probably the most easily managed characteristic of the catchment which plays a significant role in mediating the rain-runoff response. Vegetation can alter retention capacity and infiltration of precipitation in headwaters (Koutnỳ et al., 2014). Certain vegetation adds organic matter to the soil, arresting erosion by slowing down surface runoff (Bathurst et al., 2011; Koutnỳ et al., 2014; Krishnaswamy et al., 2012). Replacing natural vegetation with fast growing species(Calder & Dye, 2001; Jackson et al., 2005; Venkatesh et al., 2014) including those found in the Western Ghats such as eucalyptus (Sikka et al., 2003; Chand et al., 2009; Sharda et al., 1988; Samraj et al., 1988), wattle (Dye & Jarmain, 2004; Prinsloo & Scott, 1999; Clulow et al., 2011) greatly increases evapotranspiration and can have serious impacts on stream flow, particularly during the dry season.

Understanding the relationship between rainfall and peak discharge in this altered landscape is also critical for flood prediction. The hydrologic impact of wattle in has not been empirically established in the Nilgiris (Rangan et al., 2010) and this study tries to address this gap. Here, we compare the hydrologic response of the two native land covers, grasslands and shola forests, and the introduced invasive wattle. Woody invasives could enhance transpiration and thus reduce antecedent moisture. At the same time their litter may not integrate into soil compared to native vegetation thereby reducing infiltration (Bonell et al., 2010).

1.1 Study Area

The Nilgiris or Blue Mountains, 76°-77°15'E: 11°15'-12°15'N, are within the Western Ghats Biodiversity hot-spot (Myers et al., 2000)and are part of the Nilgiri Biosphere Reserve, the first biosphere-reserve established in India in 1986 (Daniels, 1996). The Nilgiris are home to 15 different indigenous tribes and harbour a large number of threatened and endemic species of flora and fauna (Daniels, 1996). Elevation in the Nilgiris ranges from 1000 m to 2600 m asl which has given rise to diverse vegetation types such as montane-rain-forests in the valleys, locally known as sholas, interspersed by high-altitude grasslands.

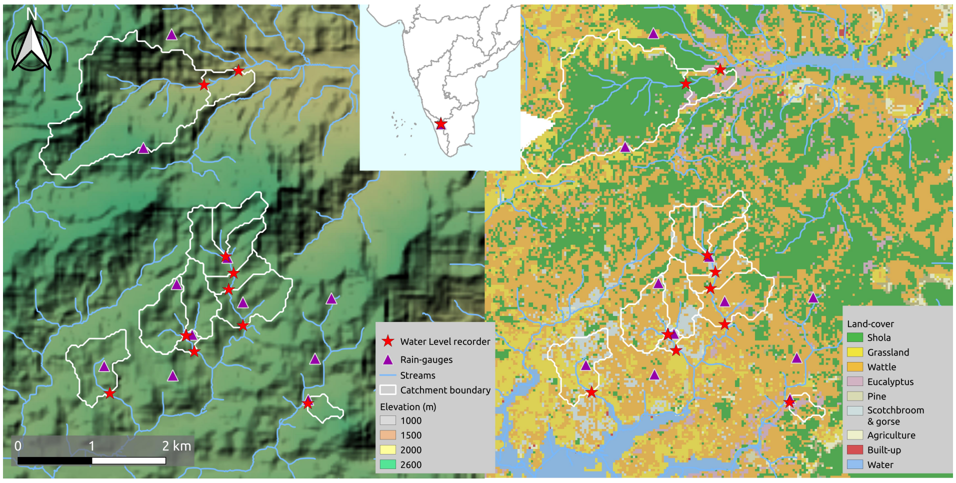

Figure 1. The Upper Nilgiris showing different catchments and the locations of water level recorders and rain-gauges. Left panel shows elevation gradient and right panel shows land-cover types in different catchments.

This study was conducted in the Nilgiris Reserve Forest, in the Western Ghats mountains in South India (Figure 1). Nilgiris forms an important catchment area for several perennial tributaries of the Cauvery (India - WRIS Project Team, n.d.) including the Bhavani, on which large human populations are dependent downstream. These streams and rivers are managed extensively for power generation, irrigation and drinking water through a chain of dams and reservoirs (*Upper Bhavani Dam D00756* -, n.d.). In the year 2018 and 2019, several parts of the Western Ghats have repeatedly witnessed heavy rains, and subsequent floods have destroyed several villages and triggered a large number of landslides leading to the loss of many human lives and livelihoods (Mishra et al., 2018; Arathi Menon, 2019; Safi, 2018). Avalanche, in the Nilgiris, where the project site is located, was the epicentre of ERE during August 2019, which resulted in a large number of landslides and floods throughout the region (Premkumar, 2019; TWC India, 2019). Unfortunately, the floods washed away all the water level recorders. Floods and landslides in the Western Ghats have often been attributed to changes in land-cover and land-use (Kumar & Bhagavanulu, 2008) over the last century. A large number of exotic plants were introduced in the natural grasslands and sholas, and some of these exotics, particularly, wattles, *Acacia mearnsii* and *Acacia dealbata*, have invaded natural grasslands (Joshi et al., 2018).

2 Materials and Methods

2.1 Data Collection

We conducted our study in the 1000 km^2 area of the Nilgiris Forest Division which covered 11 catchments dominated by three distinct land covers: sholas (2 catchments), montane grasslands (1 catchment) and wattle (8 catchments) (Table 1). We collected and analysed three years of rainfall-runoff data from January 2014 to December 2016. Data from after 2016 was not used because a forest fire in the last weeks of February, 2017, completely altered the land cover (Sriramamurthy et al., 2020). Rainfall was measured at one minute intervals from 26 tipping bucket rain gauges (RainWise, 2012) placed in an approximate grid of one kilometre. Ten of these were located within the study catchments. We used the mean rainfall recorded when two or more rain gauges were present in the same catchment. Water levels were measured at five minute intervals in eleven streams instrumented with stilling wells and capacitance probe based water level records (WLRs) (Dataflow Systems Limited, 2017), stage values were converted to discharge using the velocity-area method (Shaw et al., 2010). The streams were low order (1-3) and the total catchment area covered was 1,200ha. Digital Elevation Models obtained from SRTM (NASA JPL, 2013) were used to delineate the catchments. Dominant vegetative cover in each of the catchments (henceforth referred as land cover) was estimated from a supervised vegetation map generated using Landsat 8 images for the year 2017 (additional description in Appendix A).

Table 1. Land cover and other morphometric characteristics of the catchments.

Catchment ID	Land cover	Area (ha)	Elevation range (m)	Shape	Steepness	Drainage density (m/m^2)	Rainfall range (mm)
101	Wattle	28.026	2,344 - 2,588	0.4508	1.031	0.0013	1,898 - 5,165
102	Wattle	81.63	2,329 - 2,588	0.6076	0.937	0.0016	1,898 - 5,165
103	Wattle	44.33	2,292 - 2,412	0.6062	0.819	0.0015	1,900 - 5,138
104	Wattle	81	2,290 - 2,412	0.5471	0.793	0.0014	1,900 - 5,138
105	Wattle	101.14	2,325 - 2,588	0.513	0.895	0.0015	1,898 - 5,165
106	Wattle	87.29	2,281 - 2,412	0.5944	0.806	0.0018	1,473 - 4,252
107	Grassland	50.51	2,279 - 2,371	0.5349	0.729	0.0013	1,427 - 3,979
108	Shola	258	2,052 - 2,588	0.5102	1.21	0.0016	2,719 - 7,238
109	Shola	280.03	2,004 - 2,588	0.4291	1.195	0.0017	2,719 - 7,238
114	Wattle	150.97	2,282 - 2,588	0.4631	0.847	0.0016	1,790 - 4,987
115	Wattle	10.76	2,283 - 2,481	0.6051	0.978	0.0001	1,011 - 3,130

Note: Dominant vegetative cover of catchment; Shape: Catchment shape measured by the circulatory Index CI; Steepness: Mean steepness of slope factor.

