

1 Generalising 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 analyse large global datasets related to impacts of forest cover on streamflow. Using three different approaches, they all find a strong relationship between forestation, de-forestation and streamflow. The data for the recent three papers were reviewed, combined and re-analysed using generalised additive modelling. The overall results of the modelling indicates similar results to previous papers. The results are however problematic, the data set is unbalanced, and there are underlying correlations that suggest further factors that influence the results. The area of the catchment is strongly related to the assessment technique and the variability in the response data. A careful review of the data and the methodology in the previous papers highlights that there are four interlinked reasons that are 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 to be considered before

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results are extrapolated to greater and global scales.

5 *Keywords:* data analysis, forest cover change, global scales, literature review

6 1. Introduction

7 There is a urgent need to identify the impacts of human intervention on
8 streamflow at a global scale and to separate this from climate effects [35, 18].
9 More specifically, the impacts of global deforestation and reforestation are im-
10 portant through their perceived influence on streamflow and blue and green
11 water availability [18, 28]. The past work reviewing these impacts [2, 19, 40, 9,
12 10, 16] highlights a general consensus that if forest areas increase, streamflow
13 decreases and vice-versa. The most dramatic result is Figure 5 in Zhang et al.
14 [39] indicating (for Australian catchments) a 100% decrease in streamflow for
15 catchments with 100% forest cover. However, on the other end of the spectrum,
16 for three French catchments [13], there was no change in streamflow characteris-
17 tics in two of the catchments after deforestation. For reforestation, a modelling
18 study across the 1 million km² Murray Darling Basin also found no major ef-
19 fect, especially in larger catchments [32], but a recent study [18] found an 8%
20 changes in streamflow as a result of reforestation. Similarly a modelling study
21 by Beck et al. [3] found no significant change in streamflows in 12 catchment in
22 Puerto Rico as a result of deforestation. In contrast, in a recent study in Brazil
23 across 324 catchments, Levy et al. [22] found a significant increase in stream-
24 flow, particular in the dry season, as a result of deforestation. This suggests
25 that there can be significant variation across the different studies, methodologies
26 and geographical regions.

27 For the purpose of this paper, *watershed* and *catchment* are interchangeable
28 terms. Many of the US studies use *watershed*, while European and Australian
29 studies use *catchment*. In particular, we retained the term “paired watershed

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

32 As mentioned, several review papers have summarized the plethora of foresta-
33 tion and deforestation studies across the globe, in relation to paired watershed
34 studies [9, 8], related to reforestation in particular [16], and more generally
35 [19, 40]. These studies aim to generalize the individual experimental and re-
36 search findings and to identify if there are global trends or relationships. Others
37 have used the understanding from these studies to extrapolate to global scales
38 [18].

39 There has been a recent push in the hydrological community [14] to use
40 ‘meta-analysis’ to summarise past studies. The claim is that because a meta-
41 analysis uses clearly defined search terms and statistical methods to analyse the
42 results, that this will lead to more reliable summaries of past research.

43 From the most recent reviews on forest impact on streamflow [40, 16], the
44 study by Filoso et al. [16] is a clear meta-analysis, while the other is not. How-
45 ever, both authors have developed an impressive global database of catchment
46 studies with changes in streamflow due to changes in forest cover and use sta-
47 tistical approaches to analyse the resulting data. The Zhang et al. [40] dataset,
48 which covers over 312 studies, is described in terms of the change in stream-
49 flow as a result of the change in forest cover, where studies related to both
50 forestation (increase in forest cover) and deforestation (decrease in forest cover)
51 were included. In contrast, the paper by Filoso et al. [16] focused primarily on
52 reforestation, and covered an equally impressive database of 167 studies using
53 a systematic review. In this case the collected data is mostly coded as count
54 data and only a subset of 37 studies was analysed for actual water yield change.
55 There is some overlap between the two data sets, but there are also some studies
56 unique to both sets. The more regionally concentrated and detailed study by

57 Levy et al. [22] is a further independent dataset with no overlap with the other
58 studies. However, for this study only the flow and rainfall data is available for
59 the catchments, and the change in landcover was derived from satellite data and
60 was not made available.

61 The conclusions of the first mentioned major review paper [40] indicates that
62 there is a distinct difference in the change in flow as a result of forestation or
63 deforestation between small watersheds (catchments), defined as $< 1000 \text{ km}^2$
64 and large watersheds (catchments) $> 1000 \text{ km}^2$. While for small catchments
65 there was no real change in runoff with changes in cover, for large catchments
66 there was a clear trend showing a decrease in runoff with an increase in forest
67 cover. Their main conclusion was that the response in annual runoff to forest
68 cover was scale dependent and appeared to be more sensitive to forest cover
69 change in water limited catchments relative to energy limited catchments [40].

70 The second study [16] is a systematic review of reforestation studies (only
71 studies in which forest cover increased). This study classified the historical
72 research and highlighted gaps in the spatial distribution, the types of studies and
73 the types of analysis. Their main conclusion was also that reforestation decreases
74 streamflow, but that there were many interacting factors. For a subset of the
75 data (37 data points) they also indicated decreasing impacts of reforestation
76 with increasing catchment size (agreeing with Zhang et al. [40]), but they did
77 not identify a distinct threshold and fitted a log-linear relationship. In addition,
78 they identified that studies with shorter periods of data collection resulted in
79 larger declines in streamflow.

80 A final earlier summary paper that includes much of the same data as Zhang
81 et al. [40] and Filoso et al. [16] is Zhou et al. [43], which has one author in com-
82 mon with Zhang et al. [40]. However, this paper aims to explain the variation in
83 the data using the elasticity approach in the Fuh model. In particular, it aims

84 to link the variation in the observed data to variations in the exponent m in
 85 the Fuh model. A key observation is that in drier environments, the effects of
 86 removing forest cover are much greater than in wetter environments, which is
 87 also suggested by Figure 4 in Zhang et al. [40]. The Fuh model and variations
 88 of the Budyko equilibrium modelling approach was also used by Hoek van Dijke
 89 et al. [18] to interpret the global impact of reforestation.

90 There are some clear limitations in these studies, and some of this applies to
 91 meta-analyses in general. The main method in the work by Zhang et al. [40] is a
 92 single covariate linear regression. In contrast, the systematic review from Filoso
 93 et al. [16] emphasises the classification and distributions of the study. Zhang
 94 et al. [40] points out that a main assumption in their work is that the catchment
 95 size threshold at 1000 km² is a distinct separation between “small” and “large”
 96 catchments. However, a subset of 37 data points in Filoso et al. [16] (their
 97 Figure 9) does not appear to support this, suggesting a continuum. And while
 98 the work Filoso et al. [16] provides important insights in study types, analysis
 99 types, forest types and broad classification, there is limited quantification of
 100 actual impact.

101 In contrast to the single covariate linear regression in the earlier studies
 102 [40, 16] and the top-down Budyko modelling [43, 18], the regional Brazilian Cer-
 103 rado study [22] provides a carefully designed statistical approach using mixed
 104 effects modelling and Differences-in-Differences modelling focusing specifically
 105 on the effect of deforestation. The analysis specifically accounted for differ-
 106 ences between catchments and differences due to variations in climate. Their
 107 conclusion highlighted that in particular dry season streamflow was affected by
 108 deforestation.

