

1 Generalizing the impact of forest cover on streamflow
2 from experimental data: it is not that simple.

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4 **Abstract**

Three recent papers review and analyze large global datasets related to im-
pacts of forest cover on streamflow. Using three different approaches, they all
find a strong relationship between forestation, de-forestation and streamflow.
However, the results are problematic, the underlying data set is unbalanced,
and there are correlations in the data that warrant further investigation as this
would influence the results. For example, the area of the catchment is strongly
related to the assessment technique and the variability in the response data.
For this study, the data for the recent three papers were reviewed, combined,
and supplemented with new studies. Subsequently, the data were re-analyzed
using generalized additive modelling. The results highlight that there are four
interlinked reasons that make the general outcomes from the previous papers
problematic: 1) The existence of latent variables in the data that create the
appearance of a relationship that really does not exist; 2) The difficulty in fully
interpreting the specifics of different studies; 3) The difficulty of integrating data
from seemingly similar studies, but with quite different objectives; and 4) The
chance of transcription errors influencing the data. Overall this indicates that
while valuable data can be extracted from past studies, the above problems need

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to be considered before results are generalized and extrapolated to continental and global scales.

5 *Keywords:* meta analysis, forest cover change, global scales, statistical
6 modelling

7 1. Introduction

8 There is a urgent need to identify the impacts of human intervention on
9 stream flow at a global scale and to separate this from climate effects [38, 18].
10 More specifically, the impacts of global deforestation and reforestation are im-
11 portant through their perceived influence on stream flow and blue and green
12 water availability [18, 30]. The past work reviewing these impacts [2, 21, 44,
13 9, 10, 16] highlights a general consensus that if forest areas increase, stream
14 flow decreases and vice-versa. The most dramatic example of this is Figure 5
15 in Zhang et al. [42] indicating (for Australian catchments) a 100% decrease in
16 stream flow for catchments with 100% forest cover. However, on the other end
17 of the spectrum, for three French catchments [13], there was no change in stream
18 flow characteristics in two of the catchments after deforestation. For reforesta-
19 tion, a modelling study across the 1 million km² Murray Darling Basin also
20 found no major effect, especially in larger catchments [35], but a recent study
21 [18] found an 8% change in stream flow as a result of reforestation. Similarly
22 a modelling study by Beck et al. [3] found no significant change in stream flow
23 in 12 catchments in Puerto Rico as a result of deforestation. In contrast, in a
24 recent study in Brazil across 324 catchments, Levy et al. [24] found a significant
25 increase in stream flow, particular in the dry season, as a result of deforestation.
26 This suggests that there can be significant variation across the different studies,
27 methodologies and geographical regions.

28 For the purpose of this paper, *watershed* and *catchment* are interchangeable
29 terms. Many of the US studies use *watershed*, while European and Australian

30 studies use *catchment*. In particular, we retained the term “paired watershed
31 studies” and “quasi-paired watershed studies” as this is the most common ter-
32 minology, but further mostly use the term catchment.

33 There has been a recent push in the hydrological community [14] to use
34 ‘meta-analysis’ to summarize past studies. The suggestion is that, because meta-
35 analyses use clearly defined search terms and statistical methods to analyze
36 the results, this will lead to more reliable summaries of past research. As a
37 result, several review papers have summarized the plethora of forestation and
38 deforestation studies across the globe, in relation to paired watershed studies [9,
39 8], related to reforestation in particular [16], and more generally [21, 44]. These
40 studies aim to generalize the individual experimental and research findings and
41 to identify if there are global trends or relationships. Others have used the
42 understanding from a global analysis to extrapolate to global scales [18].

43 The recent paper by Filoso et al. [16] is a clear meta-analysis, but most others
44 [44, 18, 47] are not. However, an impressive global database of catchment studies
45 with changes in stream flow due to changes in forest cover has been developed
46 [44, 16] and statistical approaches are used to analyze the resulting data. The
47 Zhang et al. [44] data set, which covers over 312 studies, is described in terms of
48 the change in stream flow as a result of the change in forest cover, where studies
49 related to both forestation (increase in forest cover) and deforestation (decrease
50 in forest cover) were included. In contrast, the paper by Filoso et al. [16] focused
51 primarily on reforestation, and covered an equally impressive database of 167
52 studies using a systematic review. In this case the collected data is mostly
53 coded as count data and only a subset of 37 studies was analyzed for actual
54 water yield change. There is some overlap between the two data sets, but there
55 are also some studies unique to both sets. The more regionally concentrated
56 and detailed study by Levy et al. [24] is a further independent data set with

no overlap with the other studies. However, for this study only the flow and rainfall data is available for the catchments, and the change in land cover was derived from satellite data and was not made available.

The conclusions of the first mentioned major review paper [44] indicates that there is a distinct difference in the change in flow as a result of forestation or deforestation between small watersheds (catchments), defined as $< 1000 \text{ km}^2$ and large watersheds (catchments) $> 1000 \text{ km}^2$. While for small catchments there was no real change in runoff with changes in cover, for large catchments there was a clear trend showing a decrease in runoff with increases in forest cover. The 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 catchments relative to energy limited catchments [44].

The second study [16] is a systematic review of reforestation studies (only studies in which forest cover increased). This study 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 stream flow, but that there were many interacting factors. For a subset of the data (37 data points) they also indicated decreasing impacts of reforestation with increasing catchment size (agreeing with Zhang et al. [44]), but they did not identify a distinct threshold and fitted a log-linear relationship. In addition, they identified that studies with shorter periods of data collection resulted in larger declines in stream flow.

An earlier paper, that includes much of the same data as Zhang et al. [44] and Filoso et al. [16], is Zhou et al. [47], which has one author in common with Zhang et al. [44]. However, this paper aims to explain the variation in the data using the elasticity approach in the Fuh model, which is similar to well-known Budyko approaches [43]. In particular, it aims to link the variation

84 in the observed data to variations in the exponent m in the Fuh model, which
85 represents vegetation cover. A key observation is that in drier environments, the
86 effects of removing forest cover are much greater than in wetter environments,
87 which is also suggested by Figure 4 in Zhang et al. [44]. The Fuh model and the
88 related variations of the Budyko equilibrium modelling approach was also used
89 by Hoek van Dijke et al. [18] to interpret the global impact of reforestation.

90 However, concerning is that there are some clear limitations in these studies,
91 and some of this applies to meta-analyses in general. The main method in the
92 work by Zhang et al. [44] is a single covariate linear regression. In contrast, the
93 systematic review from Filoso et al. [16] mainly emphasizes the classification and
94 distributions of the study. Zhang et al. [44] points out that a main assumption
95 in their work is that the catchment size threshold at 1000 km^2 is a distinct
96 separation between “small” and “large” catchments. However, a subset of 37
97 data points in Filoso et al. [16] (their Figure 9) does not appear to support this,
98 suggesting a continuum. And while the work Filoso et al. [16] provides important
99 insights in study types, analysis types, forest types and broad classification,
100 there is limited quantification of actual impact.

101 In contrast to the single covariate linear regression in the earlier studies [44,
102 16] and the top-down Budyko modelling [47, 18], the regional Brazilian Cerrado
103 study [24] provides an example of an carefully designed statistical approach
104 using mixed effects modelling and Differences-in-Differences modelling focusing
105 specifically on the effect of deforestation. The analysis specifically accounted
106 for differences between catchments and differences due to variations in climate.
107 Not all data sets are however suitable for this kind of in-depth analysis.

108 Given all these previous reviews and the seemingly clear conclusions about
109 the impact of forest cover change on stream flow, the question is why another re-
110 view paper on this topic? There is a real attraction in the concept of statistical

analysis of past studies encapsulated in meta-analysis to be able to extrapolate findings to larger scales, and to identify factors across global scales [14]. However, there are also some hidden complications in this that can invalidate results, which this paper aims to highlight. There are four potential errors (or limitations) in such global meta-analyses:

- Impact of latent variables that are not included in the typical single covariate analysis;
- Interpretation errors due to incomplete descriptions of the experiments in the original papers;
- Aggregation of data that originates from different experiments with different objectives across a wide time period, but have similar keywords; and, finally
- Transcription errors in the data, especially if data is collected from other review papers as some of the original papers are difficult to locate.