Four different catchment morphological characteristics – shape, area, steepness of the slopes, and drainage density, were derived for each of the catchments. Catchment shape was measured using the circularity index (CI) or ratio which could help forecasting the flood potential of a basin. The CI is expressed as $CI = Ab/Ac$, where Ab is the area of the basin and Ac is the area of a circle with the same length of perimeter as the basin (Allaby, 2013). A layer of drainage networks was developed using r.watershed module in GRASS 7 (GRASS Development Team, 2018). Drainage density was expressed as m/m^2 for each catchment. Steepness of the catchment slope was also obtained using r.watershed module which generates slope steepness factor as defined for Universal Soil Loss Equation (McCool et al., 1987). The soil type was similar across all the catchments as per the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) (Sehgal et al., 1987), and is described as clayey-skeletal, mixed typic haplustalfs and typic Ustropepts (Table 1).

2.2 Analysis

Data processing and analysis was carried out using the R statistical software (R Core Team, 2018). Daily rainfall was grouped into three categories: i) low intensity (light rain) - rainfall values between 25^{th} percentile ($\geq$1.3 mm/day) and 90^{th} percentile ($<$ 5.0 mm/day); ii) heavy rain - between 90^{th} percentile ($\geq$38.0 mm/day) and 95^{th} percentile ($<$ 71.0 mm/day); and iii) extreme rainfall - 95^{th} percentile and above ($\geq$71.0 mm/day).

We excluded data from the dry season (January to April) from the analysis. Discharge (m^3s^{-1}) was measured for each stream as mean daily discharge and peak daily discharge (the maximum discharge recorded in a day). Discharge was then divided by the area of the corresponding catchment to obtain unit mean and unit peak daily discharges (mm s^{-1}).

We analysed rainfall-runoff records from 8,469 days across all the catchments. Antecedent moisture conditions are known to influence rainfall-runoff relationships (Chappell et al., 2017; Haga et al., 2005; Kim et al., 2019; Song & Wang, 2019). We therefore derived an antecedent moisture index (AMI), which is an approximation of the moisture stored within a catchment before a particular rainfall event. AMI was developed by deducting total stream flow from the cumulative rainfall over the 14 antecedent days. We found a strong correlation, r=0.96, between this index and the widely used antecedent precipitation index (API) (Kohler & Linsley, 1951) developed using a decay constant (k) value of 0.9 and considering 14 antecedent days (more details in Appendix B).

Scatter plots of (log) daily rainfall versus daily unit mean discharge and daily peak discharge suggested an exponential relationship (Fig 3 (a). This relationship was further analysed with exponential regression models using normalised values for the data. We used additive exponential regression models to test the influence of catchment land cover and other morphometric characteristics on discharge, including daily rainfall and AMI. Variables introducing collinearity in the model were identified using generalised variance inflation factor (GVIF) (Fox & Monette, 1992). Thus, catchment area and steepness of the slope were removed as they were highly correlated ($\mathrm{GVIF}^{(1/(2^*\mathrm{Df}))} > 2.00$) with land cover, catchment shape and drainage density. The most plausible explanatory variables and the best model for describing relationship between measured runoff and rainfall was selected using Akaike Information Criteria with bias adjustment (AICc) (Burnham & Anderson, 2002). The rainfall only model was used as a null model to compare the results. Model averaged coefficients were used whenever delta AICc values of less than 2 were obtained and relative variable importance values were used to select the most plausible explanatory variable.

For anlysing peak discharge, we calculated total rainfall for 24 hours starting from the time of peak discharge upto 24 hours before the event. Similarly, an AMI was developed considering the time of peak discharge. Additive exponential regression models, AICc, and relative variable importance values were used to select the most plausible explanatory variables across different rainfall intensities. In addition we estimated the time lag between daily peak discharge (m^3s^{-1}) and daily maximum rainfall (mm min^{-1}) across all the catchments. Finally, the relationship between peak discharge and catchment characteristics using box and whisker plots and regression models.

3 Results

The Nilgiris received the bulk of its rainfall between June and September (Figure 2) with an annual average of 2150mm over the three years, a maximum of 2,740 mm during 2014 and a minimum of 1,380 mm during 2016. We analysed a total of 5,542 days of rain events ($\geq$ 0.2 mm rainfall) across all the catchments. There were 3,607, 272 and 277 events in light, heavy, and extreme rainfall intensity categories, respectively.

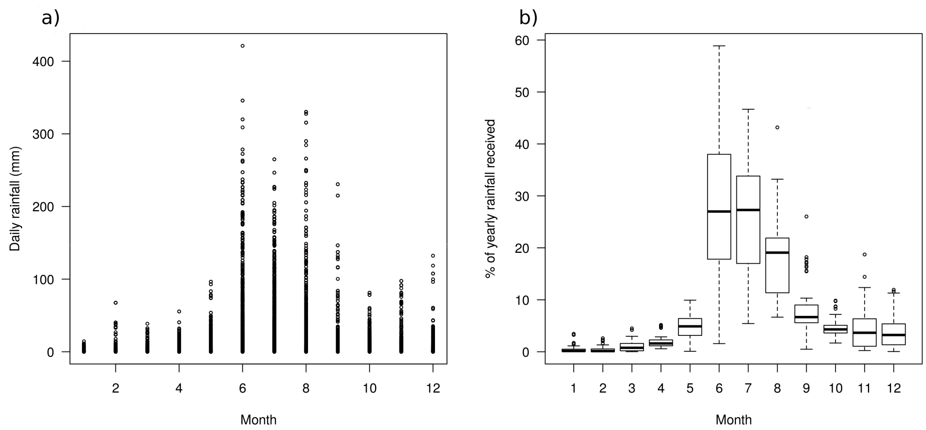

Figure 2. a) Distribution of daily rainfall across the months between 2014 and 2016. b) Contribution of each month's rainfall to the total annual rainfall across all the years. Most of the rainfall was received between June and September.

As expected, an increase in discharge with an increase in daily rainfall was observed. However, this relationship showed high variations across catchments for different rainfall intensities (Figure 3 & Figure 4). Scatter-plots and fitted exponential curves between daily rainfall and unit mean and peak daily discharges suggested greater stream discharges in grasslands and sholas when compared to wattle plantations during light rain (Figure 3 (b) & Figure 4 (b), whereas trends for wattle were above grassland and shola with increase in rainfall intensities (Figure 3 (c & d), 4 (c & d)).

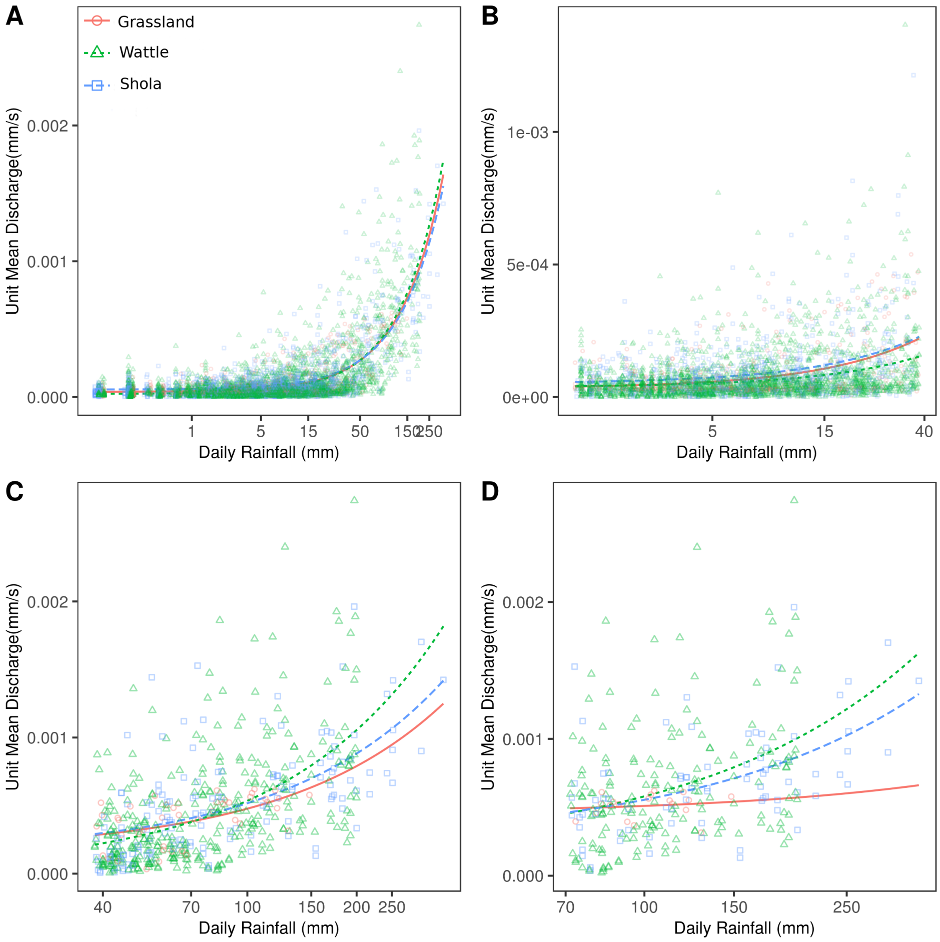

Figure 3. Mean daily discharge values plotted against log of daily rainfall suggest an exponential relationship between rainfall and runoff. This relationship varies with catchment land cover type and rainfall intensity. As the rainfall intensity increases discharge from wattle changes from lowest in light rain to the highest during ERE. a) All rainfall events, discharge of wattle > grassland > shola; b) light rain (< 38 mm/day) discharge of shola ≥ grasslands > wattle; c) heavy and extreme rain (≥38 mm/day), discharge shola > wattle > grassland; d) extreme rain (> 71 mm/day) discharge of wattle > shola > grasslands. Exp(R): Exponential rainfall; p=probability; AICc: Akaike Information Criteria with bias adjustment.