109 Given all these previous reviews and the seemingly clear conclusions about
 110 the impact of forest cover change on streamflow, the question is why another

111 paper? There is a real attraction in the meta-analysis idea of statistical analysis
112 of past studies to be able to extrapolate findings to larger scales and to identify
113 factors across global scales [14]. However, there is also a real danger in this
114 process, which this paper aims to highlight. There are four potential errors (or
115 limitations) in such global meta-analyses:

- 116 • Impact of latent variables that are not included in the typical single co-
117 variate analysis;
- 118 • Interpretation errors due to incomplete descriptions of the experiments in
119 the original papers;
- 120
- 121 • Aggregation of data that originates from different experiments with differ-
122 ent objectives across a wide time period, but have similar keywords; and,
123 finally
- 124
- 125 • Transcription errors in the data, especially if data is collected from other
126 review papers as some of the original papers are difficult to locate.

127 The aim of this paper is to first reanalyse the global dataset using some more
128 sophisticated statistical modelling and uses this to highlight examples of each of
129 these limitation. This will show how they have influenced the outcomes of the
130 past work, and provide suggestions of how we can overcome these limitations.
131 In addition, by applying more complex statistical models we will highlight the
132 conclusions that can still be drawn from this work in relation to the impact of
133 forest cover on streamflow. Finally, we will highlight future research needs in
134 this area.

135 We are taking advantage of the earlier work by Zhang et al. [40], Filoso et al.
136 [16] and Zhou et al. [43] and the large database of studies these authors have
137 shared.

138 2. Methods

139 2.1. The original data set

140 As indicated, the starting point of this paper is the data base of studies which
 141 were included in Zhang et al. [40] as supplementary material. The columns in
 142 this data set (are the catchment number, the catchment name, the Area in
 143 km², the annual average precipitation (Pa) in mm, the forest type, hydrological
 144 regime, and climate type, the change in forest cover in % ($\Delta F\%$) and the change
 145 in streamflow in % ($\Delta Qf\%$), based on equation 1 in Zhang et al. [40]), the
 146 precipitation data type, the assessment technique, and the source of the info,
 147 which is a citation. Several of these columns contain abbreviations to describe
 148 the different variables, which are summarised in Table 1. These abbreviations
 149 will later be used 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
	SG	spatial gridded

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

150 The paper by Zhang et al. [40] use the dryness index, which is the annual
 151 rainfall (Pa) divided by the potential or reference evapotranspiration (ET_0 or
 152 E_0) in their analysis, and use the dryness index to identify the climate type.
 153 However, the potential or reference ET was not originally included as part of the
 154 published data set. We combined the tables for small catchments ($< 1000 \text{ km}^2$)
 155 and large catchments ($\geq 1000 \text{ km}^2$) from Zhang et al. [40] in our analysis.

156 2.2. Additional data collection

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

161 In addition, a few additional variables were included to enhance the data
 162 set. We added latitude and longitude for the center of the catchment as an
 163 approximation of its spatial location. Mostly the data reported by the authors
 164 was used, but in some cases the variables had to be approximated from the
 165 location of the centre of the catchment using Google MapsTM. In the dataset,

an additional column has been added to indicate the source of the location data to indicate if this is directly from the paper or elsewhere.

As highlighted, Zhang et al. [40] did not provide values for evapotranspiration in the data base. Using the location information reference evapotranspiration (E_0) was extracted from the Global Aridity Index and Potential Evapotranspiration (ET_0) Climate Databasev2 [31], if a value of E_0 was not available from the original papers. For large catchments, this value (and the associated coordinates), similar to annual average rainfall, is only an approximation of the climate at the location.

Similar to Zhang et al. [40], the “dryness index” was calculated from the reference evapotranspiration and the annual average rainfall (Pa) as:

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

The length of the study can be a variable influencing the change in flow [e.g. 19, 16], as for example, more mature plantations are thought to have smaller impacts on flow or regrowth might follow a “Kuczera curve” [21]. It is not clear if this is an effect of increased water use in growth [33] or due to changes in interception [29]. 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. [40]. The length of the study was already included in the data from Filoso et al. [16], but these were checked against the original publications.

Several additional data points from catchment studies were extracted from Almeida et al. [1], Ferreto et al. [15], Zhang et al. [39], Zhao et al. [41], Borg et al. [7], Thornton et al. [30], Zhou et al. [42], Rodriguez et al. [26], Ruprecht et al. [27] and Peña-Arancibia et al. [24], and these were checked against the existing studies to prevent overlap. In the citation column in the accompanying data

191 set, the main reference for the calculated change in streamflow was generally
192 used, because sometimes the original study did not provide the quantification
193 of the change in streamflow [i.e. Table 6 in 39].

194 We conducted a thorough review of all the studies mentioned in the data
195 base of Zhang et al. [40] and sourced all the original papers. As a result of this
196 we made several changes to the data base, which are all recorded in Supplemen-
197 tary Data part 1. Overall 36 data points were changed and the most common
198 problem was a change in the sign for the change in forest cover or the change
199 in flow. We assume that these were transcription errors.

200 We also removed one data point from the data set, which corresponds to catch-
201 ment #1 (Amazon) in Zhang et al. [40]. This is because the cited reference [25]
202 only relates to 1 and 1.5 ha paired catchment studies in French Guyana, and in
203 which the actual change in forest cover is not recorded. Finally, on review of all
204 the data in Zhang et al. [40] and Filoso et al. [16], 29 potential duplicates were
205 identified and flagged in the data, and not used in the analysis.

206 The final column in the improved data base is a “notes” column, which we
207 added, but is not further used in the analysis. It gives context to some of the
208 data for future research and highlights some of the discrepancies that we found
209 between the original papers and the data in the tables from Zhang et al. [40].
210 This will allow future research to scrutinise our input for errors.

211 *2.3. Statistical modelling*

212 The aim of the statistical analysis is to highlight the most important variables
213 in the data set that explain the change flow as a consequence of changes in forest
214 cover. This first aim is similar to Zhang et al. [40], but the main difference is
215 that we start off with all variables in the data set in the model. Subsequently the
216 analysis will concentrate on how the individual variables in the dataset relate
217 to each other and how latent variables in the data set can be masked and result

218 in relationships that might not really exist. Finally, the analysis will highlight
 219 how the results are conditional on the dataset.

220 To estimate how the change in streamflow is affected by the change in forest
 221 cover, while considering the effects of the other variables, we applied generalised
 222 additive modelling (GAM) [38].

223 The general model tested is:

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

224 Here X_i are factorial variables, while Z_i are continuous variables. As a
 225 first step, the model assumes no direct interactions and that all variables are
 226 additive. A further assumption in the model is that all continuous variables
 227 Z_i (such as annual precipitation (Pa)) can have either a linear or a non-linear
 228 relationship with $\Delta Qf\%$. This means that a smooth function $s()$ can be applied
 229 to the Z_i variables. For the smoothing function we applied thin plate regression
 230 splines with an additional shrinkage penalty. The result of this approach is
 231 that for high enough smoothing parameters (i.e. if the data is very “wiggly”)
 232 the smooth term can be shrunk to 0 and thus will be no longer significant
 233 [38]. This is done because a highly flexible smooth term could always fit the
 234 data, but would not necessarily indicate a relevant relationship. In other words,
 235 the approach balances finding a smooth non-linear relationship for the variable
 236 against overfitting the data.

