

Factors determining how catchments respond to forest cover change. Re-analysing global data sets.

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Abstract

Three recent papers review and analyse large global datasets related to impacts of forest cover on streamflow. Using three different approaches, they all find a strong relationship between forestation/de-forestation and streamflow. However, the past approaches in the literature are variable and can be substantially improved in statistical rigour, and indicate different confounding factors on the impact of forestation. The data for these three papers were reviewed, combined and re-analysed to answer the following new and older questions: 1) How is streamflow impacted by the change in forest cover as a function of catchment area; 2) how is this relationship conditioned by the length of the study, and climate; and 3) are there other possible variables that impact the observed change in streamflow? Generalised additive models were used to run flexible regressions including multiple variables. Changes in forest cover cause changes in streamflow, however this change is different between deforestation and reforestation, and strongly affected by climate, with drier climates indicating larger changes in streamflow. Deforestation causes a 32% greater change in flow compared to reforestation. Area of the catchment only affects the change in streamflow after log transformation, given the wide variety in the data from small scale paired watershed studies. Smaller studies dominate the database with 42% of the data < 1 km² and 65% of the data < 10 km². Length of the study and initial year of the study did not affect the change in flow, in contrast to other reported studies. Despite these findings, overall explained variance (38%) is low due the quality of the inputs and additional unknown confounding factors.

1. Introduction

There has been an long and on-going discussion in the hydrological literature around the impact of forests on streamflow (Andréassian, 2004; Brown et al., 2013, 2005; Filoso et al., 2017; Jackson et al., 2005; Zhang et al., 2017). The historic work highlights a general consensus that if forest areas increase, streamflow decreases and vice-versa. The most dramatic result in relation to this, is

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18 Figure 5 in Zhang et al. (2011) indicating (for Australian catchments) a 100%
19 decrease in streamflow for catchments with 100% forest cover. However, on the
20 other end of the spectrum, for three French catchments (Cosandey et al., 2005),
21 there was no change in streamflow characteristics in two of the catchments
22 after deforestation.

23 For the purpose of this paper, *watershed* and *catchment* are interchangeable
24 terms. Many of the US studies use *watershed*, while European and Australian
25 studies use *catchment*. In particular, we retained the term “paired watershed
26 studies” as this is the most common terminology, but further mostly use the
27 term catchment.

28 Several review papers have summarized the plethora of forestation and defor-
29 estation studies across the globe, in relation to paired watershed studies (Bosch
30 and Hewlett, 1982; Brown et al., 2005), related to reforestation in particular
31 (Filoso et al., 2017), and more generally (Jackson et al., 2005; Zhang et al.,
32 2017). These studies aim to generalize the individual findings and to identify
33 if there are global trends or relationships that can be developed. The most
34 recent reviews (Filoso et al., 2017; Zhang et al., 2017) developed an impressive
35 global database of catchment studies in relation to changes in streamflow due
36 to changes in forest cover. The Zhang et al. (2017) dataset, which covers over
37 312 studies, is described in terms of the change in streamflow as a result of
38 the change in forest cover, where studies related to both forestation (increase
39 in forest cover) and deforestation (decrease in forest cover) were included. In
40 contrast, the paper by Filoso et al. (2017) focused primarily on reforestation,
41 and covered an equally impressive database of 167 studies using a systematic
42 review. In this case the collected data is mostly coded as count data and only a
43 subset of 37 studies was analysed for actual water yield change. There is some
44 overlap between the two data sets, but there are also some studies unique to
45 both sets.

46 The conclusions of the first paper (Zhang et al., 2017) suggest that there is
47 a distinct difference in the change in flow as a result of forestation or deforesta-
48 tion between small watersheds (catchments), defined as $< 1000 \text{ km}^2$ and large
49 watersheds (catchments) $> 1000 \text{ km}^2$. While for small catchments there was no
50 real change in runoff with changes in cover, for large catchments there was a
51 clear trend showing a decrease in runoff with an increase in forest cover. Their
52 main conclusion was that the response in annual runoff to forest cover was scale
53 dependent and appeared to be more sensitive to forest cover change in water
54 limited catchments relative to energy limited catchments (Zhang et al., 2017).

55 The second study (Filoso et al., 2017) was a systematic review which clas-
56 sified the historical research and highlighted gaps in the spatial distribution,
57 the types of studies and the types of analysis. Their main conclusion was also
58 that reforestation decreases streamflow, but that there were many interacting
59 factors. For a subset of quantitative data (37) they showed a log-linear relation-
60 ship between decreasing catchment size and an increasing decline in streamflow.
61 In addition, they identified that studies with shorter periods of data collection
62 resulted in larger declines in streamflow.

63 A final summary paper that includes much of the same data as Zhang et

64 al. (2017) and Filoso et al. (2017) is Zhou et al. (2015), which has one author
 65 in common with Zhang et al. (2017). However, this paper aims to explain the
 66 variation in the data using the Fuh model, and in particular aims to link the
 67 variation in the observed data to variations in the exponent m in the model.
 68 A key observation is that in drier environments, the effects of deforestation are
 69 much greater than in wetter environments, which is also suggested by Figure 4
 70 in Zhang et al. (2017).

71 Encouraged by the work presented by Zhang et al. (2017), Filoso et al.
 72 (2017) and Zhou et al. (2015) and the large database of studies presented by
 73 these authors, we believe more can be done to add to this important discussion.
 74 In this paper, the aim extend the analysis of the collected data and to expand
 75 and combine the data sets.

76 In particular, the main method in the work by Zhang et al. (2017) is a single
 77 covariate linear regression, and in Filoso et al. (2017) the focus is mainly on
 78 classification and there is again some single covariate linear regression. As Zhang
 79 et al. (2017) points out, a main assumption in their work is that the catchment
 80 size threshold at 1000 km² is a distinct separation between “small” and “large”
 81 catchments. However, the subset of 37 data points in Filoso et al. (2017) (their
 82 Figure 9) does not appear to support this, suggesting a continuum. And while
 83 the work Filoso et al. (2017) provides important insights in study types, analysis
 84 types, forest types and broad classification, there is limited quantification of
 85 actual impact, and focussed only on forest cover increase and did not deal with
 86 forest cover removal.

