Do larger catchments respond different to forest cover change? Re-analysing a global data set.

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Abstract

This is the abstract. It consists of two paragraphs.

Introduction

Introduction

There has been an long and on-going discussion in the hydrologcal 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 Figure 5 in Zhang et al. (2011) indicating (for Australian watersheds) a 100% decrease in stream flow for watersheds with 100% forest cover. However, on the other end of the spectrum, in a series of French watersheds (Cosandey et al., 2005), there was no change in streamflow characteristics in 2 of the three watersheds studied in relation to deforestation.

Several review papers have summarized different studies across the globe, in relation to paired watershed studies (Bosch and Hewlett, 1982; Brown et al., 2005), related to reforestation in particular (Filoso et al., 2017), and more generally (Jackson et al., 2005; Zhang et al., 2017). These studies aim to generalize the individual findings and to identify if there are global trends or relationships that can be developed. The most recent reviews (Filoso et al., 2017; Zhang et al., 2017) developed an impressive global database of watershed studies in relation to changes in streamflow due to changes in forest cover. The Zhang et al. (2017) dataset, which covers over 250 studies, is described in terms of the change in streamflow as a result of the change in forest cover, where studies related to both forestation (increase in forest cover) and deforestation (decrease in forest cover) were included. In contrast, the paper by Filoso et al. (2017) focused primarily on reforestation, and covered an equally impressive database of 167 studies using a systematic review. In this case the collected data is mostly coded as count data and only a subset of 37 studies was analysed for actual water yield change.

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The conclusions of the first paper (Zhang et al., 2017) suggest that there is a distinct difference in the change in flow as a result of forestation or deforestation between small watersheds, defined as < 1000 km^2 and large watersheds > 1000 km^2. While for small watersheds there was no real change in runoff with changes in cover, for large watersheds there was a clear trend showing a decrease in runoff with and increase in forest cover. Their main conclusion was that the response in annual runoff to forest cover was scale dependent and appeared to be more sensitive to forest cover change in water limited watersheds relative to energy limited watershed (Zhang et al., 2017).

The second study (Filoso et al., 2017) was a systematic review which classified the historical research and highlighted gaps in the spatial distribution, the types of studies and the types of analysis. Their main conclusion was also that reforestation decreases streamflow, but that there were many interacting factors. For a subset of quantitative data (37) they showed a relationship between catchment size and decline in streamflow.

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

Encouraged by the work presented by Zhang et al. (2017) and Filoso et al. (2017) and the fantastic database of studies presented by these authors, we believe we can add to the discussion. In this paper, the aim is to develop further analysis of the collected data and expanding and combining the two data sets to provide further depth.

In particular, the main method in the work by Zhang et al. (2017) is using simple linear regression, and in Filoso et al. (2017) the focus is mainly on classification. As Zhang et al. (2017) points out, the main assumption in their work is that the threshold at 1000 km^2 is a distinct separation between “small” and “large” watersheds, but the subset of data in Filoso et al. (2017) does not appear to support this. And while te work Filoso et al. (2017) provides important insights in study types, analysis types and broad classification, there is limited quantification of actual impact. This is because the work had a strict criterion to select quantitative studies. However, given the fantastic data sets collected, the analyses can be easily expanded to look at interactions between the terms and to test the assumption of a distinct threshold at 1000 km^2.

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

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

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

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

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

Methods

The original data sets

The starting point of this paper is the data base of studies which were included in Zhang et al. (2017) as supplementary material. The columns in this data set are the watershed number, the watershed name, the Area in km^2, the annual average precipitation (Pa) in mm, the forest type, hydrological regime, and climate type, the change in forest cover in % (ΔF%) and the change in streamflow in % (ΔQf(%), based on equation 1 in Zhang et al. (2017)), the precipitation data type, the assessment technique, and the source of the info, which is a citation. Several of these columns contain abbreviations to describe the different variables, which are summarised in Table 1.