237 The changes in forest cover contain both positive (forestation) and negative
 238 values (deforestation). In Zhang et al. [40], these changes were jointly analysed,
 239 assuming the effect on the change in flow was linear and the effect of removing
 240 forest cover was the same as an equivalent addition of forest cover.

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

252 A second approach is to test the change in forest cover as a non-linear re-
 253 lationship in the GAM model. Because a shrinkage penalty is used, this will
 254 also test the non-linear assumption and allows the variable for forest cover to be
 255 continuous. The disadvantage of this approach is that the relationship between
 256 forest cover and change in flow is less easy to interpret, as the non-linear fit in
 257 the GAM has no direct parametric form. Both these approaches are tested in
 258 the results.

259 The over arching test focuses on identifying the change streamflow as a result
 260 of a change in forest cover and potentially affected by different other factors (as
 261 indicated by the previous research: Zhang et al. [40]; Filoso et al. [16]; Zhou
 262 et al. [43]): climate, size of catchment and length of study. In addition to these
 263 earlier identified factors, this study also tested for the factors listed in Table 1

264 As an initial approach we only used the data from Zhang et al. [40] to make
 265 sure that the additional catchments added to the data set did not influence
 266 the results (This analysis is in supplementary material part 2). This analysis
 267 highlights that the newly added catchment and the changes to the dataset create

268 minor differences when repeating the analysis from the original paper.

269 To make all the data and code publicly available, all the final data and anal-
270 ysis for this paper are located on github:

271 https://github.com/WillemVervoort/Forest_and_water on the “publish” branch.

272 **3. Results**

273 *3.1. Description of the data*

274 The overall dataset contains 329 observations of changes in flow, which in-
275 cludes the newly identified data sets and after removing identified duplicate
276 data and lines with missing data. In contrast, the original dataset from Zhang
277 et al. [40] contained 312 catchments and the Filoso et al. [16] study used 37
278 catchments (Table S2 in Filoso et al. [16]). The current number of catchments
279 is the result of the removal of duplicates and our modifications and additions.
280 The overall distribution of changes in flow is highly skewed as is the distribution
281 of changes in forest cover and *Area km²*. The values of changes in flow greater
282 than 100% and smaller than -100% clearly create long tails on the change in
283 flow distribution. Note also the large number of studies with 100% forest cover
284 reduction. Clearly visible is also that smaller catchments dominate the database
285 with 42% of the data from catchments $< 1 \text{ km}^2$ and 65% of the data for catch-
286 ments $< 10 \text{ km}^2$ (Figure 1). This high skew in some of the data can create
287 difficulties in the statistical modelling and further transformation of the data
288 might be required.

289 *3.1.1. Geospatial location of the catchments*

290 Apart from looking at the distribution of the values, the spatial locations
291 of the data can also be important, in particular when analysing the effect of
292 climate. The catchments are spread across the world, and relative to Zhang
293 et al. [40], this dataset has a very similar geospatial distribution. The major

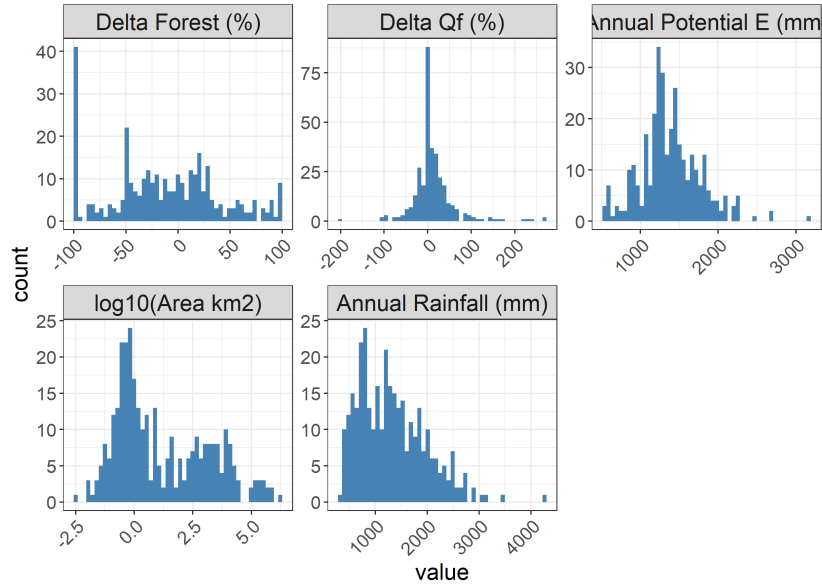


Figure 1: Overview of the distribution of the data set for five of the included variables. Note that the first panel (showing the distribution of the catchment areas) indicates the distribution of the *log₁₀* transformed Area (in km²).

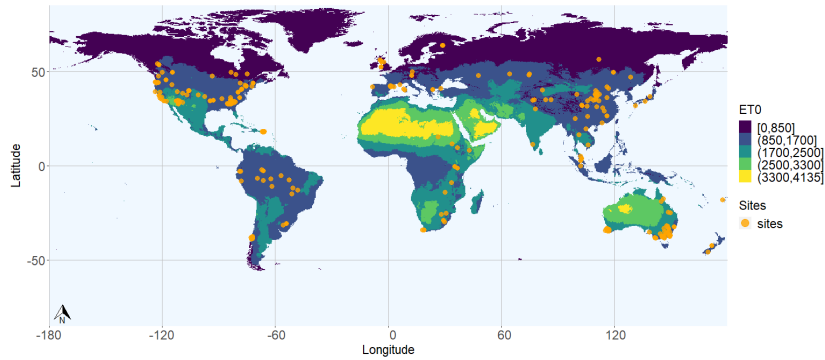


Figure 2: Distribution of included catchments across the globe based on reported or estimated latitude and longitude