The aim of this paper is to first reanalyze the global data set [44, 16] using some more detailed statistical modelling and to use this to highlight examples of each of these limitations. This will show how they have influenced the outcomes of the past work, and provide suggestions of how we can overcome these limitations. In addition, by applying more complex statistical models, we will highlight the conclusions that can be drawn from the data. Finally, we will highlight future research needs in the area of forest cover change impact on stream flow.

We are taking advantage of the earlier work by Zhang et al. [44], Filoso et al. [16] and Zhou et al. [47] and the large database of studies these authors have shared.

136 2. Methods

137 2.1. The original data set

138 As indicated, the starting point of this paper is the data base of studies which
 139 were included in Zhang et al. [44] as supplementary material. The columns
 140 in this data set are the catchment number, the catchment name, the Area in
 141 km², the annual average precipitation (Pa) in mm, the forest type, hydrological
 142 regime, and climate type, the change in forest cover in % ($\Delta F\%$) and the change
 143 in stream flow in % ($\Delta Qf\%$), the precipitation data type, the assessment tech-
 144 nique, and the source of the info, which is a citation. The change in stream flow
 145 ($\Delta Qf\%$) is based on equation 1 in Zhang et al. [44].

146 Several of these columns contain abbreviations to describe the different vari-
 147 ables, which are summarized in Table 1. These abbreviations will later be used
 148 in the models.

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
precipitation data type	OB	observed

Factor	Abbreviation	Definition
assessment technique	SG	spatial gridded
	MD	modelled
	PWE	paired watershed experiment
	QPW	quasi-paired watershed experiment
	HM	hydrological modelling
	EA	elasticity analysis
	SH	statistical modelling and hydrographs

149 The paper by Zhang et al. [44] also uses the dryness index, which is the
 150 annual rainfall (Pa) divided by the potential or reference evapotranspiration
 151 (ET_0 or E_0) in their analysis, and have used the dryness index to identify the
 152 climate type. However, the potential or reference ET used for this calculation
 153 was originally not included in the published data set. We will discuss below how
 154 we derived the dryness index in our data set. We combined the tables for small
 155 catchments ($< 1000 \text{ km}^2$) and large catchments ($\geq 1000 \text{ km}^2$) from Zhang
 156 et al. [44] in our analysis.

157 *2.2. Additional data collection*

158 To enhance the existing data set, this study added additional variables and
 159 cross-checked the studies with the data set from Filoso et al. [16]. In particular,
 160 we focused on the 37 data points related to the quantitative regression analysis
 161 used in Filoso et al. [16].

162 In addition, a few additional variables were included to enhance the data
 163 set. We added latitude and longitude for the center of the catchment as an

164 approximation of its spatial location. Mostly the data reported by the authors
 165 was used, but in some cases the variables had to be approximated from the
 166 location of the centre of the catchment using Google MapsTM. In the data set,
 167 an additional column has been added to indicate the source of the location data
 168 to indicate if this is directly from the paper or elsewhere.

169 As highlighted, Zhang et al. [44] did not provide values for evapotranspira-
 170 tion in the data base. Using the location information, reference evapotranspi-
 171 ration (E_0) was extracted from the Global Aridity Index and Potential Evapo-
 172 Transpiration (ET_0) Climate Databasev2 [34], if a value of E_0 was not available
 173 from the original papers. For large catchments, this value (and the associated
 174 coordinates), similar to annual average rainfall, is only an approximation of the
 175 climate at the location.

176 Similar to Zhang et al. [44], the Dryness index was calculated from the
 177 catchment estimate of reference evapotranspiration and the catchment estimate
 178 of annual average rainfall (Pa) as:

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

179 The length of the study can be a variable influencing the change in flow [e.g.
 180 21, 16], as for example, more mature plantations are thought to have smaller
 181 impacts on flow or regrowth might follow a “Kuczera curve” [23]. It is not clear
 182 if this is an effect of increased water use in growth [36] or due to changes in
 183 interception [31]. Therefore, the length of the study calculate as the difference
 184 between the starting data and completion date of the different studies was ex-
 185 tracted from the references provided by Zhang et al. [44]. The length of the
 186 study was already included in the data from Filoso et al. [16], but these were
 187 checked against the original publications.

188 Several additional data points from catchment studies were extracted from

Almeida et al. [1], Ferreto et al. [15], Iroumé and Palacios [19], Iroumé et al. [20], Zhang et al. [42], Zhao et al. [45], Borg et al. [7], Thornton et al. [32], Zhou et al. [46], Rodriguez et al. [28], Ruprecht et al. [29] and Peña-Arancibia et al. [26], and these were checked against the existing studies to prevent overlap. In the citation column in the accompanying data set, the main reference for the calculated change in stream flow was generally used, because sometimes the original study did not provide the quantification of the change in stream flow [i.e. Table 6 in 42].

We conducted a thorough review of all the studies mentioned in the data base of Zhang et al. [44] and sourced all the original papers. As a result of this we made several changes to the data base, which are all recorded in Supplementary Data part 1. Overall 36 data points were changed and the most common problem was a change in the sign for the change in forest cover or the change in flow. We assume that these were transcription errors.

We also removed one data point from the data set, which corresponds to catchment #1 (Amazon) in Zhang et al. [44]. This is because the cited reference [27] 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. Finally, on review of all the data in Zhang et al. [44] and Filoso et al. [16], 29 potential duplicates were identified and flagged in the data, and not used in the analysis.

The final column in the improved data base is a “notes” column, which we added, but is not further used in the analysis. It 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. [44]. This will allow future research to scrutinize our input for errors.

214 2.3. Statistical modelling

215 The aim of the statistical analysis is to highlight the most important variables
 216 in the data set that explain the change in flow as a result of changes in forest
 217 cover. This first aim is similar to Zhang et al. [44], but the main difference is
 218 that we start off with all variables in the data set in the model. Subsequently
 219 the analysis will concentrate on how the individual variables in the data set
 220 relate to each other and how latent variables in the data set can be masked
 221 and result in relationships that might not really exist. Finally, the analysis will
 222 highlight how the results are conditional on the data set.

223 In the statistical analysis we are not necessarily seeking the best “predictive”
 224 model, and as such do not perform a traditional variable selection process.
 225 Rather, we focus on analyzing the predictor variables in the full model to identify
 226 how all the variables explain the variance in the dependent variable.

227 To estimate how the change in stream flow is affected by the change in forest
 228 cover, while considering the effects of the other variables, we applied generalized
 229 additive modelling (GAM) [41].

230 The general model tested is:

$$\Delta Qf\% \sim \Delta\%forest\ cover + \sum X_i + \sum s(Z_i) + \varepsilon \quad (2)$$

231 Here X_i are factorial variables, while Z_i are continuous variables. As a first
 232 step, the model assumes no direct interactions and that all variables are additive.
 233 A further assumption in the model is that all continuous variables Z_i (such as
 234 annual precipitation (Pa)) can have either a linear or a non-linear relationship
 235 with $\Delta Qf\%$. This means that a smooth function $s()$ can be applied to the Z_i
 236 variables. For the smoothing function we applied thin plate regression splines

237 with an additional shrinkage penalty. The result of this approach is that for
 238 high enough smoothing parameters (i.e. if the data is very “wiggly”) the smooth
 239 term can be shrunk to 0 and thus will be no longer significant [41]. This is done
 240 because a highly flexible smooth term could always fit the data, but would
 241 not necessarily indicate a relevant relationship. In other words, the approach
 242 balances finding a smooth non-linear relationship for the variable against over
 243 fitting the data.

244 The changes in forest cover contain both positive (forestation) and negative
 245 values (deforestation). In Zhang et al. [44], these changes were jointly analyzed,
 246 assuming the effect on the change in flow was linear and the effect of removing
 247 forest cover was the same as an equivalent addition of forest cover.

248 However, the impact of an increase in forest cover can be different from the
 249 same fractional decrease in forest cover. The question becomes how best to
 250 analyze this. One approach would be to allow a different slope and a different
 251 intercept for the decreases relative to the increases. This can be tested by con-
 252 verting all the change in forest cover data to positive values, and an additional
 253 binary column ($sign_{forestcover}$) can be included indicating whether it was a for-
 254 est cover increase or decrease. In the model, the parameter for $sign_{forestcover}$
 255 will indicate the difference in the changes in flow for increases in forest cover
 256 compared to decreases in forest cover. The disadvantage of this approach is that
 257 the relationship with forest cover becomes discontinuous at the origin (0 change
 258 in forest cover).