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

Factor	Abbreviation	Definition
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	elastictity analysis
	SH	combined use of statistical methods and hydrographs

While Zhang et al. (2017) use the dryness index in their analysis, potential or reference evapotranspiration was not originally included as part of the published data set. We combined the tables for small (< 1000 km^2) and large (>= 1000 km^2) watershed data sets in our analysis.

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 center of the watershed 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 (ET0) Climate Databasev2 (Trabucco and Zomer, 2018), if a value of E0 was not available from the original papers. For large watersheds, this value, similar to annual average rainfall, is only an approximation of the climate at the location.

The length of the study can be a variable influencing the change in flow (e.g. Jackson et al., 2005), as for example, more mature plantations are thought to have smaller impacts on flow. 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).

Several additional data points from watershed 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 Watershed #1 (Amazon) in Zhang et al. (2017). This is because the cited reference (Roche, 1981) only relates to 1 and 1.5 ha paired watershed studies in French Guyana, and in which the actual change in forest cover is not recorded.

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).

Similar to Zhang et al. (2017), the "dryness index" was calculated as:

$$D = \frac{E0}{Pa} \tag{1}$$

Statistical modelling

```
Zhang_all <- Zhang_all %>%
  filter(`Watershed #` > 1)
```

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

The general model tested is

$$\begin{aligned} \Delta\%Q \sim \ & \Delta\% forest\ cover_{positive} + sign_{forest\ cover} + \\ & \sum X_i + \sum s(Z_i) + \varepsilon \end{aligned} \tag{2}$$

Here X_i are factorial variables, while Z_i are continous variables. The model assumes no direct interactions and all variables are additive. The changes in forest cover contain both positive (forestation) and negative values (deforestation). In Zhang et al. (2017), these changes were jointly analysed, assuming the effect on the change in flow was linear and non-hysteretic. However, the impact of an increase in forest cover can be different from the same fractional decrease in forest cover. Therefore all the change in forest cover data is converted to positive values, and an additional column (*sign_{forest cover}*) is added that indicates whether it was a forest cover increase or decrease. A further assumption in the model is that all continuous variables Z_i (such as annual precipitation (Pa)) can have a linear or non-linear relationship with $\Delta Q\%$. This means that a smooth function $s()$ is applied to the Z_i variables.

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

More generally the results were analysed to identify:

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

Results

description of the data

The overall dataset contains 311 observations of changes in flow. The overall distribution of changes in flow is highly skewed as is the distribution of changes