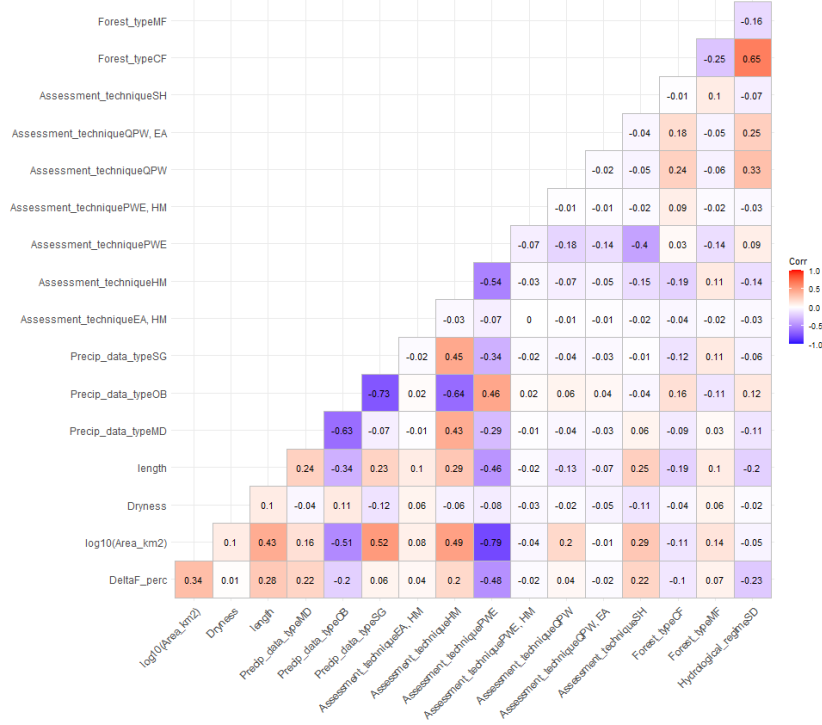


Figure 3: Correlation matrix for all variables

climate gradients are represented in the data, but there appears to be some bias in the spatial locations of the data. As the global map (Figure 2) shows, the 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.

303 The correlation plot (Figure 3) highlights several correlations that are worth
 304 investigating, even though in general cross correlation is quite low between vari-
 305 ables. Some interesting relationships that appear in this graph are:

- 306 • the negative relationship between $\log_{10}(\text{Area})$ and change in forest area
 307 (ΔF_{perc}) indicating that in the data set larger catchments tended
 308 to have (obviously) smaller areas of forest change.
- 309
- 310 • the weak positive relationship between $\log_{10}(\text{Area})$ and the assessment
 311 method using hydrological models. This highlights that paired catchment
 312 studies mostly concentrate on smaller scales.
- 313
- 314 • A strong inverse relationship between $\log_{10}(\text{Area})$ and the paired water-
 315 shed assessment method, which is simply the inverse from the last point,
 316 as also indicated by the negative relationship between the two assessment
 317 methods. This is further visible in the relationship between the change
 318 in forest cover and the paired watershed assessment method, showing the
 319 impact of the latent variable ($\log_{10}(\text{Area})$). Smaller catchments used in
 320 paired watershed assessments are easier to fully clear or fully replant.

321 3.2. Statistical analysis

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

324 This includes introducing non-linearity (Equation (2)) for the numerical vari-
 325 ables in the model. While increasing non-linearity in the model can increase the
 326 flexibility of the model, the shrinkage splines assist with limiting overfitting. Fol-
 327 lowing Wood [38], the number of degrees of freedom k in the non-linear variables
 328 was based on assessment of the effective degrees of freedom in the model output.
 329 If the effective degrees of freedom were close to $k - 1$ then k was increased and

the model rerun. By using shrinkage splines, this also results in the whole term
being shrunk to zero [38].

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

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-4.81	16.31	-0.29	0.77
DeltaF__perc	-0.6	0.06	-10.71	0
Precip_data_typeOB	-21.4	13.23	-1.62	0.11
Precip_data_typeSG	9.36	15.17	0.62	0.54
Assessment_techniqueEA,	20.64	42.73	0.48	0.63
HM				
Assessment_techniqueHM	22.81	11.71	1.95	0.05
Assessment_techniquePWE	30.63	11.94	2.57	0.01
Assessment_techniquePWE,	17.42	43.26	0.4	0.69
HM				
Assessment_techniqueQPW	39.52	20.15	1.96	0.05
Assessment_techniqueQPW,	24.39	24.42	1	0.32
EA				
Assessment_techniqueSH	45.3	11.83	3.83	0
Forest_typeCF	-9.45	7.6	-1.24	0.21
Forest_typeMF	-8.05	7.56	-1.06	0.29
Hydrological_regimeSD	3.57	9.16	0.39	0.7

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

	edf	Ref.df	F	p-value
s(log10(Area_km2))	0.79	4	0.99	0.02
s(Dryness)	4.64	9	2.26	0
s(length)	4.45	34	0.22	0.12

332 The overall explaining power of the model can be interpreted from the ad-
333 justed r^2 (which is penalised for the number of parameters). This indicates an
334 r^2 of 0.45 and deviance explained is 0.49, suggesting the model only explains
335 about 50% of the variance in the data.

336 Inspecting the significance of the variables (Table 2 and Table 3) indicates
337 some interesting features.

338 The overall partial slope of the change in forest cover is -0.6, if all other
339 variables are kept constant. This suggest quite strong change in streamflow,
340 moving from fully forested to fully cleared. Over the whole forest cover range,
341 this is a change of -120 mm, with other variables held constant. This change is
342 highly significant, as indicated by the low p-value.

343 In addition, all the smoothed variables $\log_{10}(\text{Area } (km^2))$ ($p = 0.02$), *Dry-*
344 *ness* ($p = 0$) and *length* ($p = 0.12$) explain variation in the data. For *length*,
345 the p-value is not strictly smaller, than 0.05, but still indicates some reason-
346 able evidence that the variable explains some of the variation in the change in
347 streamflow.

348 Furthermore Table 2 indicates that several of the assessment methods ex-
349 plain variation in the change in streamflow, which was also indicated in the
350 correlation analysis. In particular, the assessment methods Paired Watersheds

351 experiments (PWE), Hydrological modelling (HM) and Statistical techniques
 352 (SH) are important explaining variables ($p < 0.05$).

353 The remaining variables related to rainfall observation technique, forest type
 354 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	3182
different for forestation and deforestation	0.45	3227
non-linear across the range	0.5	3182

355 As discussed in the methods, the overall linear response to the change in
 356 forest cover was compared to a transformation of the negative forest cover to
 357 positives and a check whether the relationship might be non-linear. This ap-
 358 proach tests whether the impact on streamflow from removing forest cover is
 359 different from reforestation, as outlined in the methods. The detail of the com-
 360 parison is highlighted in Supplementary material part 3. However, generally the
 361 results of the analysis showed two main points (Table 4):

- 362 1. The model assuming a simple linear relationship between change in forest
 363 cover (both positive and negative) and the change in flow explained the
 364 most variation in the data and indicated the best performance in terms of
 365 the Aikaike Information Criterium (AIC); and

366

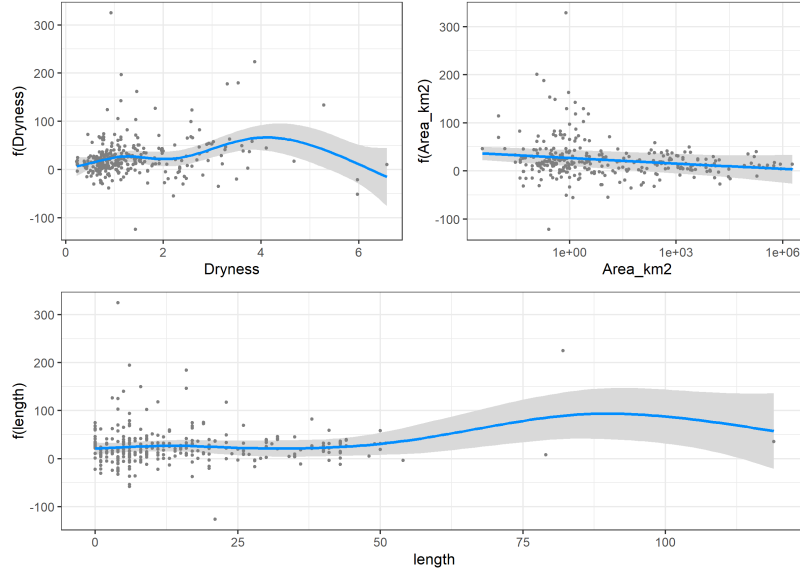


Figure 4: Visualisation of the smooth variables in the model, the shaded areas are the 95% confidence intervals associated with the fit of the smooth, the blue line is the mean smoothed relationship, with data plotted as individual points