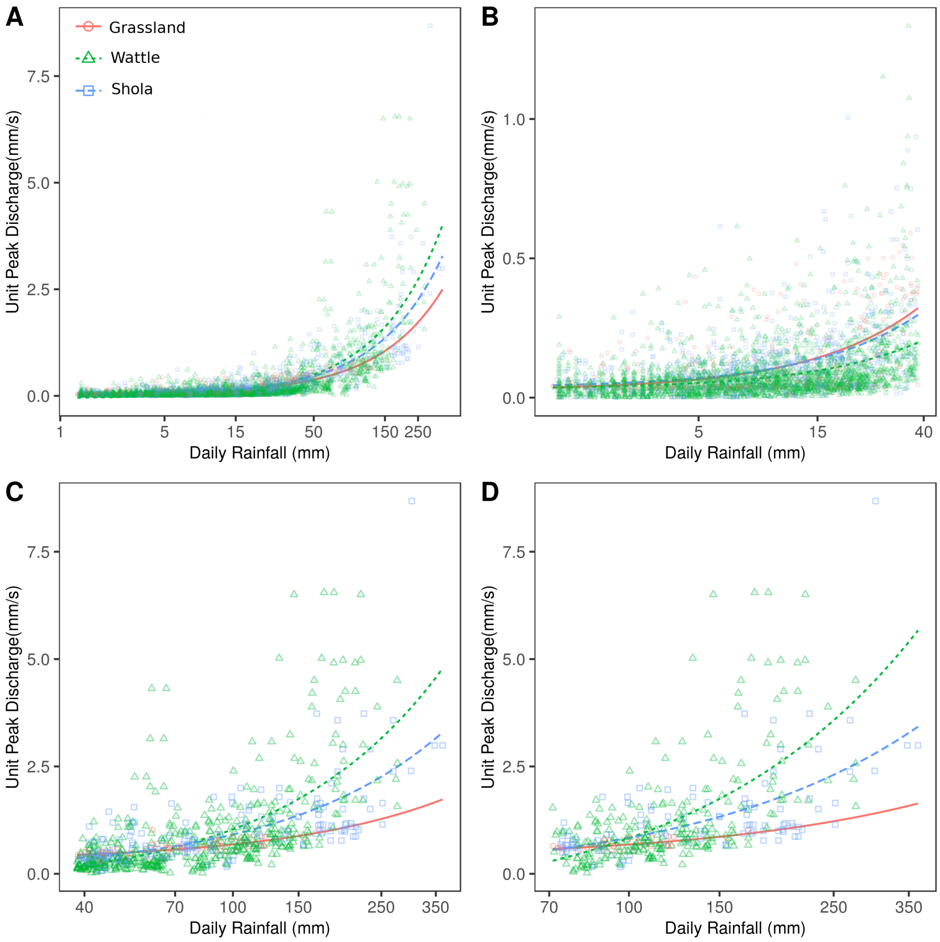

Figure 4. Unit peak discharge values plotted against log of daily rainfall suggest an exponential relationship between rainfall and runoff. Daily rainfall was calculated for a 24 hour period from the time of the event to 24 hours before the event. Discharge from wattle dominated catchments was the lowest during light rains but much higher than shola or grassland dominated catchments during heavy and ERE, the threshold being about 80mm/day. a) All rainfall, discharge of wattle > shola > grassland; b) light rain (< 38 mm/day), grassland $\geq$ shola > wattle; c) heavy rain ($\geq$38 mm/day and < 71 mm/day) wattle > shola > grassland; and d) extreme rain (> 71 mm/day) wattle > shola > grasslands. Exp(R): Exponential rainfall; p=probability; AICc: Akaike Information Criteria with bias adjustment.

Exponential regression models of unit mean daily discharge suggested land-cover to be one of the important variables that influenced the rainfall-runoff relationship (Table 2). When all the rainfall events were considered for analysis, grasslands had greater discharges for a given rainfall intensity when compared to wooded shola and wattle plantations (Table 2).

Table 2. Land cover played a major role in influencing the rainfall-runoff response.

Model	Intercept	Slope	p, r^2	AICc	Δ AICc
exp(R)[a] + LC[b] + CI[c] + AMI[d]	-0.35010		< 0.0001, 0.6962	-20433.2	0.00
Rainfall		0.3630			
LC: *Shola*		-0.0103			
LC: *Wattle*		-0.0042			
LC: *Grassland*		-			
Circulatory Index		-0.0134			
Antecedent Moisture Index		0.2089			
exp(R) + LC + CI + DD + AMI	-0.3492		< 0.0001, 0.6962	-20432.1	1.05
Rainfall		0.3631			
LC: *Shola*		-0.0135			
LC: *Wattle*		-0.0135			
LC: *Grassland*		-			
Circulatory Index		-0.0135			
Drainage Density		-0.0026			
Antecedent Moisture Index		0.2091			
NULL (Rainfall only model)	-0.4458	0.4612	< 0.0001, 0.5428	-18172.3	2260.87
	Estimate		Adj. SE	p	RVI[e]
Intercept	-0.3504		0.0056	< 0.0001	-
Rainfall	0.3630		0.0050	< 0.0001	1.00
LC: *Shola*	-0.0101		0.0022	< 0.0001	1.00
LC: *Wattle*	-0.0042		0.0018	< 0.05	
LC: *Grassland*	-		-	-	
Circulatory Index	-0.0135		0.0017	< 0.0001	1.00
Drainage Density	-0.0026		0.0040	> 0.05	0.37
Antecedent Moisture Index	0.2090		0.0027	< 0.0001	1.00

Note: Exponential regression models suggest that land cover played a major role in influencing the rainfall-runoff relationshiop. Catchment shape and drainage density are other important factors. We used all rainfall events with unit mean daily discharge as the response variable. Top models with delta AICc < 2 and the null model parameters are presented. Model averaging was done for models with delta AICc < 2.0. [a]exp(R): exponential total daily rainfall; [b]LC: Dominant Land Cover; [c]CI: Circulatory Index; [d]AMI: Antecedent Moisture Index; [e]RVI: Relative Variable Importance.

Analysis at different rainfall intensities also revealed that the land cover played an important role in determining rainfall-runoff relationships. However, the hydrologic responses at different rainfall intensities changed across land cover types with rainfall intensities. At light and heavy rainfall intensities, grassland showed greater unit area discharge compared to shola and wattle (Table 3). However, during extreme rainfall events wattle showed significantly greater unit mean discharge values compared to natural grasslands and shola forests (Table 3). In addition to land cover, we found AMI and catchment shape to have greater effect on this influence. Drainage density also had some influence on these trends (Table 2 & 3).