259 A second approach is to test the change in forest cover as a non-linear re-
 260 lationship in the GAM model. Because a shrinkage penalty is used, this will
 261 also test the non-linear assumption and allows the variable for forest cover to be
 262 continuous. The disadvantage of this approach is that the relationship between
 263 forest cover and change in flow is less easy to interpret, as the non-linear fit in

264 the GAM has no direct parametric form. All three approaches are tested in this
265 study.

266 The overarching test focuses on identifying the change stream flow as a result
267 of a change in forest cover and how this is potentially affected by different other
268 factors (as indicated by the previous research: Zhang et al. [44]; Filoso et al. [16];
269 Zhou et al. [47]): climate, size of catchment and length of study. In addition
270 to these earlier identified factors, this study also tested for the factors listed in
271 Table 1

272 As an initial approach we tested whether the additional catchments added
273 to the original data from Zhang et al. [44] did not majorly influenced the results
274 (This analysis is in supplementary material part 2). This analysis highlights
275 that the newly added catchment and the changes to the data set create minor
276 differences when repeating the analysis from the original paper. However, this
277 means that the results of the studies are still comparable.

278 To make all the data and code used for the analysis publicly available, all
279 the final data and analysis for this paper are located on github:
280 https://github.com/WillemVervoort/Forest_and_water on the “publish” branch.

281 **3. Results**

282 *3.1. Description of the data*

283 The overall data set contains 334 observations of changes in flow, which
284 includes the newly identified data sets and after removing identified duplicate
285 data and lines with missing data. In contrast, the original data set from Zhang
286 et al. [44] contained 312 catchments and the Filoso et al. [16] study used 37
287 catchments (Table S2 in Filoso et al. [16]). The overall distribution of changes
288 in flow is highly skewed as is the distribution of changes in forest cover and
289 *Area km²*. The values of changes in flow greater than 100% and smaller than

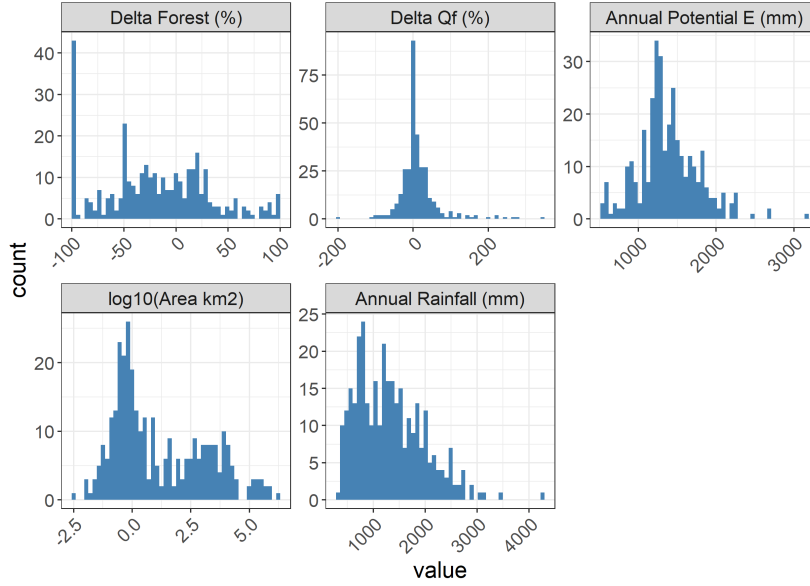


Figure 1: Overview of the distribution of the data set for five of the included variables. Note that the first panel (showing the distribution of the catchment areas) indicates the distribution of the \log_{10} transformed Area (in km^2).

290 -100% clearly create long tails in the change in flow distribution. Note also
 291 the large number of studies with 100% forest cover reduction. Clearly visible is
 292 also that smaller catchments dominate the database with 42% of the data from
 293 catchments $< 1 \text{ km}^2$ and 65% of the data for catchments $< 10 \text{ km}^2$ (Figure
 294 1). This high skew in some of the data can create difficulties in the statistical
 295 modelling and this will be discussed later.

296 3.1.1. Geospatial location of the catchments

297 Apart from looking at the distribution of the values, the spatial locations
 298 of the data can also be important, in particular when analyzing the effect of
 299 climate. The catchments are spread across the world, and relative to Zhang
 300 et al. [44], this data set has a very similar geospatial distribution. The major
 301 climate gradients are represented in the data, but there appears to be some bias
 302 in the spatial locations of the data. As the global map (Figure 2) shows, the

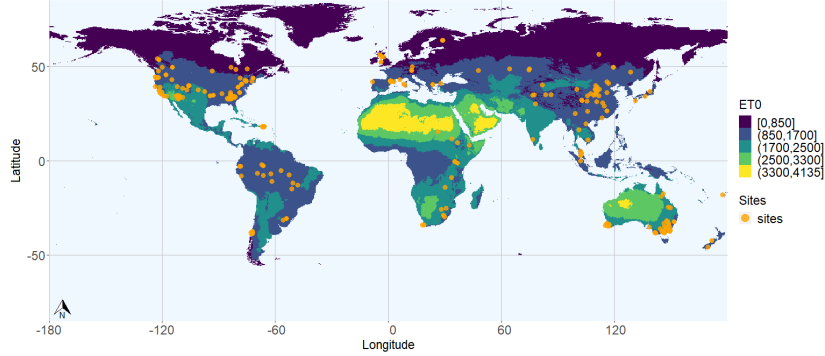


Figure 2: Distribution of included catchments across the globe based on reported or estimated latitude and longitude

distribution of case study catchments covers multiple continents. There is some spatial clustering in the studies in North America, Australia and East Asia.

3.1.2. Cross correlation between the different variables

A final data exploration is to identify potential cross correlations in the data, which can point to possible interactions or potential biases. This analysis can also provide further insight for the statistical modelling, highlighting potential latent variables in the data set.

The correlation plot (Figure 3) highlights several correlations that are worth investigating, even though in general cross correlations between variables are quite low. Some interesting relationships that appear in this graph are:

- the negative relationship between $\log_{10}(\text{Area})$ and change in forest area (ΔF_{perc}), indicating that in the data set larger catchments tended to have (obviously) smaller areas of forest change.
- the weak positive relationship between $\log_{10}(\text{Area})$ and the assessment method using hydrological models. This highlights that paired catchment

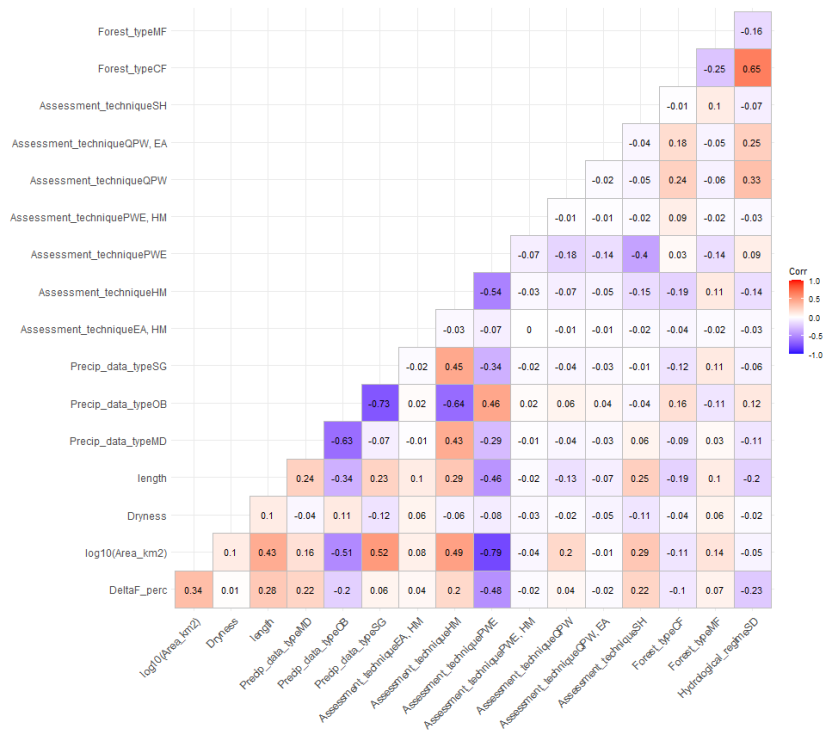


Figure 3: Correlation matrix for all variables

318 studies mostly concentrate on smaller scales.