2. There is no need to assume a non-linear relationship, as a linear relationship provides a better 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. [40], indicating that in larger catchments changes in forest cover have less impact on streamflow 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 of the data. A further problem appears to be that *length* and *Dryness* have

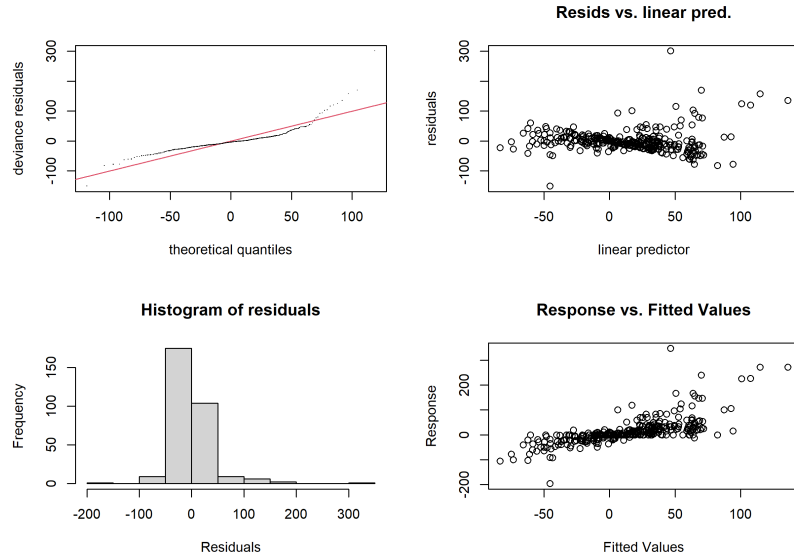


Figure 5: Residual plots for the regression model indicating a slightly fat-tailed residual distribution

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). This is related to a limited number catchments that have very high changes in streamflow 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 results of the regression difficult to interpret, and at some point can be slightly contrived.

394 Given the majority of the residuals indicate a relatively well behaved distri-
395 bution, we simply note the behaviour at the extremes and will discuss this later
396 in the paper, and explain how this relates to the characteristics of the dataset.

397 *3.2.1. Test 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
226	32.74	-111.5	Natural Drainages, Ariz., U.S.A, C
356	-25.75	28.23	Queens river

398 The flexible nature of the splines means that the length variable highlights
399 substantial non-linearity in the data, but it is unclear what exactly is captured.
400 The shape of the conditional response (Figure 4) does not reflect a similar
401 response as indicated by Filoso et al. [16] and Jackson et al. [19]. One reason
402 could be that the relationship is dominated by the few data points with very
403 long data series, which show highly variable responses (Figure 4).

404 The points related to catchments with very long studies (> 60 years) might
405 be questionable, as changes other than forest cover change could affect stream-
406 flow. In addition, a few of the catchments have Dryness values that are very
407 large (> 5) and these values have high leverage in the data, affecting the residual
408 distribution. These catchments are listed in Table 5, and are three catchments
409 in Arizona and 1 catchment in South Africa. It is possible that catchments in
410 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)	-10.17	17.98	-0.57	0.57
DeltaF_perc	-0.59	0.08	-7.45	0
Forest_SignIncrease	0.41	9.79	0.04	0.97
Precip_data_typeOB	-15.97	12.5	-1.28	0.2
Precip_data_typeSG	15.71	14.85	1.06	0.29
Assessment_techniqueEA,	20.38	41.03	0.5	0.62
HM				
Assessment_techniqueHM	26.42	11.4	2.32	0.02
Assessment_techniquePWE	28.51	12.15	2.35	0.02
Assessment_techniquePWE,	17.4	42.05	0.41	0.68
HM				
Assessment_techniqueQPW	41.49	19.53	2.12	0.03
Assessment_techniqueQPW,	24.81	23.32	1.06	0.29
EA				
Assessment_techniqueSH	47.26	11.49	4.11	0
Forest_typeCF	-9.47	7.3	-1.3	0.2
Forest_typeMF	-6.01	7.35	-0.82	0.41
Hydrological_regimeSD	2.5	8.89	0.28	0.78

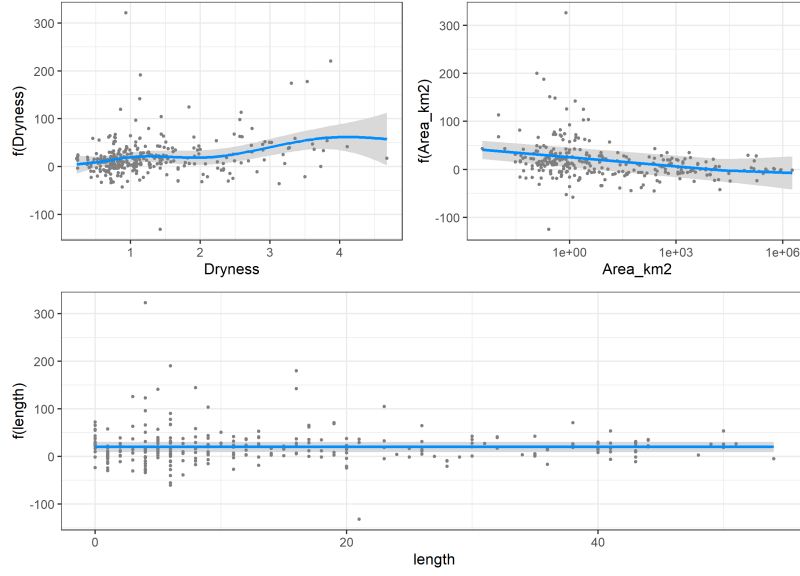


Figure 6: Visualisation of the smooth variables in the model with reduced data for dryness and length

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)	4.02	9	2.16	0
s(log10(Area_km2))	0.87	4	1.53	0.01
s(length)	0	9	0	0.98

411 Therefore it is worth investigating what effect removing these few data points
412 has on the overall model and the significance of the variables. Data that have
413 *Dryness* ≤ 5 and *length* ≤ 60 years were removed from the dataset and the
414 model based on a reduction of the data set from 329 to 310 catchments is run
415 again.

416 This model, which excludes data with long studies and very dry catchments
 417 explains only slightly less of the variation with an adjusted r^2 of 0.44 and a
 418 deviance explained of 0.48.