Table 3. Model averaged parameters for relationship between unit mean daily discharge and daily rainfall

Model averaged parameters	Estimate	Adjusted standard error	p	RVI[a]
a) Light Rain				
Intercept	-0.0111	0.0033	< 0.001	-
Rainfall	0.0128	0.0032	< 0.001	1
LC: *Shola*	-0.0012	0.0002	< 0.001	1
LC: *Wattle*	-0.0002	0.0002	> 0.05	
LC: *Grassland*	-	-	-	
Antecedent Moisture Index	0.0086	0.0029	< 0.01	1
Drainage Density	0.0003	0.0001	> 0.05	0.62
Circulatory Index	-0.0009	0.0003	< 0.01	1
b) Heavy Rain				
Intercept	-0.3644	0.135	< 0.01	-
Rainfall	0.3988	0.1138	< 0.001	1
LC: *Shola*	-0.021	0.0146	> 0.05	0.64
LC: *Wattle*	-0.0273	0.0122	< 0.05	
LC: *Grassland*	-	-	-	
Antecedent Moisture Index	0.3111	0.0162	< 0.001	1
Drainage Density	-0.0605	0.0226	< 0.01	1
Circulatory Index	-0.0141	0.0109	> 0.05	0.45
c) Extreme Rain				
Intercept	-0.1978	0.0613	< 0.01	-
Rainfall	0.289	0.0337	< 0.001	1
LC: *Shola*	-0.1015	0.0342	< 0.01	1
LC: *Wattle*	0.0234	0.029	> 0.05	
LC: *Grassland*	-	-	-	
Antecedent Moisture Index	0.359	0.0358	< 0.001	1
Drainage Density	-0.0497	0.0588	> 0.05	0.33
Circulatory Index	-0.114	0.024	< 0.001	1

Note: a) light rain ($\geq$1.3 mm/day- $<$ 38.0 mm/day); b) heavy rain (38.0 mm/day-71.0 mm/day); and c) ERE ($>$ 71 mm/day). Model averaging was done for models with Δ AICc $<$ 2.0. Land cover influenced the rainfall-runoff relationship significantly across different rainfall intensities.[a] RVI: Relative Variable Importance.

We found that daily rainfall was the best predictor variable for modelling daily peak flows ($p < 0.001$, $r^2 = 0.60$). Analysis of unit peak daily discharge did not show any influence of land cover on rainfall-runoff relationship when all rainfall values were considered in a regression model. Peak discharge was mainly determined by antecedent moisture content of the catchment (AMI – Relative variable importance 1.00) along with the daily rainfall (Table 4). In addition to this, drainage density (Relative variable importance = 0.38) and catchment shapes (Relative variable importance = 0.55) also had some influence on these observed trends in peak flows. However, when different intensities of rainfall were considered, we found landcover to have an influence on peak-flow. During low intensity rainfall, grassland showed greater peak flows (Table 4). In some contrast, during extreme rainfall events, peak flows were greater in wattle compared to natural grasslands and shola.

Table 4. Relationship between unit peak daily discharge and daily rainfall.

Model averaged parameters	Estimate	Adjusted standard error	p	RVI[a]
a) All Rain Events				
Intercept	-0.3064	0.0052	< 0.001	-
Rainfall	0.3018	0.0045	< 0.001	1.00
Antecedent Moisture Index	0.0576	0.0043	< 0.001	1.00
Circulatory Index	0.0024	0.0016	> 0.05	0.55
Drainage Density	0.0029	0.0028	> 0.05	0.38
b) Light Rain (≥1.3 to <38.0 mm/day)				
Intercept	-0.1565	0.0056	< 0.001	-
Rainfall	0.1572	0.0054	< 0.001	1.00
LC: *Shola*	-0.0019	0.0006	< 0.001	1.00
LC: *Wattle*	-0.0047	0.0005	> 0.001	
LC: *Grassland*	-	-	-	
Antecedent Moisture Index	0.0692	0.0014	< 0.001	1.00
Circulatory Index	0.0020	0.0004	< 0.001	1.00
Drainage Density	0.0029	0.0007	< 0.001	1.00
c) Heavy Rain (38.0 to 71.0 mm/day)				
Intercept	-0.6399	0.1158	< 0.001	-
Rainfall	0.5949	0.1005	< 0.001	1.00
LC: *Shola*	0.0098	0.0124	> 0.05	0.20
LC: *Wattle*	-0.0057	0.0108	> 0.05	
LC: *Grassland*	-	-	-	-
Antecedent Moisture Index	0.0376	0.0151	< 0.05	1.00
Circulatory Index	1.0135	0.0103	> 0.05	0.44
Drainage Density	0.0119	0.0166	> 0.05	0.18
d) Extreme Rain (> 71 mm/day)				
Intercept	-0.4036	0.0428	< 0.001	-
Rainfall	0.3482	0.0258	< 0.001	1.00
LC: *Shola*	-0.0152	0.0235	> 0.05	1.00
LC: *Wattle*	0.0328	0.0207	> 0.05	
LC: *Grassland*	-	-	-	
Antecedent Moisture Index	0.0853	0.0267	< 0.01	1.00
Circulatory Index	-0.0133	0.0178	> 0.05	0.25
Drainage Density	0.0262	0.0451	> 0.05	0.22

Note: Peak discharge analysed against all rainfall intensities was largely determined by antecedent moisture and daily rainfall. However, landcover (LC), influenced runoff when different rainfall intensities were considered. Model averaging was done for models with delta AICc < 2.0.[a]RVI: Relative Variable Importance.

The median time lag between rainfall and peak stream flows was 60, 72 and 89 minutes for wattle, shola, and grasslands respectively, suggesting a more rapid stream flow generation pathway in wattle plantations compared to natural land covers. (Figure 5). We did not find the influence of any other co-variate on lag-time across all the catchments.

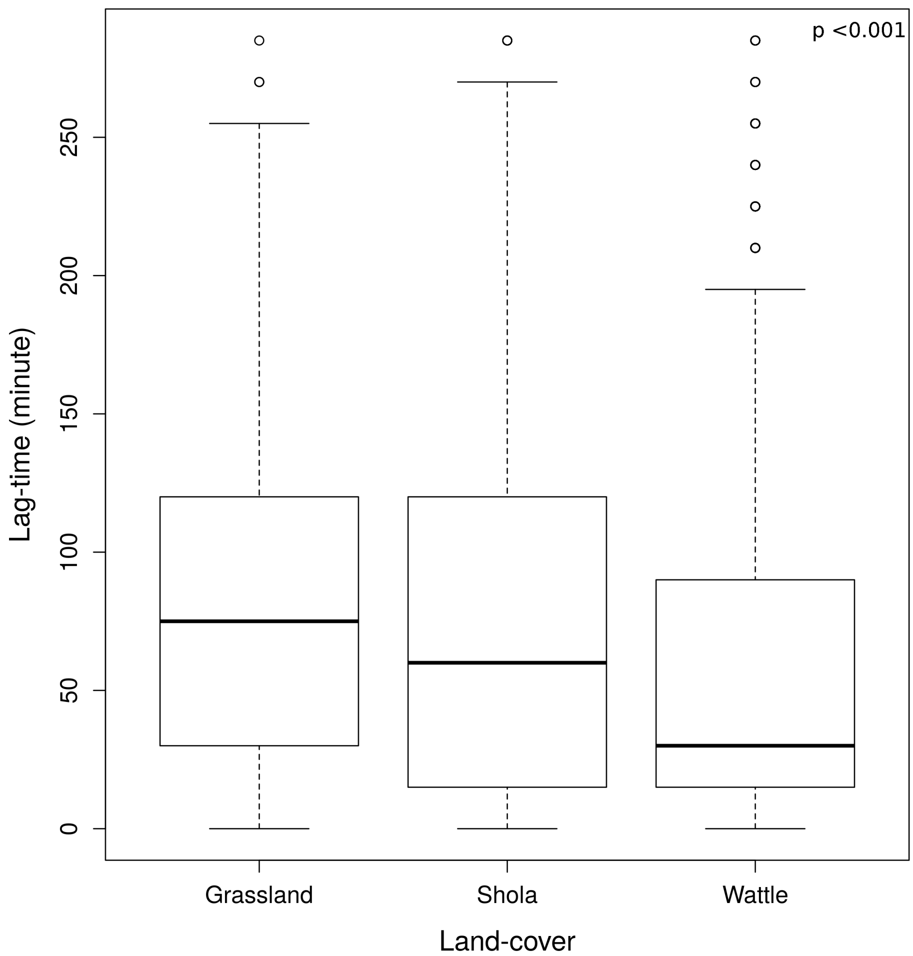

Figure 5. Time lag between peak rainfall and peak stream flow was shorter in wattle plantations compared to natural grasslands and shola forests.