319 • A strong inverse relationship between $\log_{10}(\text{Area})$ and the paired water-
320 shed assessment method (simply the inverse from the last point), which
321 is also indicated by the negative relationship between the two assessment
322 methods. This is further visible in the relationship between the change
323 in forest cover and the paired watershed assessment method, showing the
324 impact of the latent variable ($\log_{10}(\text{Area})$). Smaller catchments used in
325 paired watershed assessments are easier to fully clear or fully replant.

326 3.2. Statistical analysis

327 The results of the overall statistical model that includes all the variables (but
328 no interactions) reinforces some of the results from the correlation analysis.

329 This includes introducing non-linearity (Equation (2)) for the numerical vari-
330 ables in the model. While increasing non-linearity in the model can increase the
331 flexibility if the model, the shrinkage splines assist with limiting over fitting.
332 Following Wood [41], the number of degrees of freedom k in the non-linear vari-
333 ables was based on assessment of the effective degrees of freedom in the model
334 output. If the effective degrees of freedom were close to $k - 1$ then k was in-
335 creased and the model rerun. By using shrinkage splines, this also results in the
336 whole term being shrunk to zero if needed [41].

Table 2: Statistical summary for the linear terms the full model

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-5.37	16.19	-0.33	0.74
DeltaF_perc	-0.61	0.06	-11.03	0
Precip_data_typeOB	-21.34	13.16	-1.62	0.11
Precip_data_typeSG	9.57	15.16	0.63	0.53

	Estimate	Std. Error	t value	Pr(> t)
Assessment_techniqueEA,	20.32	42.72	0.48	0.63
HM				
Assessment_techniqueHM	23.51	11.69	2.01	0.05
Assessment_techniquePWE	30.71	11.92	2.58	0.01
Assessment_techniquePWE,	15.79	43.24	0.37	0.72
HM				
Assessment_techniqueQPW	41.29	20.14	2.05	0.04
Assessment_techniqueQPW,	25.16	24.41	1.03	0.3
EA				
Assessment_techniqueSH	46.03	11.65	3.95	0
Forest_typeCF	-7.76	7.52	-1.03	0.3
Forest_typeMF	-7.8	7.35	-1.06	0.29
Hydrological_regimeSD	1.5	9.1	0.17	0.87

Table 3: Statistical summary for the smooth terms for the full model

	edf	Ref.df	F	p-value
s(log10(Area_km2))	0.81	4	1.09	0.02
s(Dryness)	4.59	9	2.25	0
s(Length)	4.39	34	0.21	0.13

337 The overall explaining power of the model can be interpreted from the ad-
338 justed r^2 (which is penalized for the number of parameters). This indicates an
339 adjusted r^2 of 0.45 and deviance explained is 0.49, suggesting the model only
340 explains about 50% of the variance in the data.

341 Inspecting the significance of the variables (Table 2 and Table 3) indicates
342 some interesting features. The overall partial slope of the change in forest cover
343 is -0.61, if all other variables are kept constant. This suggest quite strong change
344 in stream flow, moving from fully forested to fully cleared. Over the whole forest
345 cover range, this is a change of -122 mm, with other variables held constant.
346 This change is highly significant, as indicated by the low p-value.

347 In addition, all the smoothed variables $\log_{10}(\text{Area } (km^2))$ ($p = 0.02$)), *Dry-*
348 *ness* ($p = 0$) and *Length* ($p = 0.13$)) explain variation in the data. For *Length*,
349 the p-value is not strictly smaller than 0.05, but still indicates some reasonable
350 evidence that the variable explains some of the variation in the change in stream
351 flow.

352 Furthermore Table 2 indicates that several of the assessment methods ex-
353 plain variation in the change in stream flow, which was also indicated in the
354 correlation analysis. In particular, the assessment methods Paired Watersheds
355 Experiments (PWE), Hydrological Modelling (HM) and Statistical modelling
356 and hydrographs (SH) are important explaining variables ($p < 0.05$).

357 The remaining variables related to rainfall observation technique, forest type,
358 or hydrological regime don't appear to have an influence on the change in flow.

Table 4: Comparison of alternative models for the relationship
between the change in forest cover and the change in streamflow.
(See Supplementary Material part 3)

Model for change in forest cover	Deviation explained	AIC
linear across range	0.49	3233
different for forestation and deforestation	0.45	3281

Model for change in forest cover	Deviation explained	AIC
non-linear across the range	0.51	3233

As discussed in the methods, the overall linear response to the change in forest cover was compared to a transformation of the negative forest cover to positives and a check whether the relationship might be non-linear. This approach tests whether the impact on stream flow from removing forest cover is different from reforestation, as outlined in the methods. The detail of the comparison is highlighted in Supplementary material part 3. However, generally the results of the analysis showed two main points (Table 4):

1. The model assuming a simple linear relationship between change in forest cover (both positive and negative) and the change in flow explained the most variation in the data and indicated the best performance in terms of the Aikake Information Criterium (AIC); and
2. There is no need to assume a non-linear relationship, as a linear relationship provides a similar performance for the fit to the data.

The smoothed variables in the model can be inspected visually to identify if there are any issues with the fit. This is in addition to the earlier mentioned checks using `gam.check()` in the R package `mgcv` to test whether the number of degrees of freedom k is adequate.

Figure 4 highlights that the relationship between $\log_{10}(\text{Area } km^2)$ and the change in flow is essentially linear. It indicates the negative slope that was also clear from Zhang et al. [44], indicating that in larger catchments changes in forest cover have less impact on stream flow than for smaller catchments.

Both the *Length* and *Dryness* variables show strong non-linearity, but the relationships do not show a clear trend due to the scatter and the distribution

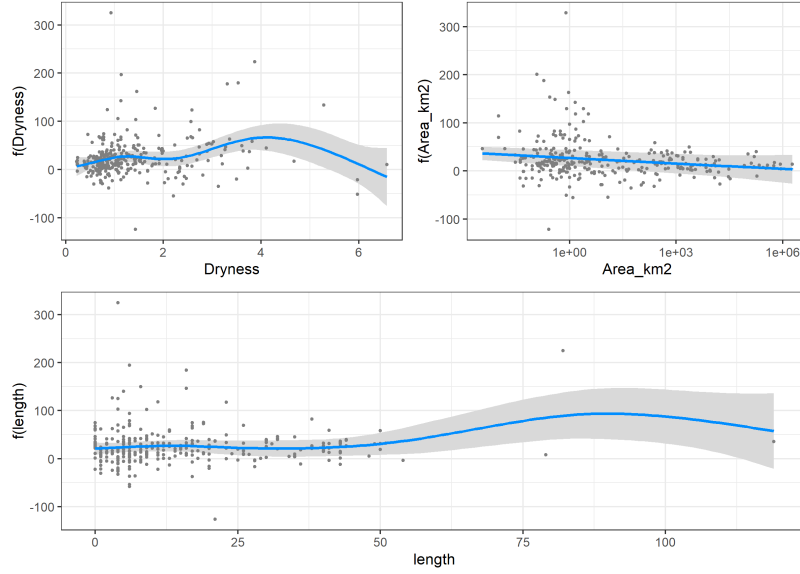


Figure 4: Visualisation of the smooth variables in the model, the shaded areas are the 95% confidence intervals associated with the fit of the smooth, the blue line is the mean smoothed relationship, with data plotted as individual points

of the data. A further problem appears to be that *Length* and *Dryness* have several points with very high leverage that determine much of the non-linearity in the relationship.

As this is not always shown in papers discussing regression relationship, the residual distribution is provided in more detail (Figure 5). Visually, the residuals appear approximately normal, although there is a noticable skew in a limited number of the data in the upper part of the distribution (Figure 5, top left). This is related to a limited number catchments that have very high changes in stream flow in the data set. In other words, the distribution of the residuals is somewhat fat-tailed.