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

425 **Possibly insert here a model to investigate total forest area as a**
 426 **random effect**

Table 8: Distribution of assessment techniques in the data set

Assessment__technique	n
PWE	185
HM	57
SH	42
EA	32
QPW	7
QPW, EA	4
EA, HM	1
PWE, HM	1

427 One concern with the results presented so far is that there are a few assess-
 428 ment techniques in the data set with a very low number of observations and
 429 could influence the results of the analysis. This includes the category of Quasi
 430 paired watersheds and combinations of elasticity analysis and hydrological mod-

elling (EA, HM) and paired watersheds and hydrological modelling (PWE, HM)
 (Table 8).
 Therefore, the model was rerun excluding the combined assessment tech-
 niques (EA, HM), (PWE, HM) and (QPW, EA).

Table 9: Statistical overview of the linear components of the model
 removing studies with limited observations in the assessment tech-
 niques

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-12.17	14.9	-0.82	0.41
DeltaF_perc	-0.58	0.05	-10.79	0
Precip_data_typeOB	-16.53	12.37	-1.34	0.18
Precip_data_typeSG	15.32	14.39	1.06	0.29
Assessment_techniqueHM	28.74	11.16	2.57	0.01
Assessment_techniquePWE	31.37	11.3	2.78	0.01
Assessment_techniqueQPW	44.15	18.89	2.34	0.02
Assessment_techniqueSH	49.42	11.32	4.37	0
Forest_typeCF	-8.72	7.25	-1.2	0.23
Forest_typeMF	-3.94	7.43	-0.53	0.6
Hydrological_regimeSD	2.01	8.86	0.23	0.82

Table 10: Statistical overview of the smooth components of the model removing studies with limited observations in the assessment techniques

	edf	Ref.df	F	p-value
s(Dryness)	3.37	9	2.79	0
s(log10(Area_km2))	0.85	9	0.68	0.01
s(length)	0	9	0	0.84

Concentrating only on the assessment techniques that have more than 10 observations in the data set does not change much in the results (Table 9 and 10). 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 strongly bias the outcomes.

However, the model results also clearly highlight that some of the assessment techniques (in particular paired watershed studies (PWE) and combined use of statistical methods and hydrographs (SH)), have a strong impact on the predicted change in flow. Particularly, relative to EA (elasticity approaches) all other assessment techniques have higher predicted changes in flow. In other words, there is a distinct difference in the way the change in flow is assessed, and the EA method (for example in Zhou et al. [43]) appears to suggest a much smaller effect on the change in flow.

4. Discussion

The results presented so far, while using generalised additive modelling rather than single variable regression, end up with roughly the same conclu-

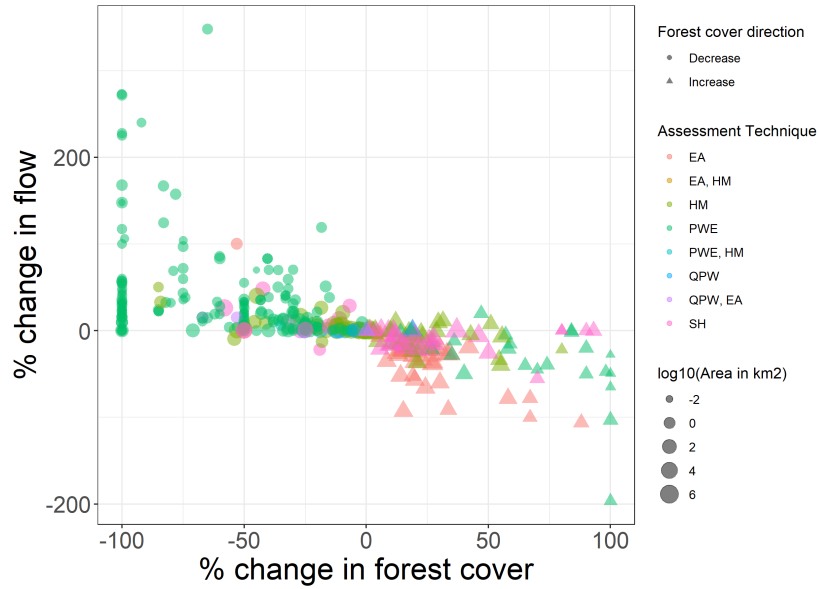


Figure 7: Overview of the data highlighting the dominance of small catchment studies which are fully forested or cleared and the scatter in the data

sions as earlier papers [40, 16]. It appears that:

1. Larger catchments show lower impact of forest cover change on streamflow;
2. Drier catchments show a greater impact of forest cover change on streamflow; and
3. There is a general linear relationship between the change in forest cover and the change in streamflow.

Figure 7 provides a further overview of the whole data set and 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

465 forest cover and different methods, such as hydrological modelling and elasticity
466 analysis. This confirms the model results (Table 9) and the earlier correlation
467 analysis (Figure 3).

468 It is possible that one of the reasons why Zhang et al. [40] separated their
469 analysis in large ($> 1000 \text{ km}^2$) and small ($< 1000 \text{ km}^2$) catchments, is that
470 they realised this difference in assessment methods and wanted to account for
471 this. However, this is not explicitly identified, and there is no real physical
472 explanation of the 1000 km^2 threshold.

473 The other interesting point in Figure 7 is that the variation in the data
474 increases as the catchment size decreases and the change in forest cover increases.
475 This also means that the overall variation in the data for paired watershed
476 experiments (PWE) is much greater than for any of the other methods.

477 *4.1. Is there a problem with extending local experimental data to larger scales?*

478 The overarching reason for combining past studies at a global scale is to infer
479 relationships that can be used to make more general statements or develop more
480 global scale modelling of impacts [i.e. 43, 19, 18]. Therefore, the results from the
481 analysis could be seen as a confirmation of the earlier research [40, 16, 43, 19].
482 However, the explaining power of the developed model is quite low and a lot of
483 variation in the data is unexplained. As is highlighted in the introduction there
484 are four major issues with this type of analysis, and the results from this paper
485 also highlight these issues. Here, these issues are further explained.

486 *4.1.1. Issue 1: Latent variables are not included in the typical single covariate* 487 *analysis*

488 The results show that it is simply impossible to analyse a single covariate
489 relationship, as there are several latent variables in the data. An example of
490 this is the general relationship of the change in flow as a function of the change

491 in forest cover. Clearly the relationship is highly impacted by the fact that all
492 the small catchments have large changes in forest cover and are all associated
493 with paired watershed experiments. Without taking these factors into account,
494 a definite answer about the impact of forest cover on the change in flow cannot
495 be given. Furthermore, the large variability in the change in flow data for these
496 small catchments (Figure 7) indicates that there is a further (unknown) variable
497 that explains the variation in the data.

498 If the remaining variation in the residuals is small relative to the trend, then
499 there is little need to identify further latent variables, but if the variation is
500 large, then it is unclear if it is the latent variable that determines the trend, or
501 the actual relationship in the data.