87 As a result the objective of this paper is to 1) enhance the data set from
 88 Zhang et al. (2017) with further catchments (such as from Filoso et al. (2017))
 89 and spatial coordinates and 2) to analyse the possibility of non-linear and con-
 90 founding partial effects of the different factors and variables in the data using
 91 generalised linear (GLM) and generalised additive models (GAM Wood (2006)).

92 Building on the analyses by Zhang et al. (2017) and Filoso et al. (2017),
 93 and combining their conclusions, the main hypothesis to test is that the change
 94 in streamflow is impacted by the change in forest cover. However, this change is
 95 is potentially modulated by the area under consideration (affecting the length
 96 of the flowpaths Zhou et al. (2015)), the length of the study (c.f. Jackson et al.
 97 (2005); Filoso et al. (2017)) and the climate (as indicated by either E0/Pa or
 98 latitude and longitude Filoso et al. (2017); Zhou et al. (2015)).

99 However, there could be further confounding factors, which are eluded to by
 100 Filoso et al. (2017):

- 101 • the type of analysis, i.e. paired watershed studies, modelling, time series
 102 analysis etc.
- 103 • the age of the study, assuming that historical studies might not have
 104 had the ability to measure at the accuracy that currently is available
 105 to researchers, or that more careful historical attention to detail in field
 106 studies might have been lost more recently due to reductions in research
 107 investment.

108 Finally, this work aims to point to further research that can expand this area
 109 of work, based on the collected data, to better understand the impact of forest
 110 cover change on streamflow.

111 2. Methods

112 2.1. The original data sets

113 The starting point of this paper is the data base of studies which were
 114 included in Zhang et al. (2017) as supplementary material. The columns in this
 115 data set are the catchment number, the catchment name, the Area in km², the
 116 annual average precipitation (Pa) in mm, the forest type, hydrological regime,
 117 and climate type, the change in forest cover in % ($\Delta F\%$) and the change in
 118 streamflow in % ($\Delta Qf\%$), based on equation 1 in Zhang et al. (2017)), the
 119 precipitation data type, the assessment technique, and the source of the info,
 120 which is a citation. Several of these columns contain abbreviations to describe
 121 the different variables, which are summarised in Table 1.

122 Table 1 Summary of abbreviations of factors used in the Zhang et al. (2017)
 123 data set

Factor	Abbreviation	Definition
forest type	CF	coniferous forest
	BF	broadleaf forest
	MF	mixed forest
hydrological regime	RD	rain dominated
	SD	snow dominated
climate type	EL	energy limited
	WL	water limited
	EQ	equitant
precipitation data type	OB	observed
	SG	spatial gridded
	MD	modelled
assessment technique	PWE	paired watershed experiment
	QPW	quasi-paired watershed experiment
	HM	hydrological modelling
	EA	elasticity analysis
	SH	combined use of statistical methods and hydrographs

124 While Zhang et al. (2017) use the dryness index in their analysis, and
 125 calculate the variable climate type from this index, the potential or reference
 126 evapotranspiration was not originally included as part of the published data set.
 127 In this paper, we used only the dryness index and did not use the climate type
 128 as a variable (as they are interchangeable). We combined the tables for small
 129 catchments (< 1000 km²) and large catchments (>= 1000 km²) in our analysis.

2.2. Additional data collection

To enhance the existing data set, this study added additional variables and cross-checked the studies with the data set from Filoso et al. (2017). In particular, we focussed on the 37 data points included in the quantitative analysis in Filoso et al. (2017).

In addition, additional variables added were the latitude and longitude for the centre of the catchment as an approximation of its spatial location. Using this information reference evapotranspiration (E_0) was extracted from the Global Aridity Index and Potential Evapo-Transpiration (ET_0) Climate Databasev2 (Trabucco and Zomer, 2018). For large catchments, this value, similar to annual average rainfall, is only an approximation of the climate at the location.

Similar to Zhang et al. (2017), the “dryness index” was calculated from the reference evapotranspiration and the annual average rainfall (Pa) as:

$$D = \frac{E_0}{Pa} \quad (1)$$

The length of the study can be a variable influencing the change in flow (Filoso et al., 2017; e.g. Jackson et al., 2005), as for example, more mature plantations are thought to have smaller impacts on flow or regrowth might follow a “Kuczera curve” (Kuczera, 1987). Therefore, the length of the study calculate as the difference between the starting data and completion date of the different studies was extracted from the references provided by Zhang et al. (2017). The length of the study was already included in the data from Filoso et al. (2017), but these were checked against the original publications.

Several additional data points from catchment studies were extracted from Zhang et al. (2011), Zhao et al. (2010), Borg et al. (1988), Thornton et al. (2007), Zhou et al. (2010), Rodriguez et al. (2010), Ruprecht et al. (1991) and Peña-Arancibia et al. (2012), and these were checked against the existing studies to prevent overlap. In the citation column in the data set, in general the main reference for the calculated change in streamflow was used, because sometimes the original study did not provide the quantification of the change in streamflow (i.e. Table 6 in Zhang et al. (2011)). We also removed one data point from the analysis, which corresponds to catchment #1 (Amazon) in Zhang et al. (2017). This is because the cited reference (Roche, 1981) only relates to 1 and 1.5 ha paired catchment studies in French Guyana, and in which the actual change in forest cover is not recorded. Furthermore, the change in flow for catchment #76 was corrected from 600% to 157% after review of the original publication (Baker Jr., 1984). Finally, on review of all the data in Zhang et al. (2017) and Filoso et al. (2017) and the additional studies, 29 potential duplicates were identified and flagged in the data.

The final column in the improved data set is a “notes” column, which is not further used in the analysis, but gives context to some of the data for future research and highlights some of the discrepancies that we found between the original papers and the data in the tables from Zhang et al. (2017).