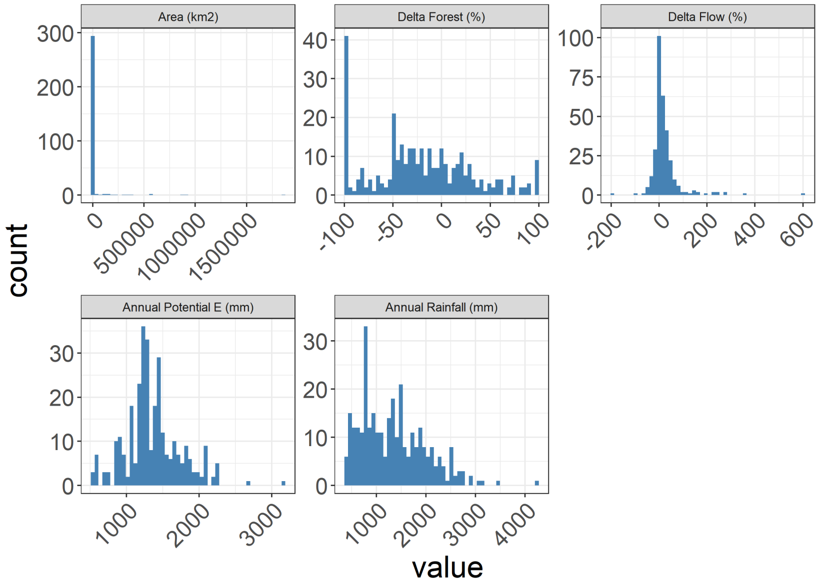


Figure 1: Overview of the distributions of some of the variables in the data set

in forest cover and Area. The values of changes in flow greater than 100% and smaller than -100% clearly create long tails on the change in flow distribution. Note also the large number of studies with 100% forest cover reduction. Smaller watersheds dominate the database with 42% of the data from watersheds < 1 km^2 and 65% of the data for watersheds < 10 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.

The initial relationship between change in forest cover and streamflow

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

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	8.97	6.55	1.37	0.17
DeltaF__perc__pos	0.53	0.1	5.23	0
Forest__Signincrease	-32.55	6.96	-4.68	0

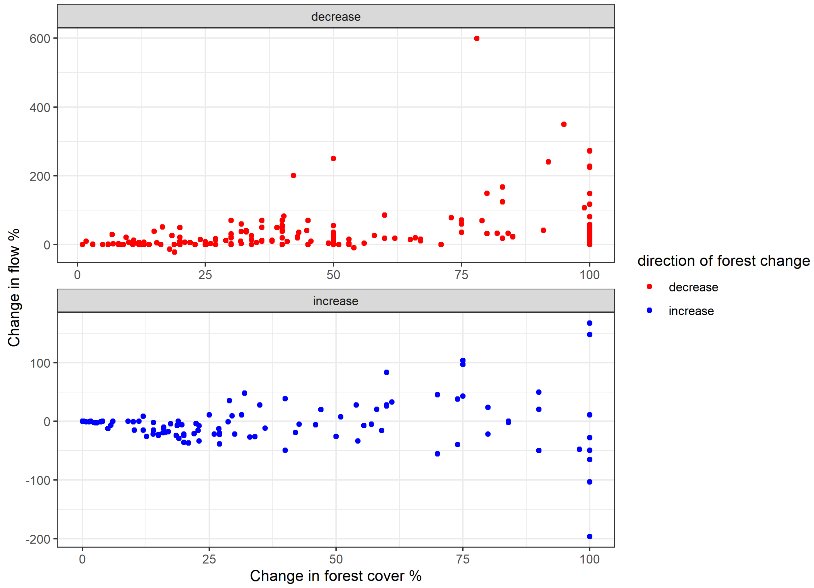


Figure 2: Changes in flow as a function of increases and decreases in forest cover

While the overall variance explained in this model is not high at 0.16, it clearly supports the hypothesized relationship between the change in forest cover and the change in flow. The model suggests that for every 1% change in forest cover, on the average, the flow changes 0.5%. However the change in flow is different for forest cover decreases compared to forest cover increases. In fact, forest cover increases decrease flow by 32% less than a similar decrease in forest cover causes flow to increase. So roughly speaking, a 1% forest cover increase on the average decreases flow by $(1 - 0.32) * 0.5\%$, while a the percentage forest cover decrease will increase flow by 0.5%.

It is however clear from the lack of explaining power, that there could be confounding factors, as alluded to in the methods. The obvious ones being catchment dryness and area (following Zhang et al. (2017)).

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	23.27	9.21	2.53	0.01
DeltaF_perc_pos	0.54	0.1	5.2	0
Forest_Signincrease	-33.29	6.99	-4.77	0
Area_km2	0	0	-0.16	0.87
Pa_mm	-0.01	0	-2.13	0.03

Including area and annual precipitation does not really improve the overall explaining power of the model, in fact, annual precipitation appears to be only a very small confounding factor, representing only a -0.01/% partial effect in the