502 Similarly, the data for the larger catchments containing smaller changes in
503 forest cover are dominated by hydrological modelling studies, resulting in a
504 further complication. If the response of the streamflow in the modelling studies is
505 the result of the conceptualised relationship between streamflow and forest cover
506 (possibly from a subset of the paired catchment studies), then it is impossible
507 to say if the change in streamflow is real, or simply a result of a pre-conceived
508 model relationship. Is the smaller variation in the data for smaller changes in
509 forest cover (Figure 7) a result of similar conceptualised model relationships, or
510 actual variation between catchments and climate types? Currently this question
511 cannot be answered.

512 This becomes problematic when extrapolated to larger scales. A clear exam-
513 ple of this is the paper by Hoek van Dijke et al. [18] where the conceptualised
514 relationship between forest cover and streamflow pre-determines the outcomes
515 of the global modelling.

516 The only way to analyse changes in streamflow as a function of forest cover
517 in larger catchments is to actually derive this from observed data of long term

518 streamflow and forest cover (as was done in Levy et al. [22]).

519 We are not arguing that there is no relationship between streamflow and for-
520 est cover, and there might indeed be a global relationship that can be discovered.
521 But, this relationship can only be discovered if we are able to address some of
522 the major other factors that explain the variability, and work with actual data
523 and not model outputs.

524 *4.1.2. Issue 2: Interpretation errors due to complex descriptions of the experi-*
525 *ments in the original papers*

526 The second major issue that became clear from reviewing many of the origi-
527 nal papers is that some of the variability might be an interpretation problem.
528 In many cases the original description in the paper is interpreted to extract the
529 % change in streamflow from the % change in forest cover. This seems like a
530 simple activity, but this is not always the case.

531 Two examples can be highlighted:

- 532 • The papers from Almeida et al. [1] and Ferreto et al. [15] partly discuss
533 the same experiment and the same catchment. In Almeida et al. [1],
534 the methods discuss how two experimental catchments of approximately
535 80ha in size which were harvested. One catchment was 100% harvested
536 and the other 30% harvested. Throughout the paper the catchments are
537 indicated as 100% harvested and 30% harvested. However, only after
538 reading Ferreto et al. [15], did we discover that in fact the 100% and
539 30% refer to the “eucalyptus plantation area”, which was about 60% of
540 the total area. This is in fact mentioned in Table 1 in Almeida et al.
541 [1], but does not appear in the text. The question then becomes how to
542 interpret this in the data base for this paper. Clearly it was a 100% and
543 30% change in forest cover, but only for the 60% plantation cover, not for
544 any of the other areas in the catchment, which included native vegetation

545 and riparian vegetation. There are several other examples like this in the
546 different papers [for example 6, 5].

- 547 • Another example is the paper by Waterloo et al. [36]. This modelling study
548 in Fiji of the clearing of a catchment reports the changes in streamflow
549 over parts of the year. For a period of 324 days the streamflow increased
550 from 252 mm to 580 mm (a 230% increase if calculated as $580/252 * 100$)
551 and for a second period of 309 days the streamflow increased from 90 mm
552 to 194 mm (a 215 % increase). However, how we convert this to a change
553 in annual flow (which most of the other data relate to) is difficult. The
554 original data base listed a 50 % change in flow, but it is difficult to identify
555 how this is calculated. We suspect that results from $252/580 * 100 \approx 50$
556 and $90/194 \approx 50$.

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

563 *4.1.3. Issue 3: Aggregation of data that originates from different experiments* 564 *with different objectives across a wide time period*

565 The last issue leads into the next issue. For many of the small catchment
566 studies listed in the database, the assumption is that the original experimental
567 design can be interpreted in terms of a binary “forestation” or “deforestation”.
568 However, the real situation is often much more complex and fuzzy.

569 Many of the paired watershed experiments included a harvesting and re-
570 planting or regrowth after harvesting or fire experiment [e.g. 11, 12, 37]. As a
571 result, it becomes difficult to assess how we interpret the change in flow as a

572 result of a change in cover. In many cases we would expect the flow to change
573 over time as a function of the recovery [20] and therefore the timeseries of the
574 flow needs to be assessed over a longer time.

575 Many of the papers in the database report early results (for example 1 or
576 3 years after harvesting), but some also report longer time periods. As earlier
577 work [12, 20] has highlighted, we can always expect a larger effect directly
578 after harvesting, but this effect diminishes over time (even if it does not always
579 return to the original state). Comparing studies reporting results directly after
580 treatment to longer term studies therefore becomes problematic.

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

584 This is further complicated by the variation in different types of clearing
585 and the different types of vegetation. In the original Zhang et al. [40] a variable
586 to describe the *forest type* was included (Table 1), but in the model this is not
587 significant (Table 2). This is probably because the broad classification used
588 does not capture the actual variation in runoff response. In addition, as Figure
589 3 shows, there is a correlation between coniferous forests and snow dominated
590 hydrological regimes, further complicating the analysis.

591 An additional complication related to combining studies related to wild fires
592 or bush fires and logging studies is the differences in vegetation recovery. For ex-
593 ample, Heath et al. [17] found that catchments with resprouting species around
594 Sydney indicated little change in the streamflow in comparison to species re-
595 growing from seed further south on the continent Zhou et al. [44].

596 As a result, it can be difficult to exactly pinpoint the change in flow as a
597 result of the change in cover, as well as being difficult to assess what the exact
598 change in cover actually was.

599 As indicated before, if the overall variation due to this issues is small, then
600 this would not be an issue for upscaling the results, but the large variation for
601 the smaller catchments suggest that effects could be considerable. As Jones et al.
602 [20] indicate, this really needs time series analysis of the different experiments.
603 However, some of the time series data might not be recoverable from the older
604 experiments, which will limit the opportunities for analysis. We will discuss this
605 further below.

606 4.1.4. Issue 4: Transcription errors in the data

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

612 This does influence the results in Zhang et al. [40], comparing the results in
613 Supplementary material 2 with the original paper. The main example is that in
614 this study the largest catchment (watershed #1 in Zhang et al. [40]) had to be
615 removed, as this study actually involved paired watershed experiments on very
616 small plots, for which the characteristics were not recoverable.

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

620 In the end, careful review of the data and the original papers can circumvent
621 most of this issue. And, making the data available (as Zhang et al. [40], Zhou
622 et al. [43] and Filoso et al. [16] have done) provides an opportunity for review by
623 other researchers, and over time most of the transcription errors can be resolved.