One solution could be to transform the data, however this is not that simple. As the data for the change in flow cover the domain \mathbb{R} , a simple log or Gamma transformation is not a solution. More complex transformations make the re-

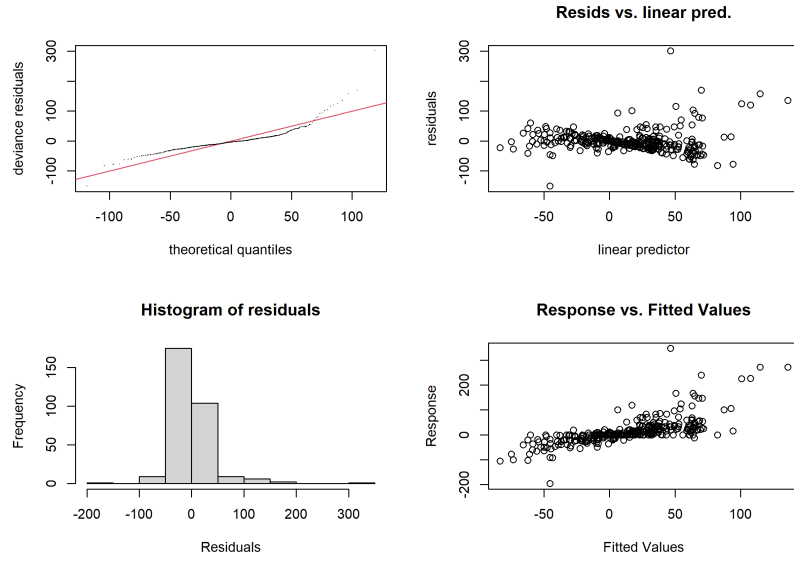


Figure 5: Residual plots for the regression model indicating a slightly fat-tailed residual distribution

sults of the regression difficult to interpret, and at some point can be slightly contrived.

Given the majority of the residuals indicate a relatively well behaved distribution, we simply note the behaviour at the extremes and will discuss this later in the paper, and explain how this relates to the characteristics of the data set.

3.2.1. Removal of studies of great length and for very dry catchments

Table 5: Catchments for which the dryness index > 5

Number	Latitude	Longitude	Catchment name
76	34.67	-111.7	Beaver Creek, AZ #3-2
225	32.74	-111.5	Natural Drainages, Ariz., U.S.A, A

Number	Latitude	Longitude	Catchment name
226	32.74	-111.5	Natural Drainages, Ariz., U.S.A, C
356	-25.75	28.23	Queens river

401 The flexible nature of the splines means that the Length variable highlights
402 substantial non-linearity in the data, but it is unclear what exactly is captured.
403 The shape of the conditional response (Figure 4) does not reflect a similar
404 response as indicated by Filoso et al. [16] and Jackson et al. [21]. One reason
405 could be that the relationship is dominated by the few data points with very
406 long data series, which show highly variable responses (Figure 4).

407 The points related to catchments with very long studies (> 60 years) might
408 be questionable, as changes other than forest cover change could affect stream
409 flow. In addition, a few of the catchments have Dryness values that are very
410 large (> 5) and these values have high leverage in the data, affecting the residual
411 distribution. These catchments are listed in Table 5, and are three catchments
412 in Arizona and 1 catchment in South Africa. It is possible that catchments in
413 these climate zones behave different from the rest of the catchments.

Table 6: Statistical summary for the linear terms the restricted model

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-10.69	17.85	-0.6	0.55
DeltaF_perc	-0.61	0.08	-7.69	0
Forest_SignIncrease	1.12	9.72	0.12	0.91
Precip_data_typeOB	-16.23	12.46	-1.3	0.19

	Estimate	Std. Error	t value	Pr(> t)
Precip_data_typeSG	15.96	14.86	1.07	0.28
Assessment_techniqueEA,	19.97	41.02	0.49	0.63
HM				
Assessment_techniqueHM	27.07	11.39	2.38	0.02
Assessment_techniquePWE	28.54	12.11	2.36	0.02
Assessment_techniquePWE,	15.91	42.05	0.38	0.71
HM				
Assessment_techniqueQPW	43.3	19.52	2.22	0.03
Assessment_techniqueQPW,	25.33	23.33	1.09	0.28
EA				
Assessment_techniqueSH	47.84	11.3	4.23	0
Forest_typeCF	-7.89	7.22	-1.09	0.27
Forest_typeMF	-6.26	7.17	-0.87	0.38
Hydrological_regimeSD	0.54	8.83	0.06	0.95

Table 7: Statistical summary of the smooth terms reducing dataset to studies with the study length shorter than 60 years and Dryness ≤ 5 .

	edf	Ref.df	F	p-value
s(Dryness)	3.82	9	2.15	0
s(log10(Area_km2))	0.89	4	1.66	0.01
s(Length)	0	9	0	0.97

Therefore it is worth investigating what effect removing these few data points has on the overall model and the significance of the variables. Data that have

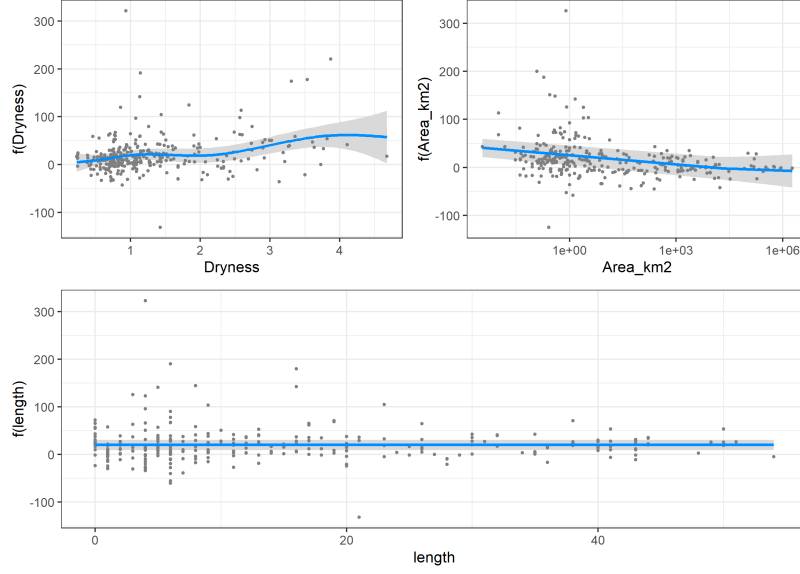


Figure 6: Visualisation of the smooth variables in the model with reduced data for dryness and length

416 *Dryness* ≤ 5 and *Length* ≤ 60 years were removed from the data set and the
 417 model based on a reduction of the data set from 334 to 315 catchments is run
 418 again.

419 This model, which excludes data with long studies and very dry catchments
 420 explains only slightly less of the variation with an adjusted r^2 of 0.45 and a
 421 deviance explained of 0.48.

422 Investigating the non-linear responses suggest that *Dryness* has a clear non-
 423 linear response, which is significant, where changes in forest cover in drier catch-
 424 ments having a greater impact on stream flow (Figure 6 and Table 7). Catch-
 425 ment area ($\log_{10}(\text{Area } (km^2))$) still has an impact on flow with $p = 0.01$, and
 426 the relationship looks almost linear. More importantly, the variable *Length* is
 427 no longer significant, after removal of the two studies with very long lengths.

Table 8: Distribution of assessment techniques in the data set

Assessment_technique	n
PWE	187
HM	57
SH	45
EA	32
QPW	7
QPW, EA	4
EA, HM	1
PWE, HM	1

One concern with the results presented so far is that there are a few assessment techniques in the data set with a very low number of observations and could influence 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 8).

Therefore, the model was rerun excluding the combined assessment techniques (EA, HM), (PWE, HM) and (QPW, EA) and the assessment technique QPW, which were all non-significant (Table 8). This resulted in a data set of 328 catchment studies.

The model based on assessment techniques that have more than 10 observations in the data set does not change much in the results (results not shown). It strengthens the significance of the different assessment techniques, but generally results in the same interpretation. Overall this suggests that although those observations have some impact on the overall relationships, they do not

443 strongly bias the outcomes.