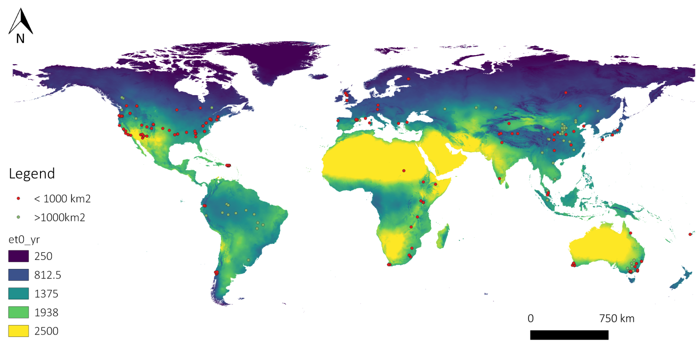


Figure 3: Distribution of included catchments across the globe based on reported or estimated latitude and longitude

change in streamflow, holding all other factors constant. In contrast to earlier reported studies (Filoso et al., 2017; Zhang et al., 2017), watershed area has no effect on the change in stream flow. This supports our approach (in contrast to Zhang et al. (2017)) to consider watershed area as a continuous variable and making no separation between larger and smaller watersheds The main effects remain the change in forest cover and whether this is an increase or decrease.

The effect of location on the globe

As indicated, a second hypothesis relates to whether there is a strong spatial global gradient as captured by latitude and longitude. As the global map (@ref(fig:global_map)) shows, the distribution of case study catchments covers multiple continents and shows some distinct clustering in parts of the world. Of interest is whether the spatial clustering also indicates a difference in response to forest cover change.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	35.23	10.31	3.42	0
DeltaF_perc_pos	0.51	0.1	4.92	0
Forest_Signincrease	-38.06	7.26	-5.24	0
Area_km2	0	0	-0.46	0.64
Pa_mm	-0.01	0.01	-2.54	0.01
Latitude	-0.31	0.13	-2.49	0.01
Longitude	-0.01	0.04	-0.28	0.78

This linear model shows that there is a significant gradient in the Latitude and with annual average rainfall, with watersheds closer to the equator having lower changes in the runoff compare to watersheds further away from the equator. This suggests an influence of radiation, which will be tested next. In addition, the model suggests an influence of the annual average rainfall, with wetter watersheds having slightly lower changes in runoff. The total explaining power of the model is still low at 0.18 suggesting further confounding factors currently not included in the model.

There is no relationship with Longitude, suggesting that the different continents do not show a trend in the East-West direction.

Impact of the dryness index

The previous analysis suggests an influence of radiation on evapotranspiration, and most likely related to the dryness index, as also indicated in Zhang et al. (2017). Increased evapotranspiration could lead to drier catchments, unless balanced by rainfall (such as possibly in the tropics). This model introduces the dryness index as a linear variable and drops the annual average precipitation as a variable.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1.08	8.76	0.12	0.9
DeltaF__perc__pos	0.5	0.1	4.74	0
Forest__Signincrease	-39.12	7.28	-5.37	0
Area__km2	0	0	-0.54	0.59
Latitude	-0.32	0.13	-2.51	0.01
Longitude	-0.01	0.04	-0.19	0.85
Dryness	13.64	3.64	3.75	0

The results from this model confirm that dryness is a significant confounding factor of the change in streamflow as function of the change in forest cover change. In fact if the dryness index doubles (remembering that Dryness = 1 when E0 = Pa, so in this case E0 = 2*Pa, which is very dry), the change in runoff is ~14% greater. However, more interesting, Latitude remains a significant predictor with each degree in latitude causing an -0.31% change in runoff. This indicates that Dryness (i.e. an increase in radiation) alone does not explain the trend in the Latitude and some other unknown confounding factor is captured by Latitude.