171 2.3. Statistical modelling

172 To estimate how the change in streamflow is affected by the change in forest
 173 cover while considering the effects of the other variables, we applied generalised
 174 additive modelling (GAM) (Wood, 2006).

175 The general model tested is:

$$\Delta Qf\% \sim \Delta\%forest\ cover_{positive} + sign_{forest\ cover} + \sum X_i + \sum s(Z_i) + \varepsilon \quad (2)$$

176 Here X_i are factorial variables, while Z_i are continuous variables. The model
 177 assumes no direct interactions and all variables are additive. The changes in
 178 forest cover contain both positive (forestation) and negative values (deforesta-
 179 tion). In Zhang et al. (2017), these changes were jointly analysed, assuming the
 180 effect on the change in flow was linear and the effect if removing forest cover
 181 was the same as an equivalent reforestation. However, the impact of an increase
 182 in forest cover can be different from the same fractional decrease in forest cover.
 183 Therefore all the change in forest cover data is converted to positive values, and
 184 an additional column ($sign_{forestcover}$) is added that indicates whether it was a
 185 forest cover increase or decrease. A further assumption in the model is that all
 186 continuous variables Z_i (such as annual precipitation (Pa)) can have a linear or
 187 non-linear relationship with $\Delta Qf\%$. This means that a smooth function $s()$ is
 188 applied to the Z_i variables. For the smoothing function we applied thin plate
 189 regression splines with an additional shrinkage penalty which means the terms
 190 can be shrunk to 0 if not significant (Wood, 2006).

191 For the model in equation 2, we initially only used the data from Zhang et
 192 al. (2017) to make sure that the additional catchments added to the data set
 193 did not influence the results. Subsequently the analysis was repeated and the
 194 additionally identified catchments were added.

195 More generally the results were analysed to identify:

- 196 1. the significance of the different variables
- 197 2. the direction of the categorical or shape of the smooth variables

198 3. Results

199 3.1. description of the data

200 The overall dataset contains 355 observations of changes in flow, which in-
 201 cludes the newly identified data sets and after removing identified duplicate
 202 data and lines with missing data. In contrast, the original dataset from Zhang
 203 et al. (2017) contained 312 catchments and the Filoso et al. (2017) study used
 204 37 catchments (Table S2 in Filoso et al. (2017)). The overall distribution of
 205 changes in flow is highly skewed as is the distribution of changes in forest cover
 206 and Area. The values of changes in flow greater than 100% and smaller than
 207 -100% clearly create long tails on the change in flow distribution. Note also the
 208 large number of studies with 100% forest cover reduction. Smaller catchments

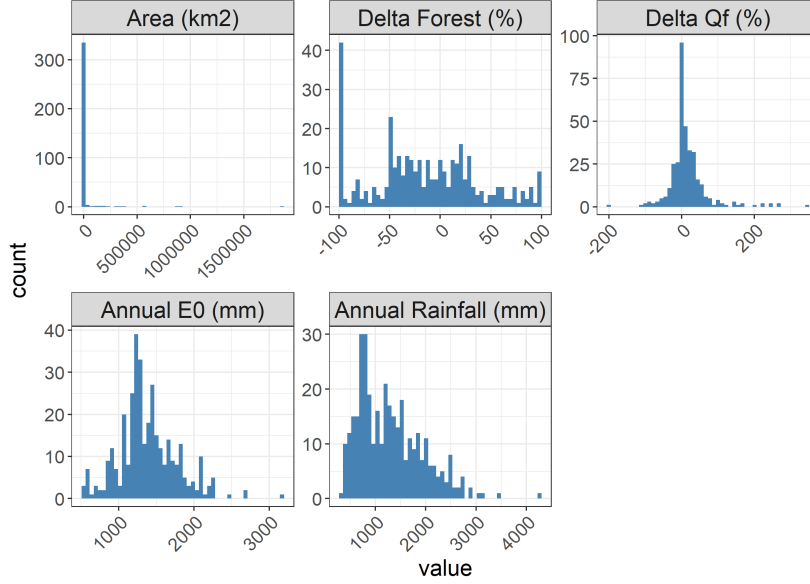


Figure 1: Overview of the distribution of the data set for five of the included variables.

dominate the database with 42% of the data from catchments $< 1 \text{ km}^2$ and 65% of the data for catchments $< 10 \text{ km}^2$.

This shows that for the data related to forest decreases, there is almost always a positive flow change. In other words, flow almost always increased. However, for increases in forest cover, this is not the case, and flow can both increase and decrease. However in both cases the variability in the reported change in flow increases with the increase in forest cover change.

3.2. The general relationship between change in forest cover and streamflow

Following Zhang et al. (2017), the first step is to investigate the percent change in flow as a linear effect of the percent change forestry and modulated by the direction of the change, either an increase in forest cover, or decrease in forest cover:

$$\Delta Qf\% \sim \Delta\%forest\ cover_{positive} + sign_{forest\ cover} + \varepsilon \quad (3)$$

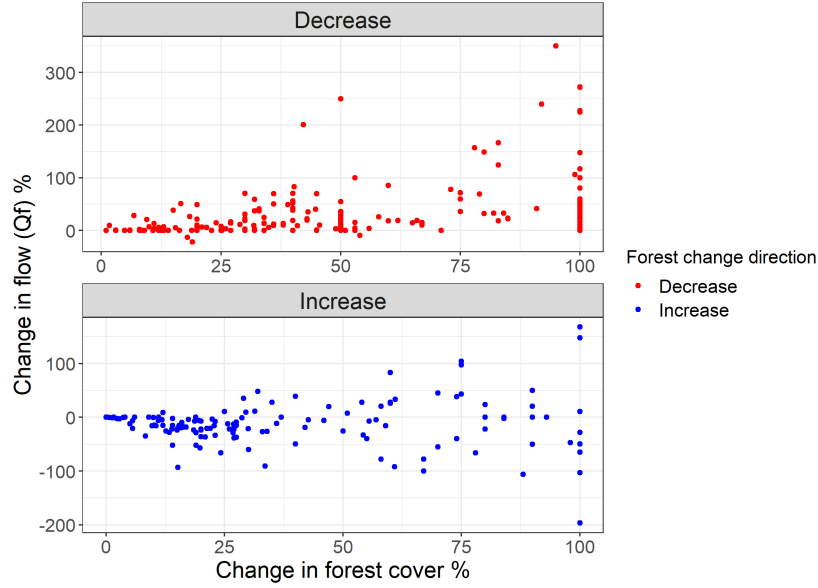


Figure 2: Changes in flow as a function of increases and decreases in forest cover