444 The overall model results clearly highlight that some of the assessment tech-
445 niques (in particular paired watershed studies (PWE) and combined use of sta-
446 tistical methods and hydrographs (SH)), have a strong impact on the predicted
447 change in flow. Particularly, relative to EA (elasticity approaches) all other
448 assessment techniques have higher predicted changes in flow. In other words,
449 there is a distinct difference in the way the change in flow is assessed, and the
450 EA method (for example in Zhou et al. [47]) appears to suggest a much smaller
451 effect on the change in flow.

452 4. Discussion

453 The generalized additive models appear to reach the same conclusions as the
454 single variable regression in earlier papers [44, 16]. It appears that:

- 455 1. Larger catchments show lower impact of forest cover change on stream
456 flow;
- 457 2. Drier catchments show a greater impact of forest cover change on stream
458 flow; and
- 459 3. There is a general linear relationship between the change in forest cover
460 and the change in stream flow.

461 This might suggest that the simpler models have reached the correct conclu-
462 sion. However, this is somewhat premature. given that the other major point
463 coming out of the results is:

- 464 4. There is a clear relationship between size of catchments, area cleared and
465 type of experiments, with particular Paired Watershed Experiments con-
466 taining the smallest catchments, the largest percent forest cover change
467 and the largest variability in the flow response.

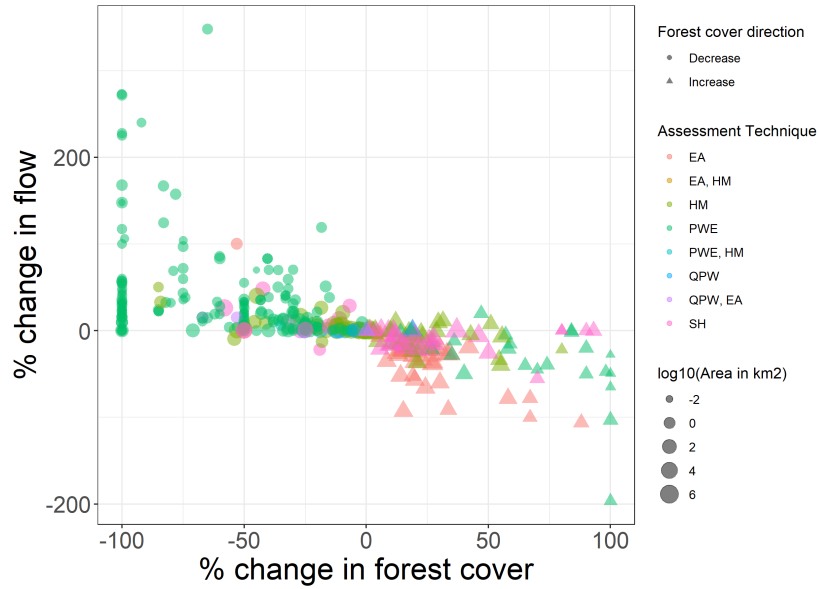


Figure 7: Overview of the data highlighting the dominance of small catchment studies which are fully forested or cleared and the scatter in the data

Figure 7 provides a clear overview of the whole data set, and in this figure the size of the catchments and the different assessment methods are highlighted. This figure clearly indicates that the data relating to high changes in forest cover are all small catchments and relate mostly to paired watershed experiments. In contrast, data related to large catchments are related to smaller changes in forest cover and different methods, such as hydrological modelling and elasticity analysis. This confirms the model results (Table 6) and the earlier correlation analysis (Figure 3).

It is possible that one of the reasons why Zhang et al. [44] separated their analysis in large ($> 1000 \text{ km}^2$) and small ($< 1000 \text{ km}^2$) catchments, is that they realized this difference in assessment methods and wanted to account for this. However, this is not explicitly identified, and there is no real physical explanation of the 1000 km^2 threshold.

The other interesting point in Figure 7 is that the variation in the data

482 increases as the catchment size decreases and the change in forest cover increases.
483 This also means that the overall variation in the data for paired watershed
484 experiments (PWE) is much greater than for any of the other methods.

485 *4.1. Is there a problem with extending local experimental data to larger scales?*

486 The overarching reason for combining past studies at a global scale is to infer
487 relationships that can be used to make more general statements or develop more
488 global scale modelling of impacts [i.e. 47, 21, 18]. Therefore, the results from the
489 analysis could be seen as a confirmation of the earlier research [44, 16, 47, 21].
490 However, the explaining power of the developed model is quite low and a lot of
491 variation in the data is unexplained. As is highlighted in the introduction there
492 are four major issues with this type of analysis, and the results from this paper
493 also highlight these issues. Here, these issues are further explained.

494 *4.1.1. Issue 1: Latent variables are not included in the typical single covariate* 495 *analysis*

496 The results show that it is simply impossible to analyze a single covariate
497 relationship, as there are several latent variables in the data. An example of
498 this is the general relationship of the change in flow as a function of the change
499 in forest cover. Clearly the relationship is highly impacted by the fact that all
500 the small catchments have large changes in forest cover and are all associated
501 with paired watershed experiments. Without taking these factors into account,
502 a definite answer about the impact of forest cover on the change in flow cannot
503 be given. Furthermore, the large variability in the change in flow data for these
504 small catchments (Figure 7) indicates that there is a further (unknown) variable
505 that explains the variation in the data.

506 If the remaining variation in the residuals is small relative to the trend, then
507 there is little need to identify further latent variables, but if the variation is

508 large, then it is unclear if it is the latent variable that determines the trend, or
509 the actual relationship in the data.

510 Similarly, the data for the larger catchments containing smaller changes in
511 forest cover are dominated by hydrological modelling studies, resulting in a fur-
512 ther complication. If the response of the stream flow in the modelling studies
513 is the result of the conceptualized relationship between stream flow and for-
514 est cover (possibly from a subset of the paired catchment studies), then it is
515 impossible to say if the change in stream flow is real, or simply a result of a
516 pre-conceived model relationship. Is the smaller variation in the data for smaller
517 changes in forest cover (Figure 7) a result of similar conceptualized model rela-
518 tionships, or actual variation between catchments and climate types? Currently
519 this question cannot be answered.

520 This becomes problematic when extrapolated to larger scales. A clear exam-
521 ple of this is the paper by Hoek van Dijke et al. [18] where the conceptualized
522 relationship between forest cover and stream flow pre-determines the outcomes
523 of the global modelling.

524 The only way to analyze changes in stream flow as a function of forest cover
525 in larger catchments is to actually derive this from observed data of long term
526 stream flow and forest cover (as was done in Levy et al. [24]).

527 One of these latent variables could be the total area of forest in a catchment,
528 as was analysed in Levy et al. [24]. In this case, the total % area of forest was
529 not included in the data. As a test, the total % area of forest for the larger
530 catchments ($> 1000 \text{ km}^2$ in Zhang et al. [44]) were added to the data set and the
531 model for just the large catchments was tested. This showed that the % area of
532 forest was not significant to explain the change in flow for the larger catchments
533 (retaining all other variables in the model, results not shown). While this might
534 be an area of further research on the full data set, it is complicated for two

535 reasons:

- 536 1. The area of forest is not always indicated in the original papers, or a range
537 of values is given, complicating the data collection.
- 538 2. Many of the small catchments have 100% area covered in forest, introduc-
539 ing a strong skew in the data and complicating if total area of forest has
540 an impact on the change in flow.

541 We are not arguing that there is no relationship between stream flow and
542 forest cover, and there might indeed be a global relationship that can be discov-
543 ered. But, this relationship can only be discovered if we are able to address some
544 of the major other factors that explain the variability, and work with actual data
545 and not model outputs.

546 *4.1.2. Issue 2: Interpretation errors due to complex descriptions of the experi-*
547 *ments in the original papers*

548 The second major issue that became clear from reviewing many of the origi-
549 nal papers is that some of the variability might be an interpretation problem.
550 In many cases the original description in the paper is interpreted to extract the
551 % change in stream flow from the % change in forest cover. This seems like a
552 simple activity, but this is not always the case.