4 Discussion

The relationship between different rainfall intensities and mean daily discharge in the Upper Nilgiris were influenced by land cover. This relationship, however, varied with rain intensity. During light rain (< 38 mm/day) grasslands showed higher discharges than either shola forest or wattle plantations. This may be explained by the wider spread and deeper root systems of trees when compared to grasses and higher soil organic matter in the form of leaf litter could help in greater rainfall infiltration and retention during light rains. Vegetation cover is known to increase surface roughness and infiltration which slows surface run-off (Koutnỳ et al., 2014). Canopy cover also intercepts rain and thereby reduces immediate runoff (Levia et al., 2011; Cui et al., 2012; Livesley et al., 2014).

In contrast, wattle plantations were least able to retain rainfall during ERE, resulting in higher and more rapid stream runoff. Both mean daily discharge and peak flows were higher in wattle compared to natural grasslands and shola forests during heavy and extreme rainfall. In other words, ERE are more likely to generate floods from catchments converted from natural grasslands to wattle plantations or those invaded by wattle. A greater incidence of saturation excess overland flows (Haga et al., 2005) in wattle might explain this rapid response. Soil under wattle plantations was shown to have a lower saturated hydraulic conductivity than either natural grasslands or shola forests during an earlier study in these sites (Krishnaswamy et al., 2017), also see Appendix C. This also explains why wattle had a shorter time lag between rainfall and peak daily discharge; 60, 72 and 89 minutes for wattle, shola and grasslands respectively.

During heavy and extreme rainfall, wattle plantations resulted in greater discharges, even though antecedent moisture played a greater role in determining runoff response than did land cover in these catchments. This is in contrast with other studies which found that light to moderate rainfall influenced peak stream-flow, while the role of landcover was minimal during extreme rains (Bathurst et al., 2011). Sub-surface flows in wattle plantations would explain the low flows during light rains which increase as rain intensity increases. Prior studies in the region suggest that wattle plantations with their extended root systems are dominated by subsurface stream flows (Krishnaswamy et al., 2017). The decreasing time-lag with increase in woody cover also suggests that higher rain intensities trigger rapid sub-surface flows, as predicted for regions such as the Nilgiris which have a sub-surface dominated runoff system (Chappell et al., 2017).

Antecedent moisture clearly plays an important role in controlling run-off responses in the Nilgiris. This indicates that the responses are not only dependent on infiltration excess (Liu et al., 2008)but are a result of complex relationships between catchment infiltration rate, soil saturation, water-holding capacity, and subsurface flows, all of which are influenced by land-cover. The drainage network of catchments also influences stream flows; high drainage density increases peak discharges, while reduces overall runoff through retaining much of the rainfall across the catchments. Similarly, stream runoff from the catchment is reduced as the shape becomes more circular.

Natural vegetation has been found to reduce flood risks in different parts of the world (Bathurst et al., 2011; Koutnỳ et al., 2014; Krishnaswamy et al., 2012). Our results suggest that wattle plantations, when compared with native vegetation, increase flood-risk during high and extreme rainfall. The invasion of natural grasslands by wattle therefore has serious ramifications for downstream flooding during the peak rainy season.

Several studies suggest that wattle and other plantations significantly increase evapotranspiration and reduce stream-flow (Dye & Jarmain, 2004; Sikka et al., 2003, 1998; Chand et al., 2009; Sharma, 1984). Grasslands continue to be seen as 'degraded' areas and have been targeted for afforestation historically, often with non-native plantation crops (Chandran, 1997; Jha et al., 2000; Joshi et al., 2018; Arasumani et al., 2018). This perception of grasslands being degraded and their conversion to plantations persists globally (Veldman et al., 2015) and in some current policies in India (Ministry of Environment and Forests, 2010), which seek to combat climate change through large scale afforestation, disregarding the potential impact on water resources (Jackson et al., 2005). Another example of this is the Atlas of Forest Landscape Restoration Opportunities (*Atlas of Forest and Landscape Restoration Opportunities*, 2014), which identifies several of the natural montane grasslands in the Western Ghats as Areas for wide-scale restoration.

In the Nilgiris, however, removal of wattle and restoration of the montane grasslands has been mandated by the government following a public interest litigation filed in 2014 (G.Vinod Kumar, 2014). Successful removal of wattle, however, requires sustained efforts. Once established, wattle builds substantial seed banks and rapidly regenerates after removal. This would amplify the hydrologic impact of wattle stands, which unlike the mature shola forests, are likely to have a far higher evapotranspiration rate (Cui et al., 2012).

Our results suggest that planted and invasive wattle stands have a significant hydrologic footprint and might be detrimental to hydrologic services from catchments in the Nilgiris, in both the dry and wet seasons. We found that wattle plants, which have invaded several of the montane grassland systems in the Nilgiris (Joshi et al., 2018), increase flood risks during extreme rainfall events. This study finds that high intensity rain like > 70 mm of rainfall in a day behaves differently when it is over a wattle plantation compared to shola forests or grasslands. An extreme rain is more likely to generate a flood in a wattle dominated catchment than one dominated by the natural shola forest and grassland mosaic. We found that along with landcover, catchment morphometric characteristics such as catchment shape and drainage density also influence the rainfall-runoff relationship. Therefore, future flood early warning systems and risk management strategies should consider the differential effects of land-cover including wooded vegetation and catchment morphometric properties along with antecedent moisture conditions to predict likelihood of floods at different rainfall intensities.

5 Acknowledgements

The data supporting the conclusions can be obtained from NERC's Environmental Information Data Centre (Bhalla et al., 2020). This research was made possible by funding from the Ministry of Earth Sciences Government of India (MoES) and the Natural Environment Research Council, UK (NERC) Changing Water Cycle programme (Grant Ref: MoES/NERC/16/02/10 PC-II) and the MoES funded Hydrologic footprint of Invasive Alien Species project (MOES/PAMC/H&C/85/2016-PC-II). Additional funding was provided by UKRI NERC grant NE/I022450/1 (Western Ghats-Capacity within the NERC Changing Water Cycle programme) and WWF-India as part of the Noyyal-Bhavani program. We acknowledge the Tamil Nadu Forest Department for granting us research permits for work in the Nilgiri Range Forest and the sustained help and support from their officers and staff. We also acknowledge the support from the Tamil Nadu Electricity Board for housing our field stations in the Emerald and Avalanche colony. We gratefully acknowledge the years of dedicated work by our field staff led by S. Saravanan, the field coordinator of the Nilgiris field station.

Appendix A Land Use Land Cover Map of Nilgiris

We developed a land-cover map for the Nilgiris using LANDSAT 8 images for the year 2017. We collected a total of 3411 ground control points representing nine different land cover types using hand held GPS units (Garmin 20x) with a horizontal accuracy of about 5 meters. These nine classes were Shola (montane evergreen forests), water bodies, built-up land, commercial plantation (tea), agriculture land, natural grassland and forest plantation, which is a combination of exotic tree species such as wattle (*Acacia mearnsii* and *Acacia dealbata*), blue gum (*Eucalyptus globulus*) and pine (*Pinus patula*), and scrub patches dominated by scotch broom and gorse. These point locations were then converted into polygons by digitising around the points using Google Earth imagery for the year 2017.

Google earth engine (`http://earthengine.google.com`) was used to develop land use/land cover maps. The 2017 LANDSAT 8 images available at a resolution of 30 m were used for the classification. A Random forest classifier algorithm (`http://earthengine.google.com`) with a random seed of 40, was used for the classification. We used top of atmosphere corrected (ToA) b1, b2, b3, b4, b5, b6 and b7 bands from Landsat, along with a Normalised Difference vegetation Index (ndvi) layer and an elevation and slope layer derived from Advances Land Observation Satellite (ALOS) DEM (`https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm`), for the classification. The estimated kappa accuracy for the developed maps was 81%.