Table 2: Summary results of the first regression model predicting change in streamflow from change in forest cover and accounting for the direction of the change. The first three rows relate to the model using the original data base from Zhang et al. (2017). The bottom three rows are the results of the model including the new data

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	8.66	5.52	1.57	0.12
DeltaF_perc_pos	0.5	0.09	5.81	0
Forest_SignIncrease	-31	5.87	-5.28	0
(Intercept)	10.74	5.29	2.03	0.04
DeltaF_perc_pos	0.46	0.08	5.6	0
Forest_SignIncrease	-39.7	5.3	-7.49	0

221 The overall variance explained in this model (equation (3)) is not high with
 222 an adjusted r^2 of 0.23, it generally supports the hypothesized relationship be-
 223 tween the change in forest cover and the change in flow. The model suggests
 224 that for every 1% change in forest cover, on the average, the flow changes 0.45%.
 225 However the change in flow is different for forest cover decreases compared to
 226 forest cover increases. In fact, forest cover increases decrease flow by 29% less
 227 than a similar decrease in forest cover causes flow to increase. So roughly speak-
 228 ing, a 1% forest cover increase on the average decreases flow by $(1 - 0.29) * 0.45\%$,

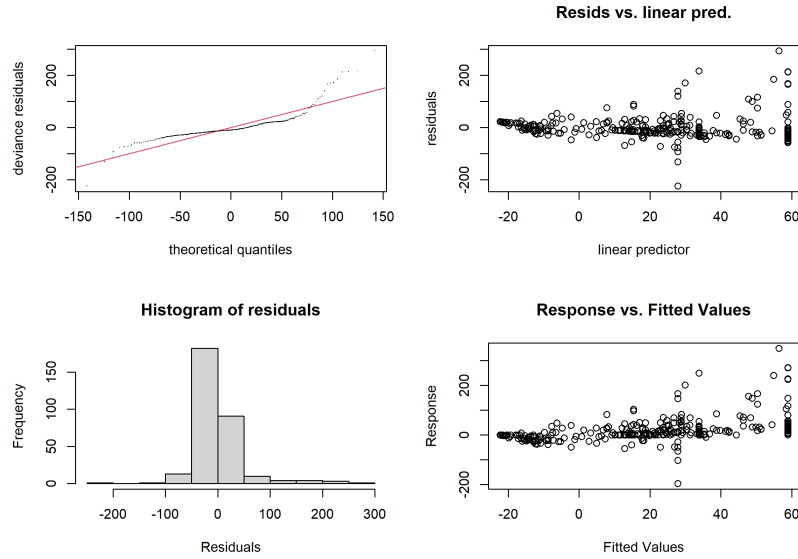


Figure 3: Residual plots for the first simple regression model indicating a slightly fat-tailed residual distribution

229 while a the percentage forest cover decrease will increase flow by 0.45%.

230 Of importance here is to highlight the residuals of this regression (equation
 231 (3) and Figure 3). These are approximately normal, although there is still
 232 significant skew on the upper and lower parts of the distribution (Figure 3). In
 233 other words, the distribution of the residuals is somewhat fat-tailed. We will
 234 discuss this later.

235 Including the data from some of the newly identified studies indicates that
 236 this mainly strengthens the difference between the forest cover increases and
 237 decreases (Table 2), and the result indicate a reduction in the mean decrease in
 238 flow as a result of forest cover change if the new data is included.

239 It is however it is clear from the lack of explaining power for the model, that
 240 there could be confounding factors, as alluded to in the methods. The obvious
 241 ones being catchment dryness and area (following Zhang et al. (2017)), which
 242 we will analyse later.

243 3.3. The effect of location on the globe

244 As indicated, an initial hypothesis relates to whether there is a strong spatial
 245 global gradient as captured by latitude and longitude. These data were added
 246 for the different studies, mostly by using the data reported by the authors, but
 247 in some cases approximating the location of the centre of the catchment using
 248 Google Maps. In the dataset, an additional column is added to indicate the
 249 source of the location data. As the global map (Figure 4) shows, the distribution
 250 of case study catchments covers multiple continents and shows some distinct

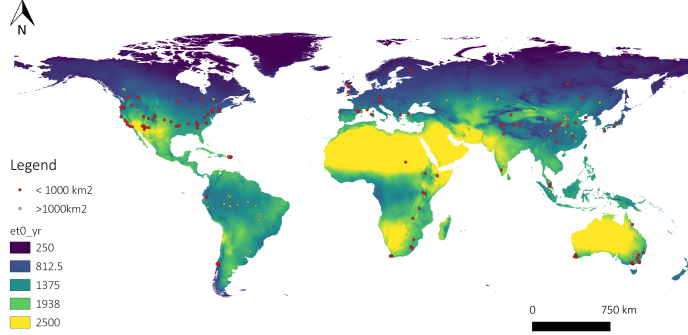


Figure 4: Distribution of included catchments across the globe based on reported or estimated latitude and longitude

251 clustering in parts of the world. Of interest is whether the spatial clustering
 252 also indicates a difference in response to forest cover change:

$$\Delta Qf\% \sim \Delta\%forest\ cover_{positive} + sign_{forest\ cover} + Latitude + Longitude + \varepsilon \quad (4)$$

Table 3: Results of the model including Latitude and Longitude including new data

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	12.02	5.66	2.12	0.03
DeltaF_perc_pos	0.47	0.08	5.67	0
Forest_SignIncrease	-41.77	5.53	-7.55	0
Latitude	-0.05	0.09	-0.55	0.58
Longitude	0.02	0.03	0.56	0.58

253 There appears to be no significant gradient in either latitude or longitude
 254 (Table 3), suggesting that the distribution of the catchments across the globe
 255 has little influence on the overall result. The total explaining power of the model
 256 is still low with an adjusted r^2 of 0.24 suggesting further factors influencing the
 257 change in streamflow that are currently not included in the model.