However, the result also indicates possible issues with the data, some of the Dryness values are very large (> 4) and these values have high leverage in the data. These catchment are listed in Table XX:

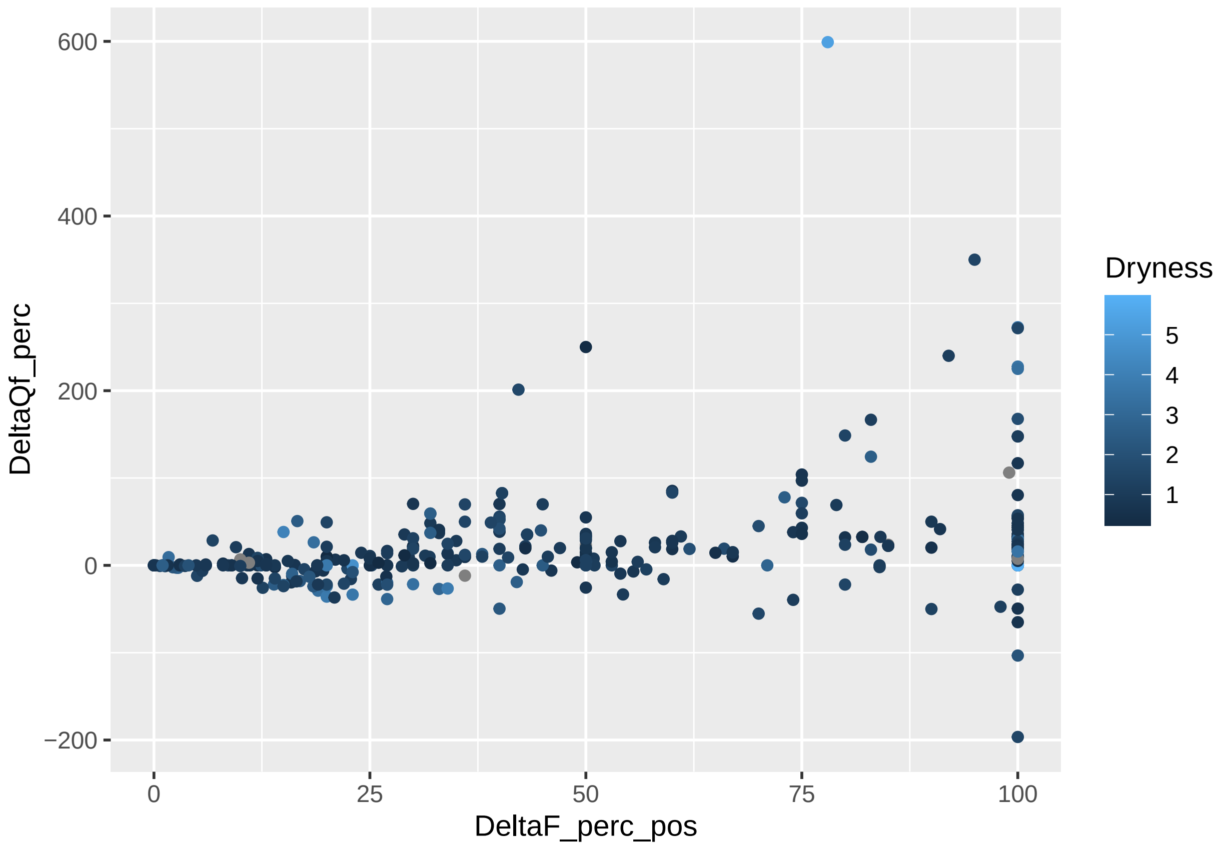
Latitude	Longitude	Watershed name
34.67	-111.7	Beaver Creek, AZ #3-2
36.4	-120.4	Cantua
34.43	-112.3	White Spar, Ariz., U.S.A, B
32.74	-111.5	Natural DRDages, Ariz., U.S.A, A