553 Two examples can be highlighted:

- 554 • The papers from Almeida et al. [1] and Ferreto et al. [15] partly discuss
555 the same experiment and the same catchment. In Almeida et al. [1],
556 the methods discuss how two experimental catchments of approximately
557 80ha in size which were harvested. One catchment was 100% harvested
558 and the other 30% harvested. Throughout the paper the catchments are
559 indicated as 100% harvested and 30% harvested. However, only after
560 reading Ferreto et al. [15], did we discover that in fact the 100% and

30% refer to the “eucalyptus plantation area”, which was about 60% of the total area. This is in fact mentioned in Table 1 in Almeida et al. [1], but does not appear in the text. The question then becomes how to interpret this in the data base for this paper. Clearly it was a 100% and 30% change in forest cover, but only for the 60% plantation cover, not for any of the other areas in the catchment, which included native vegetation and riparian vegetation. There are several other examples like this in the different papers [for example 6, 5].

- Another example is the paper by Waterloo et al. [39]. This modelling study in Fiji of the clearing of a catchment reports the changes in stream flow over parts of the year. For a period of 324 days the stream flow increased from 252 mm to 580 mm (a 230% increase if calculated as $580/252 * 100$) and for a second period of 309 days the stream flow increased from 90 mm to 194 mm (a 215 % increase). However, how we convert this to a change in annual flow (which most of the other data relate to) is difficult. The original data base listed a 50 % change in flow, but it is difficult to identify how this is calculated. We suspect that results from $252/580 * 100 \approx 50$ and $90/194 \approx 50$.
- A final example is around the choice of control or treatment. In the data base the assumption is that the change in flow is relative to the original situation. This can be either a “before and after” analysis, which can be problematic by itself due to climate variation, or a comparison of a treatment with a control. But even in this case comparing across catchments can be tricky. For example, at one extreme, some controls in the database are a bamboo catchment and a tea plantation [6, 5]. A clearer example is the Brigalow catchment study in Queensland, Australia [33], catchment #336 in the data set. This is a paired watershed experiment

588 of conversion of native Brigalow (an Acacia species) into cropland and
589 pasture. We chose to use the cropped catchment (C2 Thornton et al.
590 [33]) as the deforestation treatment resulting in a change of flow of 140%,
591 based on Table 4 in Thornton et al. [33]. However, had we used the pasture
592 catchment as the treatment then the change in flow would have been up
593 to 165%.

594 Clearly, interpreting older papers can be difficult and this can result in vari-
595 ation in the data that is being analyzed. Similar to the last issue, if these errors
596 only introduce small variation in the data, then it will not limit the interpola-
597 tion to larger scales. At this point, it is not clear if this is indeed the case. The
598 large variation in the experimental watershed data suggests that this might be
599 a more serious problem.

600 *4.1.3. Issue 3: Aggregation of data that originates from different experiments*
601 *with different objectives across a wide time period*

602 For many of the small catchment studies listed in the database, the assump-
603 tion is that the original experimental design can be interpreted in terms of a
604 binary “forestation” or “deforestation”. However, the real situation is often
605 much more complex and fuzzy.

606 Many of the paired watershed experiments included a harvesting and re-
607 planting or regrowth after harvesting or fire experiment [e.g. 11, 12, 40]. As a
608 result, it becomes difficult to assess how we interpret the change in flow as a
609 result of a change in cover. In many cases we would expect the flow to change
610 over time as a function of the recovery [22] and therefore the time series of the
611 flow needs to be assessed over a longer time.

612 Many of the papers in the database report early results (for example 1 or
613 3 years after harvesting), but some also report longer time periods. As earlier
614 work [12, 22] has highlighted, we can always expect a larger effect directly

615 after harvesting, but this effect diminishes over time (even if it does not always
616 return to the original state). Comparing studies reporting results directly after
617 treatment to longer term studies therefore becomes problematic.

618 In our work, the variable *Length* was used in the model to test for some of
619 these effects, but this was insignificant in the model (Table 7). Given the other
620 variation in the data, this does not necessarily mean that there is no effect.

621 This is further complicated by the variation in different types of clearing
622 and the different types of vegetation. In the original Zhang et al. [44] a variable
623 to describe the *forest type* was included (Table 1), but in the model this is not
624 significant (Table 2). This is probably because the broad classification used
625 does not capture the actual variation in runoff response. In addition, as Figure
626 3 shows, there is a correlation between coniferous forests and snow dominated
627 hydrological regimes, further complicating the analysis.

628 An additional complication related to combining studies related to wild fires
629 or bush fires and logging studies is the differences in vegetation recovery. For ex-
630 ample, Heath et al. [17] found that catchments with resprouting species around
631 Sydney, Australia, indicated little change in the stream flow in comparison to
632 species regrowing from seed further south on the continent [48].

633 As a result, it can be difficult to exactly pinpoint the change in flow as
634 a result of the change in cover, as well as being difficult to assess what the
635 exact change in cover actually was. In addition, using only the overall change
636 in stream flow can discard a lot of information from observations in individual
637 years. Many papers give stream flow values for multiple years, often showing
638 significant variation. Summarizing this into one average value discards all the
639 information on the variance.

640 As indicated before, if the overall variation in the data due to this issues is
641 small, then this would not be an issue for upscaling the results, but the large

variation for the smaller catchments suggest that effects could be considerable. As Jones et al. [22] indicate, this really needs time series analysis of the different experiments. However, some of the time series data might not be recoverable from the older experiments, which will limit the opportunities for analysis. We will discuss this further below.

4.1.4. *Issue 4: Transcription errors in the data*

This issue seems to mainly occur if data is collected from other review papers. This might be because some of the original papers are difficult to locate and therefore values from reporting papers are used. In supplementary data part 1, several changes to the original data sets have been documented, and as can be seen several of these are transcription errors.

This does influence the results in Zhang et al. [44], comparing the results in Supplementary material 2 with the original paper. The main example is that in this study the largest catchment (watershed #1 in Zhang et al. [44]) had to be removed, as this study actually involved paired watershed experiments on very small plots, for which the characteristics were not recoverable.

Clearly, this is a problem for all reviews that attempt to bring together large numbers of results from published papers, and where actual results are copied rather than using some sort of automated text analysis.

In the end, careful review of the data and the original papers can circumvent most of this issue. And, making the data available (as Zhang et al. [44], Zhou et al. [47], Filoso et al. [16] and this paper have done) provides an opportunity for review by other researchers, and over time most of the transcription errors can be resolved.

4.2. *General discussion*

In this paper, a few studies have been singled out to demonstrate the main point that extrapolating individual studies to global scales is not that simple

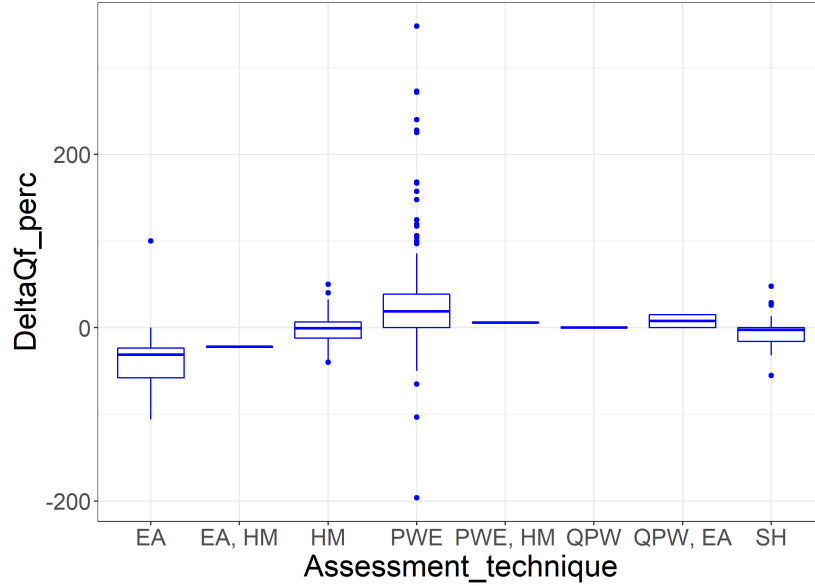


Figure 8: Boxplot of the variation in the change in flow for the different assessment techniques, showing the dominance of the variation and the outliers in the dataset in the paired watershed experiments

669 in natural systems. Not only is there significant natural variation and latent
670 variables, interpretation and aggregation can cause further unforeseen problems.
671 The choice of papers to focus on was mainly driven by the data that was made
672 available by the authors of these papers [44, 16], which provide a rich case study
673 for the current paper.