258 3.4. Impact of climate

259 Climate, and in particular evapotranspiration can have a significant effect
 260 on the streamflow change as represented by the dryness index, which is also
 261 highlighted by both Zhang et al. (2017) and Jackson et al. (2005). Increased
 262 evapotranspiration could lead to drier catchments, unless balanced by rainfall

(such as possibly in the tropics). Initially, we tested models using annual average precipitation (Pa (mm)), but because of the interactions between precipitation, evapotranspiration and the dryness index, we concentrated on the dryness index as the key variable. Given that Latitude and Longitude were not significant, we dropped these from the model.

$$\Delta Qf\% \sim \Delta\%forest\ cover_{positive} + sign_{forest\ cover} + Dryness + \varepsilon \quad (5)$$

Table 4: Results of the model including the dryness index

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	8.43	6.39	1.32	0.19
DeltaF_perc_pos	0.46	0.08	5.58	0
Forest_SignIncrease	-40.3	5.37	-7.51	0
Dryness	1.81	2.73	0.66	0.51

The results from this model (equation (5) and Table 4) indicate no impact of dryness on the change in streamflow as a function of the change in forest cover change, which is surprising in light of earlier reported results (Filoso et al., 2017; Zhang et al., 2017). In this case the evidence is highly doubtful ($p = 0.51$). However, it is very well possible that there is a further interaction in the data that this simpler version of the model cannot identify. Again, overall variance explained is not very much, with an adjusted r^2 of 0.23.

Table 5: catchments for which the dryness index > 4

Latitude	Longitude	Watershed name
34.67	-111.7	Beaver Creek, AZ #3-2
36.4	-120.4	Cantua
32.74	-111.5	Natural DRDages, Ariz., U.S.A, A
32.74	-111.5	Natural Drainages, Ariz., U.S.A, C
34.43	-112.3	White Spar, Ariz., U.S.A, B
-25.75	28.23	Queens river

There are also possible issues with the data, a few of the catchments have Dryness values that are very large (> 4) and these values have high leverage in the data, affecting the residual distribution. These catchments are listed in Table 5.

279 *3.5. Is there a distinct effect of area?*

280 The major hypothesis to test is the effect of area on the change in flow,
 281 following the analysis by Zhang et al. (2017) and Filoso et al. (2017). Given
 282 the highly skewed distribution of the catchment areas (Figure 1), a log base 10
 283 transformation was applied to the variable *Area (km²)*. The effect of Dryness
 284 remains in the model, given that there could be interactions that are worth
 285 exploring.

$$\Delta Q f\% \sim \Delta\%forest\ cover_{positive} + sign_{forest\ cover} + \log_{10}(Area\ (km^2)) + Dryness + \varepsilon \quad (6)$$

Table 6: Results of the model including Area and the dryness index

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	13.86	7.2	1.92	0.06
DeltaF_perc_pos	0.38	0.1	3.77	0
Forest_SignIncrease	-38.44	5.48	-7.02	0
Dryness	2.45	2.75	0.89	0.37
log10(Area_km2)	-2.75	1.7	-1.62	0.11

286 The results of this model (Equation (6)) indicate a reduction in the effect of
 287 forest cover change with Area (km²) (Table 6). In fact, the results suggests that
 288 for every additional 10 km² in catchment size the mean change in flow reduces by
 289 3.5%. Another interesting fact to note is that with the inclusion of Area (km²) as
 290 a variable in the model, the effect of Dryness becomes more significant, possibly
 291 suggesting an interaction between Dryness and Area. Including this interaction
 292 suggest that the interaction term (log10(Area) by Dryness) would be significant,
 293 but this replaces the effect of Area (results not shown).

294 *3.6. Are some of the variables possibly non-linear?*

295 The work by Filoso et al. (2017) and earlier by Jackson et al. (2005) has
 296 indicated that the length of the study might influence the response. This links
 297 to the idea from Kuczera (1987) that the effect of logging or deforestation or
 298 reforestation reduces with the length of time post intervention (see also Jackson
 299 et al. (2005)). In addition to adding *length* (being the difference between the
 300 reported start date and end date of data collection in the specific study) as
 301 a variable, three other continuous variables (*Dryness*, *Area*, *From*) were con-
 302 sidered non-linear in this model. This is also indicated a shrinkage smoothing
 303 spline (Wood, 2006) was applied to these variables. *From* represents the starting
 304 date of the data collection.

	Estimate	Std. Error	t value	Pr(> t)
DeltaF_perc_pos	0.3	0.1	3.16	0
Forest_SignIncrease	-26.28	6.64	-3.96	0
Precip_data_typeOB	-7.03	13.51	-0.52	0.6
Precip_data_typeSG	13.98	15.5	0.9	0.37
Assessment_techniqueEA, HM	18.74	45.33	0.41	0.68
Assessment_techniqueHM	25.27	11.91	2.12	0.03
Assessment_techniquePWE	54.21	11.81	4.59	0
Assessment_techniquePWE, HM	31.99	46.11	0.69	0.49
Assessment_techniqueQPW	29.16	20.96	1.39	0.17
Assessment_techniqueQPW, EA	34.71	34.04	1.02	0.31
Assessment_techniqueSH	37.64	11.87	3.17	0
Forest_typeCF	-11.48	8.07	-1.42	0.16
Forest_typeMF	-8.65	7.72	-1.12	0.26
Hydrological_regimeSD	13.8	10.15	1.36	0.18

Table 10: Statistical summary for the smooth terms for the full model

	edf	Ref.df	F	p-value
s(log10(Area_km2))	0.32	9	0.05	0.25
s(Dryness)	0.48	9	0.09	0.19
s(length)	0.88	9	0.69	0.01
s(From)	1.79	9	0.96	0.01

318 This model explains more of the variance, but the improvement is marginal
319 compared to the previous model with a deviance explained of 0.31. This indi-
320 cates that the categorical variables explain a limited amount of the variance.
321 However, interesting to note from Table 9 that several of the assessment methods
322 are significant. In particular Paired Watersheds experiments (PWE), Hydrolog-
323 ical modelling (HM) and Statistical techniques (SH) are strongly significant
324 ($p < 0.05$). In this case, $Area (km^2)$ is no longer a significant predictor.