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## DeltaQf_perc ~ DeltaF_perc_pos + Forest_Sign + s(Dryness, bs = "ts") +
##     s(Latitude, bs = "ts") + Precip_data_type + Assessment_technique +
##     Forest_type + Hydrological_regime
##
## Parametric coefficients:
##                                Estimate Std. Error t value Pr(>|t|)
## (Intercept)                    -14.1541    26.6625  -0.531  0.59595
## DeltaF_perc_pos                  0.4961     0.1165   4.257 2.86e-05 ***
## Forest_Signincrease            -28.4355     8.6675  -3.281  0.00117 **
## Precip_data_typeOB              -1.6722    18.5282  -0.090  0.92816
## Precip_data_typeSG              23.1345    21.4482   1.079  0.28172
## Assessment_techniqueEA, HM      43.8506    56.2639   0.779  0.43644
## Assessment_techniqueHM          14.5238    20.0687   0.724  0.46987
## Assessment_techniquePWE         24.0991    20.0296   1.203  0.22996
## Assessment_techniquePWE, HM     55.2315    62.4275   0.885  0.37709
## Assessment_techniqueQPW         16.5020    30.8514   0.535  0.59317
## Assessment_techniqueQPW, EA     36.7969    33.9341   1.084  0.27917
## Assessment_techniqueSH          22.5635    22.0306   1.024  0.30666
## Forest_typeCF                    2.3144    11.1946   0.207  0.83637
## Forest_typeMF                  -16.6438    10.5710  -1.574  0.11654
## Hydrological_regimeSD           12.8365    12.4739   1.029  0.30437
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                 edf Ref.df     F p-value
## s(Dryness)  8.493      9 5.989 < 2e-16 ***
## s(Latitude) 3.907      9 1.695 0.00238 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.305   Deviance explained = 36.7%
## GCV = 3065.1  Scale est. = 2783.3    n = 298
```

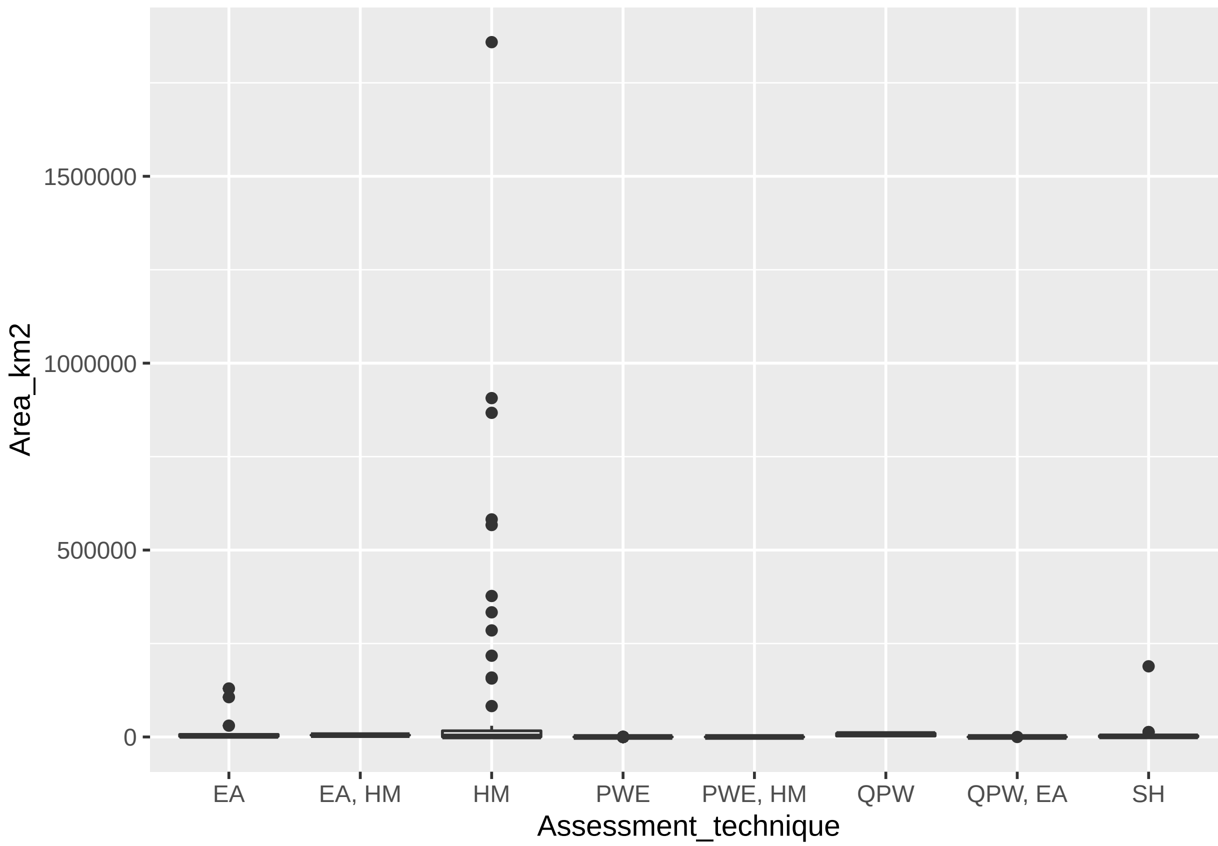
```
model6_reduc <- gam(DeltaQf_perc ~ DeltaF_perc_pos + Forest_Sign +
                    s(Dryness, bs="ts" ) + s(Latitude, bs="ts" ) +
                    Assessment_technique +
                    Hydrological_regime, data = Zhang_all2)
summary(model6_reduc)
```