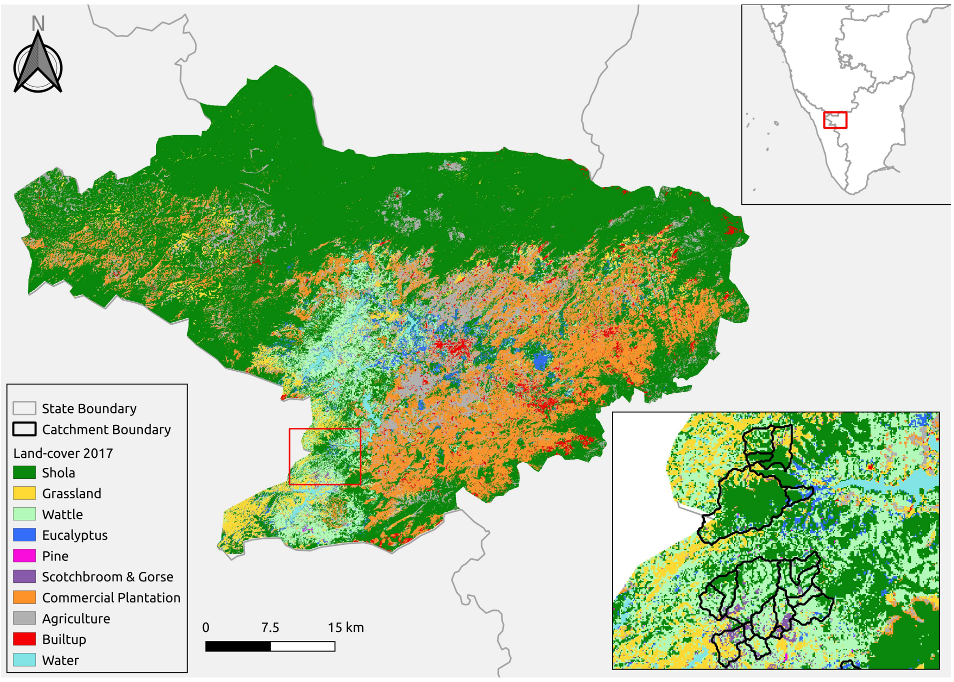

Figure A1. Land-cover map of Nilgiris developed using supervised classification of Landsat images for the year 2017.

Appendix B Peak discharge across landcover types

We found Antecedent moisture content as an important factor that determined peak discharges along with rainfall. This influence was evident across all the landcover types (Supplementary Table 1). Boxplots suggested that the distribution of AMI was comparable across all the landcover types (Figure B1). The median AMI values were 0.094, 0.097, and 0.11 for grassland, wattle and shola respectively. Exponential regression models with antecedent moisture index (AMI) as the only predictor variable suggested a significant influence on peak discharge ($p < 0.001$) across all the land-cover types (Table B1). However, the variation in unit peak discharges explained by AMI differed across landcover types; nearly 33% of variation was explained by AMI alone in grassland catchment, 22% in shola catchments and only 13% in wattle (Table B2).

Table B1. Influence of antecedent moisture index (AMI) on runoff-rainfall relationships.

Landcover type	Model	AICc	Δ AICc
Grassland	1) exp(R) +AMI	-2623.5	0
	2) exp(R)	-2484	139.53
Wattle	1) exp(R) +AMI	-11632.7	0
	2) exp(R) +AMI+DD	-11632.3	0.42
	3) exp(R)+AMI+CI	-11631.2	1.46
	4) exp(R) +AMI+DD+CI	-11630.8	1.89
	5) exp(R)	-11552.3	80.43
Shola	1) exp(R) +AMI+CI	-3708.5	0
	2) exp(R) +AMI+DD	-3708.5	0
	3) exp(R)	-3587.6	120.87

Note: Top models with delta AICc < 2 and the null model (rainfall only model) across the landcover types.

Table B2. Slope estimate and p value for linear regression analysis of unit peak discharge (response variable) and antecedent moisture index (AMI).

Landcover type	Slope	r^2, p
Grassland	0.154373	0.3286, < 0.001
Wattle	0.183716	0.1272, < 0.001
Shola	0.156564	0.2198, < 0.001

Appendix C Infiltration rates across land cover types

We compared the observed rainfall intensity to the measured saturated hydrologic conductivity across soils under wattle plantations, grasslands and shola forests. Our find-

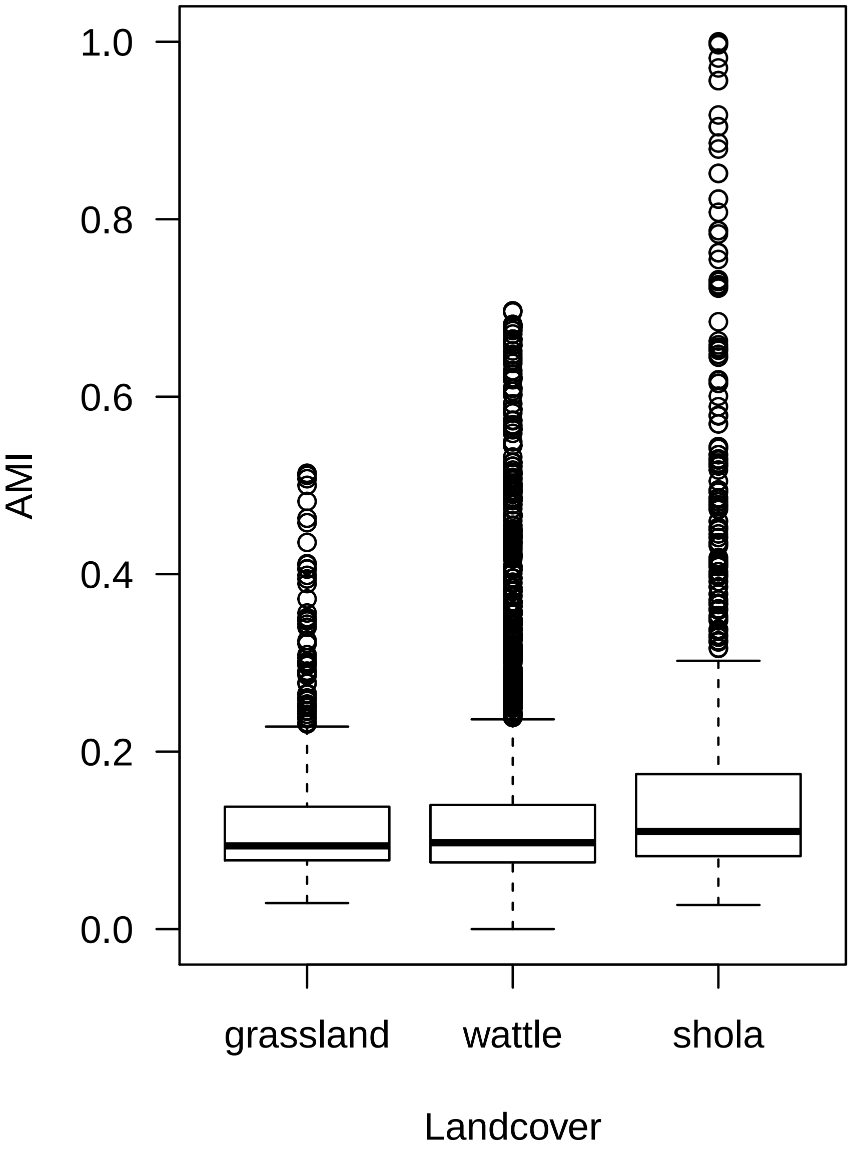

Figure B1. Distribution of antecedent moisture across different landcover types.

354 ings suggest that soils under wattle plantations have a lower infiltration rate and are more
355 vulnerable to infiltration-excess overland flow compared to soil under shola forests and
356 grasslands (Figure C1).