325 Figure 5 highlights that the relationship between $\log_{10}(Area \text{ km}^2)$ and the
326 change in flow is essentially linear, not significant, and does not need to be
327 smoothed (this is the value of using penalized smooths following Wood (2006)).
328 It still has a negative slope, indicating that in larger catchments the impact
329 of changes in forest cover on streamflow is less than for smaller catchments.
330 Similarly, the length variable is not significant. However, both the length and
331 Dryness variables show non-linearity, but this does not show a clear trend due
332 to the scatter and the distributions of the data.

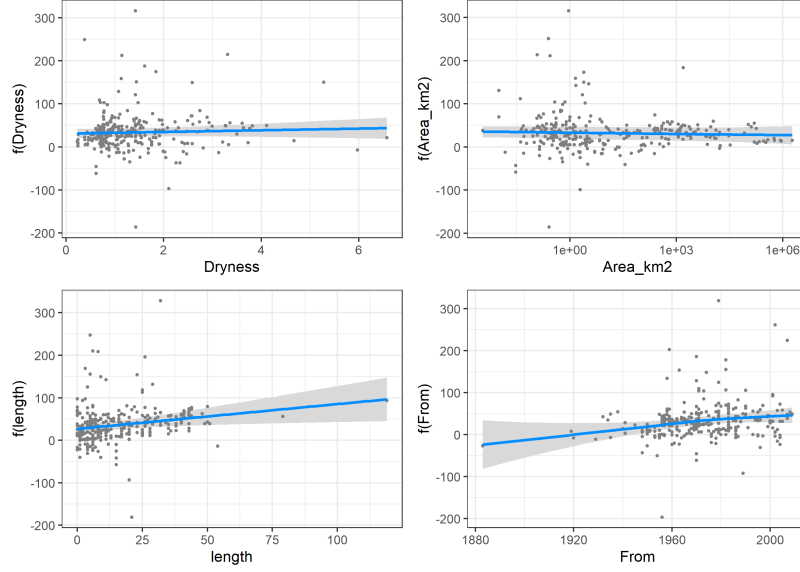


Figure 5: Visualisation of the smooth variables in the model

Table 11: Statistical summary of the smooth terms reducing dataset to studies with the study length shorter than 60 years

	edf	Ref.df	F	p-value
s(Dryness)	0.2	9	0.03	0.25
s(log10(Area_km2))	0	9	0	0.33
s(length)	3.81	9	1.19	0.02
s(From)	3.94	9	1.31	0.01

333 The flexible nature of the splines means that the length variable captures
334 some substantial variation in the data, but it is unclear what exactly is captured.
335 The shape of the conditional response (Figure 5) also does not reflect the type
336 of response highlighted in Filoso et al. (2017) and Jackson et al. (2005). One
337 reason could be the few data points with very long data series, and very old
338 studies (before 1930 essentially), and highly variable responses (Figure 5). Red-
339 ucing the flexibility of the splines, removing any studies longer than 60 years
340 and removing the 4 studies with Dryness > 4 (Table 11) results in log10(Area)
341 once again showing a significant effect with larger catchments having less impact
342 of changes in forest cover. Dryness now shows a clear non-linear response with
343 drier catchments having a greater impact of changes in forest cover. Finally,
344 more recent studies also show greater impacts of changes in forest cover (Figure
345 6).

346 4. Discussion

347 4.1. Catchment size

348 Essentially, the analysis shows that there is a clear effect of catchment size
349 (Figure 6), even though, in contrast to Zhang et al. (2017), there is no evidence
350 a distinct threshold in the size of the catchment that influences the change in
351 the streamflow as a result of changes in forestry. If anything the scatter in the
352 data (in the change in flow) is greater for the smaller catchments than for the
353 larger catchments (Figure 7). In other words, the response to changes in forest
354 cover is more consistent for larger catchments than it is for smaller catchments.
355 An explanation for the catchment size effect might be that large catchments

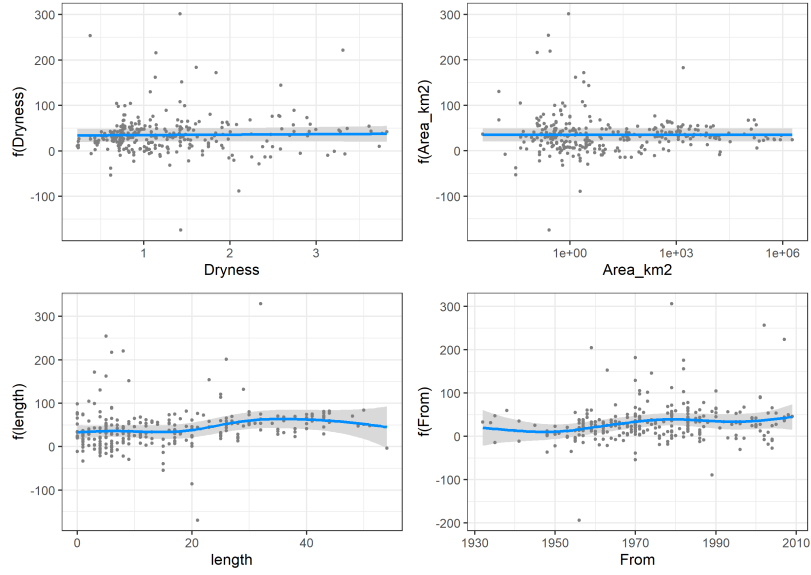


Figure 6: Visualisation of the smooth variables in the model with reduced data for dryness and length