```
##
```

```
## Family: gaussian
## Link function: identity
##
## Formula:
## DeltaQf_perc ~ DeltaF_perc_pos + Forest_Sign + s(Dryness, bs = "ts") +
##     s(Latitude, bs = "ts") + Assessment_technique + Hydrological_regime
##
## Parametric coefficients:
##                              Estimate Std. Error t value Pr(>|t|)
## (Intercept)                  -10.1399    18.3918  -0.551 0.581848
## DeltaF_perc_pos                0.4702     0.1145   4.107 5.26e-05 ***
## Forest_Signincrease          -30.3156     8.2051  -3.695 0.000265 ***
## Assessment_techniqueEA, HM    41.6430    55.5000   0.750 0.453687
## Assessment_techniqueHM        17.2590    18.9194   0.912 0.362425
## Assessment_techniquePWE       18.4065    18.6123   0.989 0.323542
## Assessment_techniquePWE, HM   53.7505    60.2840   0.892 0.373360
## Assessment_techniqueQPW        9.2813    29.4994   0.315 0.753278
## Assessment_techniqueQPW, EA   30.4467    32.8946   0.926 0.355457
## Assessment_techniqueSH        18.6532    21.0133   0.888 0.375472
## Hydrological_regimeSD         18.3329     9.5617   1.917 0.056210 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                