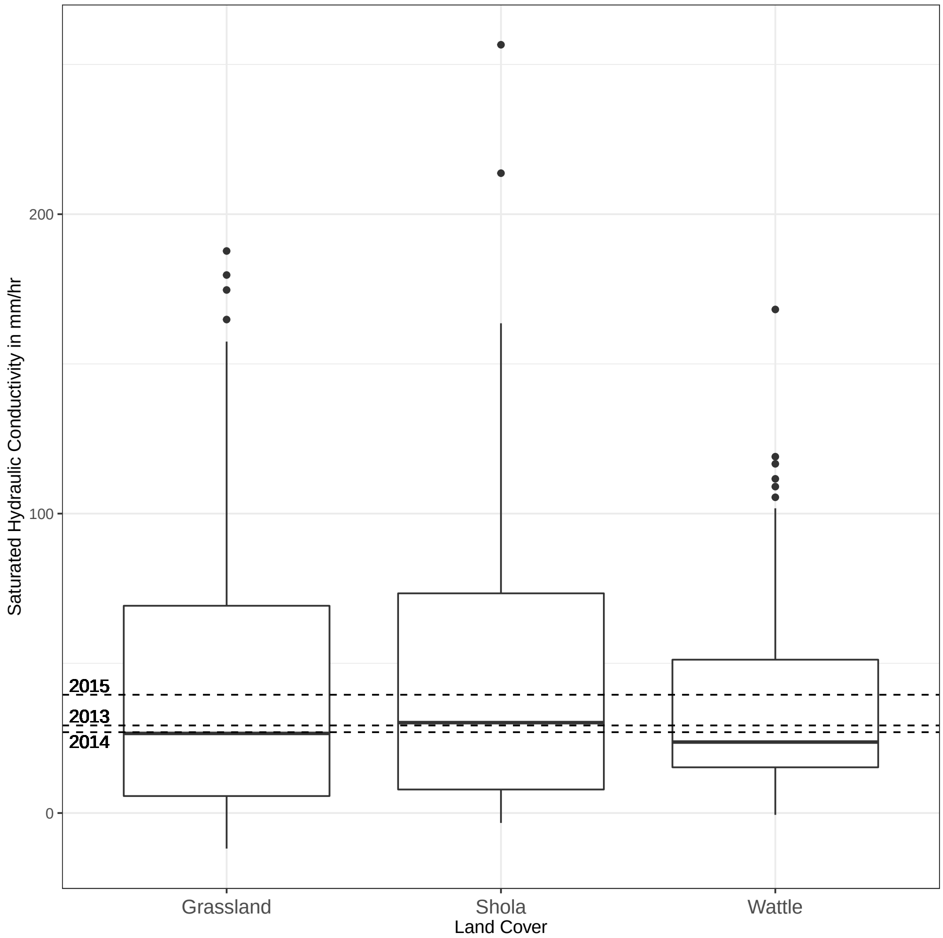

Figure C1. Box and Whiskers plots of Infiltration under different land-cover in the Nilgiris overlayed with maximum rain intensities recorded in 2013, 2014 and 2015.

References

Allaby, M. (Ed.). (2013). *A Dictionary of Geology and Earth Sciences* (Fourth Edition ed.). OUP Oxford.

Arasumani, M., Khan, D., Das, A., Lockwood, I., Stewart, R., Kiran, R. A., ... Robin, V. V. (2018, January). Not seeing the grass for the trees: Timber plantations and agriculture shrink tropical montane grassland by two-thirds over four decades in the Palani Hills, a Western Ghats Sky Island. *PLOS ONE*, *13*(1), e0190003. doi: 10.1371/journal.pone.0190003

Arathi Menon. (2019, August). *Extreme rainfall devastates Kodagu yet again.* https://india.mongabay.com/2019/08/extreme-rainfall-devastates-kodagu-yet-again/.

Atlas of Forest and Landscape Restoration Opportunities. (2014, May). https://www.wri.org/resources/maps/atlas-forest-and-landscape-restoration-opportunities.

Bathurst, J. C., Iroumé, A., Cisneros, F., Fallas, J., Iturraspe, R., Novillo, M. G., ... Coello, C. (2011). Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 1: Field data analysis. *Journal of Hydrology*, *400*(3-4), 281–291.

Bhalla, J., R.S.;Krishnsawamy, Chappell, N., Kumaran, K., Vaidyanathan, S., Nayak, R., & Ghatwai, P. (2020). *Daily rainfall, stream discharge and hydraulic conductivity of soils from catchments dominated by different vegetation types, western ghats, india, 2014 - 2016.* NERC Environmental Information Data Centre. Retrieved from `https://doi.org/10.5285/9257a999-2844-4be1-80d1-fd29e2ccf9ef` doi: 10.5285/9257a999-2844-4be1-80d1-fd29e2ccf9ef

Bonell, M., Purandara, B. K., Venkatesh, B., Krishnaswamy, J., Acharya, H. A. K., Singh, U. V., ... Chappell, N. (2010). The impact of forest use and reforestation on soil hydraulic conductivity in the Western Ghats of India: Implications for surface and sub-surface hydrology. *Journal of Hydrology*, *391*(1-2), 47–62.

Borga, M., Stoffel, M., Marchi, L., Marra, F., & Jakob, M. (2014). Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows. *Journal of Hydrology*, *518*, 194–205.

Burnham, K. P., & Anderson, D. R. (2002). Model selection and multimodel inference: A practical information-theoretic approach. The University of Chicago Press New York.

Calder, I. R., & Dye, P. (2001). Hydrological impacts of invasive alien plants. *Land use and water resources research*, *1*(1732-2016-140259).

Chand, S., Sikka, A. K., & Sharda, V. N. (2009). Environmental Implications of Converting Natural Grassland into Eucalyptus Plantations in Hydro Power Catchments in Nilgiris, Tamil Nadu: An Economic Analysis. *Indian Journal of Agricultural Economics*, *64*(902-2016-67906).

Chandran, M. S. (1997). On the ecological history of the Western Ghats. *Current Science*, 146–155.

Chappell, N. A., Jones, T. D., Tych, W., & Krishnaswamy, J. (2017). Role of rainstorm intensity underestimated by data-derived flood models: Emerging global evidence from subsurface-dominated watersheds. *Environmental Modelling & Software*, *88*, 1–9.

Clulow, A. D., Everson, C. S., & Gush, M. B. (2011). The long-term impact of Acacia mearnsii trees on evaporation, streamflow and ground water resources. *Water Research Commission Report No. TT505/11, WRC, Pretoria, South Africa*.

Cui, X., Liu, S., & Wei, X. (2012). Impacts of forest changes on hydrology: A case study of large watersheds in the upper reach of Yangtze River Basin. *Hydrology & Earth System Sciences Discussions*, *9*(5).

Daniels, R. R. (1996). *The Nilgiri Biosphere Reserve: A review of conservation status with recommendations for a holistic approach to management: India* (No. 16). South-South Cooperation Programme on Environmentally Sound Socio-Economic ....

Dataflow Systems Limited. (2017). *Odyssey Capacitance Water Level Logger.* http://odysseydatarecording.com/index.php?route=product/product&path=59&product_id=50.

D'Odorico, P., & Rigon, R. (2003). Hillslope and channel contributions to the hydrologic response. *Water resources research*, *39*(5).

Dye, P., & Jarmain, C. (2004). Water use by black wattle (Acacia mearnsii): Implications for the link between removal of invading trees and catchment streamflow response: Working for water. *South African Journal of Science*, *100*(1), 40–44.

Fowler, H. J., & Kilsby, C. G. (2003). A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. *International Journal of Climatology*, *23*(11), 1313–1334.

Fox, J., & Monette, G. (1992). Generalized collinearity diagnostics. *Journal of the American Statistical Association*, *87*(417), 178–183.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). Increasing trend of extreme rain events over India in a warming environment. *Science*, *314*(5804), 1442–1445.

GRASS Development Team. (2018). *Geographic resources analysis support system (GRASS GIS) software.* USA.

Guhathakurta, P., Sreejith, O. P., & Menon, P. A. (2011). Impact of climate change on extreme rainfall events and flood risk in India. *Journal of earth system science*, *120*(3), 359.

G.Vinod Kumar. (2014, March). *Proceedings of the Principal Chief Conservator of Forests, Chennai.*

Haga, H., Matsumoto, Y., Matsutani, J., Fujita, M., Nishida, K., & Sakamoto, Y. (2005). Flow paths, rainfall properties, and antecedent soil moisture controlling lags to peak discharge in a granitic unchanneled catchment. *Water Resources Research*, *41*(12).

India - WRIS Project Team. (n.d.). *Cauvery.* http://www.india-wris.nrsc.gov.in/wrpinfo/index.php?title=Cauvery#Water_Resources.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., ... Murray, B. C. (2005). Trading water for carbon with biological carbon sequestration. *science*, *310*(5756), 1944–1947.

Jha, C. S., Dutt, C. B. S., & Bawa, K. S. (2000). Deforestation and land use changes in Western Ghats, India. *Current Science*, 231–238.

Joshi, A. A., Sankaran, M., & Ratnam, J. (2018). 'Foresting'the grassland: Historical management legacies in forest-grassland mosaics in southern India, and lessons for the conservation of tropical grassy biomes. *Biological Conservation*, *224*, 144–152.

Kim, J., Johnson, L., Cifelli, R., Thorstensen, A., & Chandrasekar, V. (2019). Assessment of antecedent moisture condition on flood frequency: An experimental study in Napa River Basin, CA. *Journal of Hydrology: Regional Studies*, *26*, 100629.

Kohler, M. A., & Linsley, R. K. (1951). *Predicting the runoff from storm rainfall* (Vol. 30). US Department of Commerce, Weather Bureau.