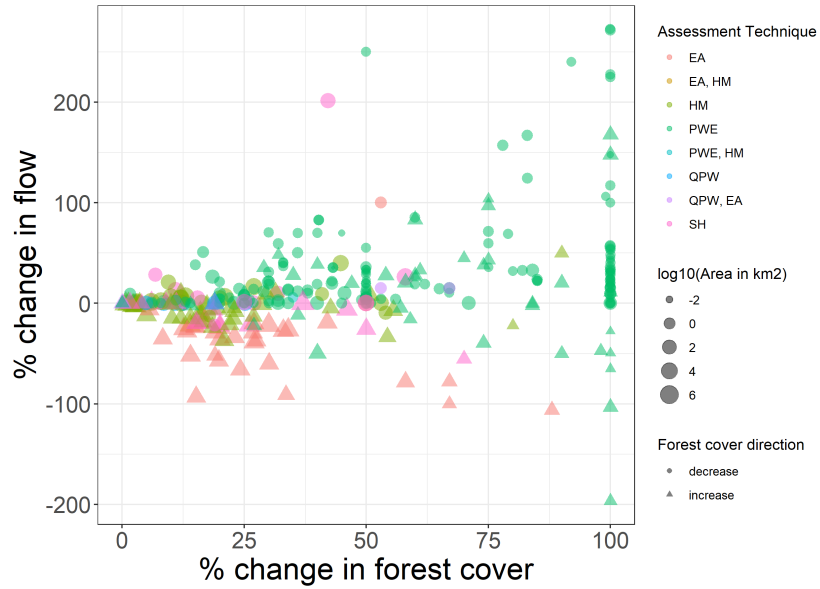


Figure 7: Overview of the data highlighting the dominance of small catchment studies which are fully forested or cleared and the scatter in the data

data” using paired watershed studies, while for larger catchments, the analysis are mostly based on modelling approximations using either elasticity analysis (EA), Hydrological modelling (HM) or a combined use of statistical methods (SH) or quasi paired watershed analysis (QPW) (Figure 7). These techniques for larger catchments all provide an approximation of the effect of forestry on streamflow rather than a direct comparison of catchments. This is a confounding factor that is not easily addressed in the regression modelling attempted here. Furthermore, the catchments analysed using EA, are concentrated in the drier end of the Dryness index scale compared to the other methods, with only the paired watershed experiment (PWE) assessment technique covering the full range of dryness indices.

In other words, the current data sets cannot resolve whether there actually is a non-linear catchment size \times forest cover effect, which then feeds into the buffering in larger catchments.

Apart from a difficulty of analysing complex confounding factors in the data, a general limitation of the type of analysis presented is that this work does not consider the spatial arrangement of the forest clearing in the catchments. While for fully or almost fully cleared smaller catchments this might not be an issue, it is perceivable that for larger catchments being partially cleared, a interaction between spatial location and clearing could be a factor in determining the change in streamflow. Clearing head water catchments on shallower soils might have a larger impact than clearing in downstream areas on deeper soils.

4.2. Model residuals

As pointed out earlier the residuals of the model diverge from the normal distribution for large positive and large negative residuals. These residuals are mainly associated with the small catchments from the paired watershed studies (Figure 7), which show very high variability. The final model removing the data with large values of Dryness and long study lengths has removed some of the spreading, mainly for the large negative residuals (Figure 8).

The reason why the regression model is better able to resolve the variance in the data for the negative residuals (generally related to increases in forest cover) compared the large positive residuals might link back to the issue of buffering and flow paths in the catchments. Small catchments that are stripped of most of the forest cover would provide little buffering, interception and infiltration, does leading to greater changes in flow. In contrast, revegetated catchments would have increased interception and buffering and therefore relatively smaller changes in flow. This also provides an explanation for the differences between forest cover removal and forest cover restoration (Figure 2).

4.3. The effect of assessment techniques with very small numbers of observations

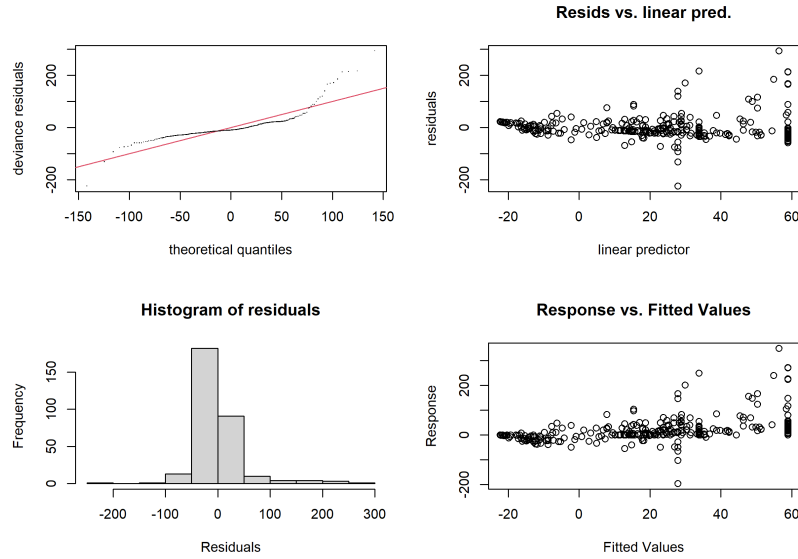


Figure 8: Residual plots for the final model indicating a small improvement in the residual distribution towards normal

Table 12: Distribution of assessment techniques in the data set

Assessment_technique	n
PWE	208
HM	57
SH	43
EA	34
QPW	7
QPW, EA	4
EA, HM	1
PWE, HM	1

One concern is that there are a few assessment techniques in the original dataset with a very low number of observations and this might skew the results of the analysis. This includes the category of Quasi paired watersheds and combinations of elasticity analysis and hydrological modelling (EA,HM) and paired watersheds and hydrological modelling (PWE,HM) (Table 12 and Figure 9).