edf Ref.df     F  p-value
## s(Dryness)  8.497      9 5.950  < 2e-16 ***
## s(Latitude) 3.725      9 1.884 0.000881 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.302   Deviance explained = 35.4%
## GCV = 2973.4  Scale est. = 2746.3    n = 304
```


600
400
200
0
−200
0
25
50
75
100
DeltaQf_perc
DeltaF_perc_pos
Dryness
5
4
3
2
1

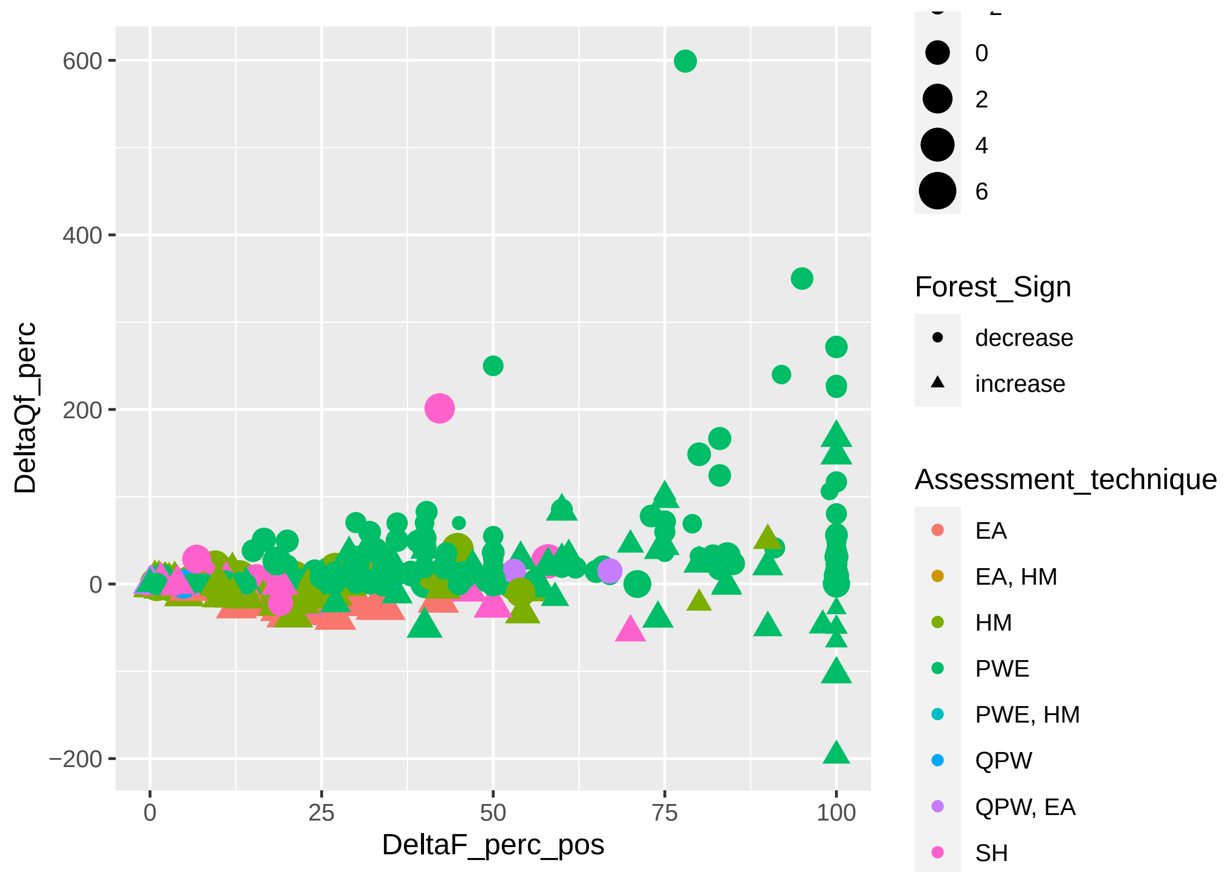
322




```
Zhang_all2 %>%
  filter(Area_km2 > 3e+06)
```

No evidence of effect of area

```
Zhang_all %>%
  ggplot(aes(Assessment_technique,log10(Area_km2))) + geom_boxplot()
```




```
## pdf
##   2
```

```
Zhang_all2 %>%
  ggplot(aes(Longitude, Latitude, colour = DeltaF_perc, size = DeltaQf_perc/100 )) + geom_po
```

```
Zhang_all %>%
  ggplot(aes(Area_km2)) + geom_histogram(fill="blue", bins =50) +
  scale_x_log10()
total <- nrow(Zhang_all)
length(Zhang_all$Area_km2[Zhang_all$Area_km2<10])/total
```

```
Zhang_all2 %>%
  ggplot(aes(length)) + geom_histogram(fill="blue", bins =50)
```

Essentially, the analysis shows at the moment that their is no evidence that the size of the catchment influences the

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