674 Field research is by nature limited in space and time, due to the high costs
675 involved of setting up experiments. This is particularly true for experiments in
676 hydrology and forest hydrology, where field sites need to cover sufficient spatial
677 and temporal variability. This means there is a general need to extrapolate the
678 local results to larger scales to inform decision making and policy.

679 However, as is demonstrated in this paper, there are multiple issues when
680 this local scale data is extrapolated to larger scales. It clearly demonstrates that
681 the results of any model (in this case a regression model) is highly dependent

682 on the data, but also on the assumptions in the model. From the perspective of
683 extrapolating local data to global scales for policy advice and decision making
684 [i.e. 18, 21], this is an important point.

685 4.2.1. *Residuals of the model*

686 The residuals of the final model presented in this paper (Figure 5) indicate
687 that the residual distribution remains fat-tailed, causing deviations from an
688 assumed $\epsilon \sim N(0, \sigma^2)$. This once again highlights that there is unexplained
689 variation at the extremes of the distribution, once again related to the paired
690 watershed experiments (Figure 8). Generally, in statistical models, the approach
691 would be to further normalize the residuals through transformations. However,
692 in this case this might be difficult and might not resolve all the issues due to
693 the large variation in the data.

694 4.2.2. *Interactions*

695 The current modelling approach does not consider any interactions between
696 the variables, and this would offer another approach to understand the variation
697 in the data. As already indicated in Figure 3, there are interactions between
698 different variables. This further complicates the extrapolation of the local scale
699 experiment data to global scales and to extend historical data to current man-
700 agement and decisions.

701 In this case, interactions were not included because, as was shown, there are
702 bigger problems with trying to extrapolate the existing data, and the data itself
703 can be problematic. To be able to model the interactions well, the nature of the
704 variables and interactions need to be understood and or clearly hypothesized.
705 Otherwise it becomes another case of correlation without causation.

706 *4.2.3. Implications for other “meta-analysis” studies*

707 There has been a recent push to develop more meta-analysis studies in hy-
708 drology [38, 14], and we strongly believe that developing new insights by com-
709 bining historical data sets from reviewed papers is highly valuable. However,
710 this paper highlights that there is considerable chance that large historical data
711 sets include latent variables and are more complex than envisioned. This is par-
712 ticularly true for work in natural systems and more historical work, as methods
713 of observation and even approaches to management have changed considerably.
714 The same management description is not necessarily the same action on the
715 ground. A carefully designed and systematic approach can prevent some of big-
716 ger problems as is demonstrated in Wang et al. [38], where both the approach
717 and the catchment area are investigated as latent variables. This is particularly
718 relevant, where the results of meta-analyses are extrapolated to make global
719 predictions without clearly quantified uncertainties (such as in Hoek van Dijke
720 et al. [18] and Wang et al. [38]).

721 A second potential danger is the extrapolation of the local small catchment
722 results and conclusions to larger scales, but beyond the original scope of the
723 studies. For example, the current database is mainly related to forest harvest,
724 bush fire and reforestation/plantation management. It is tempting to use the
725 result of a large scale analysis of this data to make inferences about overall land
726 use change [25, 38], but this would not be valid, as not all deforestation studies
727 are a transition to an agricultural land use or pasture, as in Levy et al. [24].
728 Many are logging or bushfire studies regrowing into forest after the initial treat-
729 ment. Similarly, using the plantation studies to extrapolate to “reforestation”
730 (as in Filoso et al. [16] and Hoek van Dijke et al. [18]) is also tenuous. Plan-
731 tation forests are generally fast growing hybrids that will have quite different
732 ecophysiology, particularly in South America [22, 4], while other reforestation,

733 for example for salinity control in Australia, might focus on a mix of native
734 species. Given the link between ecophysiology and water and carbon budgets
735 [21], care should be taken in extrapolation, introducing a further error.

736 As highlighted summarizing highly variable observed time series into sin-
737 gle mean values introduces further potential problems, as well as discarding
738 information about the variance.

739 A final factor is ignoring the effect of climate change [37] on runoff, even if
740 the effects are still minor. Earlier papers [25, 38] have analyzed climate effects
741 relative to management effects in the data, but these studies did not explicitly
742 test for climate change. Given that the database of studies now captures almost
743 100 years of work, we cannot ignore a climate change trend that is potentially
744 hidden in the data. A simple inclusion of the start date of the experiment (*From*)
745 in the GAM model does suggests an increase in change in the percentage of flow
746 over time. However, as the data distribution is uneven in time, and consists
747 of multiple assessment techniques there could be multiple complicating factors,
748 and drawing a firm conclusion would be premature.

749 4.2.4. Future research needs (implications for forest hydrology)

750 Beyond a more formal approach to investigating climate change effects in the
751 data, this study also points to several further opportunities and future research
752 needs.

753 A major focus of many of the papers related to forest hydrology has been
754 on the impact of plantation forest operations on the catchment, rather than
755 the transition of forestry to agriculture. As the paper by Jones et al. [22]
756 highlights this means there are opportunities to analyze the time evolution of
757 the catchment response to forestation. Given the large number of studies that
758 look at a time evolution of forest cover (i.e. either clearing and regrowth, or
759 burning and regrowth), this data can offer further insights into the dynamic

760 response of catchments to changes in land cover. In addition, this might allow
761 analysis of the variance of the response in addition to the mean response. While
762 some of the older data is not fully recoverable, but there is often a series of
763 papers related to one experiment, which at least would provide individual time
764 points.

765 More generally there is a clear need for a more in depth analysis of the data
766 base of studies used here. In particular, more detailed data can potentially be
767 extracted from many of the studies in terms of vegetation species, stream flow
768 responses and responses of components of stream flow (slow flow, quick flow
769 etc.), as well as a more in depth description of the management and actual
770 experimental design.

771 There is also a clear need to understand the impact of the assessment meth-
772 ods with respect to scale. Extrapolating paired watershed experiment results
773 into models can possibly overlook landscape interactions that are visible at
774 larger scales, but do not occur on smaller scales. For example, this could be the
775 effects of lateral flow and groundwater connectivity and impacts of elevation on
776 land use. A carefully designed simulation study that specifically investigates the
777 change in stream flow response with scale using local field data for verification
778 can help solve this problem.

779 At the moment, providing answers to the impact of stream flow at larger
780 scales should generally not be approached by simulation modelling. A better
781 approach is analyzing stream flow data at multiple spatial and temporal scales
782 for responses (rather than running simulations) and using satellite data to dy-
783 namically include land use changes. The highlighted paper by Levy et al. [24]
784 is currently the best example of a solid statistical approach to analyzing stream
785 flow responses. Simulation modelling can be an approach to analyze different
786 scenarios, if there is clear recognition of the potential impact of the model struc-

ture (the algorithms and parameters that describe for example plantation tree growth) on the simulation outcomes.

We envision that in the future more innovative approaches to analyzing data at different scales will be developed.

5. Conclusions

This study demonstrates that the analysis of large databases of essentially “aggregated data” should be considered carefully and simple single variable regressions often present simplistic relationships that can be misleading.

On first glance, stream flow will decrease with increases in forest cover, and increase with removal of forest cover. However, the conclusions on the exact relationship between stream flow change and forest cover change are highly uncertain. There are four major interlinked reasons why earlier conclusions should be considered carefully:

- The existence of latent variables in the data that create the appearance of a relationship that really does not exist. In this case the assessment technique used to assess the change in stream flow is highly significant;
- The difficulty in fully interpreting the specifics of different studies. In this case the definition of vegetation, stream flow volume, control or time period was difficult to assess;
- The difficulty of integrating data from seemingly similar studies, but with quite different objectives. This study highlighted the many logging studies followed by regrowth, or bushfire effects; and
- The chance of transcription errors influencing the data.

While some of these issues might be overcome with careful analysis and transcription, not all can be directly or easily resolved. Any statistical analysis, including the one in this paper, needs to be considered “conditional on the data”, and given the issues indicated, extrapolation of the results of summary studies to larger scales and into global hydrological models has to be done with great care. Better would be to analyze observed data and explicitly include uncertainty in the extrapolation of the results. This therefore has implications for the recent growth in meta-analysis review papers, which has been boosted by increased computational capacity and much better on-line accessible data bases with research data. This is particularly true for natural systems involving climate variability and therefore extrapolations of experimental work in Environmental Science and Hydrology to global scales in general.

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