Table 13: Statistical overview of the linear components of the model removing studies with limited observations in the assessment techniques

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-32.33 ¹⁸	18.4	-1.76	0.08
DeltaF_perc_pos	0.31	0.09	3.22	0
Forest_SignIncrease	-26.07	6.79	-3.84	0
Precip_data_typeOB	0.12	13.84	0.01	0.99
Precip_data_typeSG	21.54	15.96	1.35	0.18
Assessment_techniqueHM	23.08	12.26	1.88	0.06
Assessment_techniquePWE	56.89	11.19	5.09	0
Assessment_techniqueQPW	29.72	21.04	1.41	0.16
Assessment_techniqueSH	35.41	11.7	3.03	0

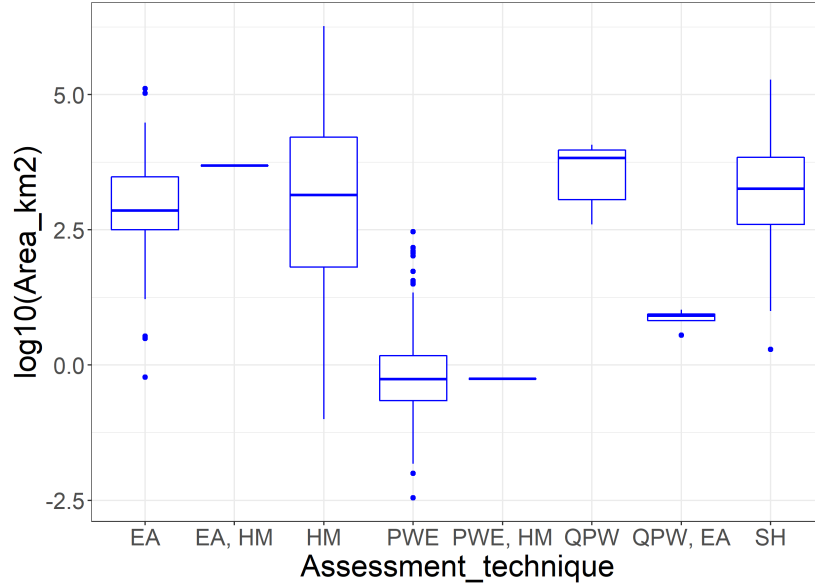


Figure 9: Boxplot of the log base 10 of the catchment area (in km²) for the different assessment techniques, showing the dominance of small catchments in the paired watershed experiments

Table 14: Statistical overview of the smooth components of the model removing studies with limited observations in the assessment techniques

	edf	Ref.df	F	p-value
s(Dryness)	0	9	0	0.31
s(log10(Area_km2))	0	9	0	0.35
s(length)	4.58	9	1.59	0.01
s(From)	0.87	9	0.64	0.01

Concentrating only on the assessment techniques that have more than 10 observations in the data set does not change much in the results (Table 13 and 14). It strengthens the significance of the different assessment techniques but slightly reduces the importance of some of the smooth variables ($\log_{10}(\text{Area } km^2)$) and *From*). Overall this suggests that although those observations have some impact on the overall relationships, they do not strongly bias the outcomes.

However, the model results also clearly highlight that some of the assessment techniques (in particular paired watershed studies (PWE) and combined use of statistical methods and hydrographs (SH)), have a strong impact on the predicted change in flow. Particularly, relative to EA (elasticity approaches) all other assessment techniques have higher predicted changes in flow. In other words, there is a distinct difference in the way the change in flow is assessed,

and the EA method (for example in Zhou et al. (2015)) appears to suggest a much smaller effect on the change in flow. However, as indicated earlier, the EA studies are all on the drier end of the Dryness spectrum, highlighting another unresolved interaction in the data.

4.4. The effect of climate

In drier catchments, changes in forest cover have greater impact on flow, which is similar to the observations in earlier studies (Filoso et al., 2017; Zhang et al., 2017; Zhou et al., 2015). This is most likely because in these catchments the overall flow is surface flow dominated and therefore the buffering that is afforded by the groundwater inputs is not as great. As the dataset currently does not include a separate variable for groundwater inputs (although this effect is estimated in several of the studies), the effect again cannot be analysed separately.

Excluding the few catchments that have very high dryness values, clarified the *Dryness* trend, agreeing with earlier studies and showing an increase in the change in flow for drier catchments. However, this really only starts to have an effect for Dryness > 2.

4.5. Further considerations

In contrast to Filoso et al. (2017), we did not identify the length of the observation period as a significant variable, however, we did find that the start date of the observations was significant. What is puzzling is that the effect of the start date (*From*) had a positive slope indicating that more recent studies measured a greater effect on stream flow of forest cover change. At this point, it is unclear what this trend signifies. It is also possible that there is an interaction between the start date of the observations and the length of the study, as later start dates would never have been able to present long observed data series.

There are further confounding factors in the data, which were also classified by Filoso et al. (2017) and these might create biases in the data set that can impact the overall assessment. For example, snow dominated hydrological regimes (SD), are dominated by Coniferous Forests (CF), while the majority of the rain dominated regimes are all broadleaf or mixed type forests (BF or MF). However, the forest type classification is very coarse and does not fully capture possible physiological differences that could affect evapotranspiration and therefore changes in streamflow (Vervoort et al., 2021).

5. Conclusions

More rigorous checking of data and statistical analysis results in both agreement and disagreement with older studies.

Results of this statistical analysis need to be considered “conditional on the data” Conditional on the data, the impact of forestry on streamflow is:

- Greater for forest clearing than for reforestation
- Reduced for larger watersheds

- 465 - Increases for drier watersheds
- 466 - Sensitive to the assessment method used in the historical data

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