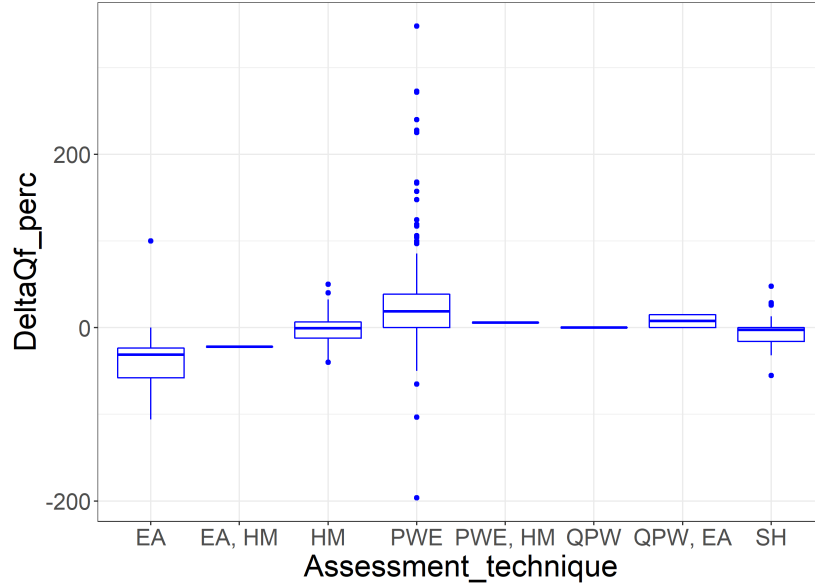


Figure 8: Boxplot of the variation in the change in flow for the different assessment techniques, showing the dominance of the variation and the outliers in the dataset in the paired watershed experiments

624 4.2. General discussion

625 In this paper, a few studies have been singled out in the analysis. The choice
626 of focus was mainly driven by the data that was made available by the authors
627 of these papers [40, 16], which provide a rich case study for the current paper.

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

633 However, as is demonstrated in this paper, there are multiple issues when
634 this local scale data is extrapolated to larger scales. It clearly demonstrates that
635 the results of any model (in this case a regression model) is highly dependent
636 on the data, but also on the assumptions in the model. From the perspective of

extrapolating local data to global scales for policy advice and decision making [i.e. 18, 19], this is an important point.

4.2.1. Residuals of the model

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

4.2.2. Interactions

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

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

4.2.3. Implications for other “meta-analysis” studies

There has been a recent push to develop more meta-analysis studies in hydrology [35, 14], and we strongly believe that developing new insights by

663 combining historical data sets from reviewed papers is highly valuable. How-
 664 ever, this paper highlights that there is considerable chance that large histor-
 665 ical data sets include latent variables and are more complex than envisioned.
 666 This is particularly true for more historical work, as methods of observation and
 667 even approaches to management have changed considerably. The same manage-
 668 ment description is not necessarily the same action on the ground. A carefully
 669 designed and systematic approach can prevent some of bigger problems as is
 670 demonstrated in Wang et al. [35], where both the approach and the catchment
 671 area are investigated as latent variables. This is particularly relevant, where the
 672 results of meta-analyses are extrapolated to make global predictions without
 673 clearly quantified uncertainties (such as in Hoek van Dijke et al. [18] and Wang
 674 et al. [35]).

675 A second potential danger is the extrapolation of the local small catchment
 676 results and conclusions to larger scales, but beyond the original scope of the stud-
 677 ies. For example, the current database is mainly related to forest harvest, bush
 678 fire and reforestation/plantation management. It is tempting to use the result
 679 of a large scale analysis of this data to make inferences about overall landuse
 680 change [23, 35], but this would not be valid, as the deforestation studies are gen-
 681 erally not a transition to an agricultural landuse or pasture, but regrowing into
 682 forest. Similarly, using the plantation studies to extrapolate to “reforestation”
 683 (as in Filoso et al. [16] and Hoek van Dijke et al. [18]) is also tenuous. Plan-
 684 tation forests are generally fast growing hybrids that will have quite different
 685 ecophysiology, particularly in South America [20, 4], while other reforestation,
 686 for example for salinity control in Australia, might focus on a mix of native
 687 species. Given the link between ecophysiology and water and carbon budgets,
 688 care should be taken in extrapolation, introducing a further error.

689 A final factor is the effect of climate change [34] on runoff, even if the effects

are still minor. Earlier papers [23, 35] have analysed climate effects relative to management effects in the data, but these studies did not explicitly test for climate change. Given that the database of studies now captures almost 100 years of work, we cannot ignore a climate change trend that is potentially hidden in the data. A simple inclusion of the start date of the experiment (*From*) in the GAM model does suggest an increase in change in the percentage of flow over time. However, this is once again not easy to analyse. As the data distribution is uneven in time, and consists of multiple assessment techniques there could be multiple complicating factors, and drawing a firm conclusion would be premature.

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

This study also points to several further opportunities and future research needs.

A major focus of many of the papers related to forest hydrology have been specifically interested in the impact of plantation forest operations on the catchment, rather than the transition of forestry to agriculture. As the paper by Jones et al. [20] highlights this means there are opportunities to analyse the time evolution of the catchment response to forestation. Given the large number of studies that look at a time evolution of forest cover (i.e. either clearing and regrowth, or burning and regrowth), this data can offer further insights into the dynamic response of catchments to changes in landcover. This will give further insights into the equilibrium state under forestry. As highlighted, some of the older data is not fully recoverable, but there is often a series of papers related to one experiment, which at least would provide individual time points.

More generally there is a clear need for a more in depth analysis of the data base of studies used here. In particular, more detailed data can potentially be extracted from many of the studies in terms of vegetation species, streamflow

717 responses and responses of components of streamflow (slow flow, quick flow
718 etc.), as well as a more in depth description of the management and actual
719 experimental design.

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

728 At the moment, providing answers to the impact of streamflow at larger
729 scales should generally not be approached by simulation modelling. A better
730 approach is analyzing streamflow data at multiple spatial scales for responses
731 (rather than running simulations) and using satellite data to dynamically in-
732 clude landuse changes appears to be the best approach. The highlighted paper
733 by Levy et al. [22] is currently the best example of a solid statistical approach
734 to analyzing streamflow responses. Simulation modelling can be an approach to
735 analyze different scenarios, if there is clear recognition of the potential impact of
736 the model structure (the algorithms and parameters that describe for example
737 plantation tree growth) on the simulation outcomes.

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

740 5. Conclusions

741 This study demonstrates that analyses of large databases of essentially “ag-
742 gregated data” should be considered carefully and simple single variable regres-

743 sions often present simplistic relationships that can be misleading.

744 While the analysis reveals similar conclusions in relation to the response of
745 streamflow to forest cover, there are four major interlinked reasons why these
746 results should be considered carefully. This subsequently has implications for
747 meta-analyses in Environmental Science and Hydrology in general. The reasons
748 highlighted in this paper are:

- 749 • The existence of latent variables in the data that create the appearance
750 of a relationship that really does not exist;
751
- 752 • The difficulty in fully interpreting the specifics of different studies;
753
- 754 • The difficulty of integrating data from seemingly similar studies, but with
755 quite different objectives; and
756
- 757 • The chance of transcription errors influencing the data.

758 Any statistical analysis, including the one in this paper, needs to be con-
759 sidered “conditional on the data”, and given the issues indicated, extrapolation
760 of the results of summary studies to larger scales and into global hydrological
761 models has to be done with great care. Better would be to analyze observed
762 data and explicitly include uncertainty in the extrapolation of the results.

763 This therefore has implications for the recent growth in meta-analysis review
764 papers, which has been boosted by increased computational capacity and much
765 better on-line accessible data bases with research data. Clearly, this requires
766 careful definition of the search terms, and follow-up review of the harvested
767 papers, as well as an understanding that the statistical relationships can be
768 hiding other unknown factors. As the old adagium says: Correlation is not the
769 same as causation.

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