Koutnỳ, L., Skoupil, J., & Veselỳ, D. (2014). Physical characteristics affecting the infiltration of high intensity rainfall into a soil profile. *Soil and Water Research*, *9*(3), 104–110.

Krishnaswamy, J., Bonell, M., Venkatesh, B., Purandara, B. K., Lele, S., Kiran, M. C., ... Rakesh, K. N. (2012). The rain-runoff response of tropical humid forest ecosystems to use and reforestation in the western ghats of India.

Journal of Hydrology, *472-473*, 216–237. doi: 10.1016/j.jhydrol.2012.09.016

Krishnaswamy, J., Chappell, N. A., Bhalla, R. S., Sankaran, M., Vaidyanathan, S., Badiger, S., & Varghese, S. (2017). *Hydrologic and carbon services in the western ghats: Response of forest and agro-ecosystems to extreme rainfall events* (Tech. Rep.). Ministry of Earth Sciences, Government of India.

Kumar, S. V., & Bhagavanulu, D. V. S. (2008). Effect of deforestation on landslides in Nilgiris district—A case study. *Journal of the Indian Society of Remote Sensing*, *36*(1), 105.

Levia, D. F., Carlyle-Moses, D., & Tanaka, T. (2011). *Forest hydrology and biogeochemistry: Synthesis of past research and future directions* (Vol. 216). Springer Science & Business Media.

Liu, B. M., Collick, A. S., Zeleke, G., Adgo, E., Easton, Z. M., & Steenhuis, T. S. (2008). Rainfall-discharge relationships for a monsoonal climate in the Ethiopian highlands. *Hydrological Processes: An International Journal*, *22*(7), 1059–1067.

Livesley, S. J., Baudinette, B., & Glover, D. (2014). Rainfall interception and stem flow by eucalypt street trees–The impacts of canopy density and bark type. *Urban Forestry & Urban Greening*, *13*(1), 192–197.

Mason, S. J., Waylen, P. R., Mimmack, G. M., Rajaratnam, B., & Harrison, J. M. (1999). Changes in extreme rainfall events in South Africa. *Climatic Change*, *41*(2), 249–257.

McCool, D. K., Brown, L. C., Foster, G. R., Mutchler, C. K., & Meyer, L. D. (1987). Revised slope steepness factor for the Universal Soil Loss Equation. *Transactions of the ASAE*, *30*(5), 1387–1396.

Ministry of Environment and Forests. (2010, May). *National Mission for a Green India* (Tech. Rep.). Government of India.

Mishra, V., Aaadhar, S., Shah, H., Kumar, R., Pattanaik, D. R., & Tiwari, A. D. (2018). The Kerala flood of 2018: Combined impact of extreme rainfall and reservoir storage. *Hydrology and Earth System Sciences Discussions*, 1–13.

Mishra, V., & Shah, H. L. (2018). Hydroclimatological perspective of the Kerala flood of 2018. *Journal of the Geological Society of India*, *92*(5), 645–650.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853.

NASA JPL. (2013). NASA Shuttle Radar Topography Mission Global 1 arc second V003. *NASA LP DAAC*. doi: DOI:10.5067/MEaSUREs/SRTM/SRTMGL1.003

Osborn, T. J., Hulme, M., Jones, P. D., & Basnett, T. A. (2000). Observed trends in the daily intensity of United Kingdom precipitation. *International Journal of Climatology*, *20*(4), 347–364.

Premkumar, R. (2019, August). Avalanche in Tamil Nadu's Nilgiris records 820 mm of rain in a day. *The Hindu*.

Prinsloo, F. W., & Scott, D. F. (1999). Streamflow responses to the clearing of alien invasive trees from riparian zones at three sites in the Western Cape Province. *Southern African Forestry Journal*, *185*(1), 1–7.

R Core Team. (2018). R Foundation for Statistical Computing; Vienna, Austria: 2015. *R: A language and environment for statistical computing*, 2013.

RainWise. (2012). *Wired Rain Gauge.* Author.

Rangan, H., Kull, C. A., & Alexander, L. (2010). Forest plantations, water availability, and regional climate change: Controversies surrounding Acacia mearnsii plantations in the upper Palnis Hills, southern India. *Regional Environmental Change*, *10*(2), 103–117.

Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., ... Henriet, F. (2011). An assessment of the potential impact of climate change on flood risk in Mumbai. *Climatic change*, *104*(1), 139–167.

Rinaldo, A., Marani, A., & Rigon, R. (1991). Geomorphological dispersion. *Water Resources Research*, *27*(4), 513–525.
Safi, M. (2018, August). Kerala floods: Death toll rises to at least 324 as rescue effort continues. *The Guardian*.
Samraj, P., Sharda, V. N., Chinnamani, S., Lakshmanan, V., & Haldorai, B. (1988). Hydrological behaviour of the Nilgiri sub-watersheds as affected by bluegum plantations, Part I. The annual water balance. *Journal of Hydrology*, *103*(3-4), 335–345.
Sehgal, J. L., Saxena, R. K., & Vadivelu, S. (1987). *Field Manual Soil Resource Mapping of Different States in India* (Tech. Rep. No. Publ. 13). NBSS&LUP, Nagpur.
Serrano-Muela, M. P., Nadal-Romero, E., Lana-Renault, N., González-Hidalgo, J. C., López-Moreno, J. I., Beguería, S., … García-Ruiz, J. M. (2015). An exceptional rainfall event in the central western Pyrenees: Spatial patterns in discharge and impact. *Land Degradation & Development*, *26*(3), 249–262.
Sharda, V. N., Samraj, P., Chinnamani, S., & Lakshmanan, V. (1988). Hydrological behaviour of the Nilgiri sub-watersheds as affected by bluegum plantations, part II. Monthly water balances at different rainfall and runoff probabilities. *Journal of Hydrology*, *103*(3-4), 347–355.
Sharma, M. L. (1984). Evapotranspiration from a Eucalyptus community. In *Developments in Agricultural and Managed Forest Ecology* (Vol. 13, pp. 41–56). Elsevier.
Shaw, E. M., Beven, K. J., Chappell, N. A., & Lamb, R. (2010). *Hydrology in practice* (Fourth Edition ed.). Taylor & Francis.
Sikka, A. K., Samra, J. S., Sharda, V. N., Samraj, P., & Lakshmanan, V. (1998). Hydrological implications of converting natural grassland into bluegum plantation in Nilgiris. *Hydrological implications of converting natural grassland into bluegum plantation in Nilgiris.*(T-38/0-5).
Sikka, A. K., Samra, J. S., Sharda, V. N., Samraj, P., & Lakshmanan, V. (2003). Low flow and high flow responses to converting natural grassland into bluegum (Eucalyptus globulus) in Nilgiris watersheds of South India. *Journal of hydrology*, *270*(1-2), 12–26.
Song, S., & Wang, W. (2019). Impacts of Antecedent Soil Moisture on the Rainfall-Runoff Transformation Process Based on High-Resolution Observations in Soil Tank Experiments. *Water*, *11*(2), 296.
Sriramamurthy, R. T., Bhalla, R. S., & Sankaran, M. (2020, January). Fire differentially affects mortality and seedling regeneration of three woody invaders in forest–grassland mosaics of the southern Western Ghats, India. *Biological Invasions*. doi: 10.1007/s10530-020-02207-7
TWC India. (2019, August). *Freak Weather in Nilgiris: 2500 mm Rainfall Recorded in Just Four Days.* https://weather.com/en-IN/india/monsoon/news/2019-08-10-freak-weather-nilgiris-2500-mm-rainfall-recorded-just-four-days.
Upper Bhavani Dam D00756 -. (n.d.). http://india-wris.nrsc.gov.in/wrpinfo/index.php?title=Upper_Bhavani_Dam_D00756.
Veldman, J. W., Overbeck, G. E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G. W., … Bond, W. J. (2015). Tyranny of trees in grassy biomes. *Science*, *347*(6221), 484–485.
Venkatesh, B., Lakshman, N., & Purandara, B. K. (2014). Hydrological impacts of afforestation—a review of research in India. *Journal of forestry research*, *25*(1), 37–42.
Zhou, Y., Lau, W. K., & Liu, C. (2013). Rain characteristics and large-scale environments of precipitation objects with extreme rain volumes from TRMM observations. *Journal of Geophysical Research: Atmospheres*, *118*(17), 9673–9689.