

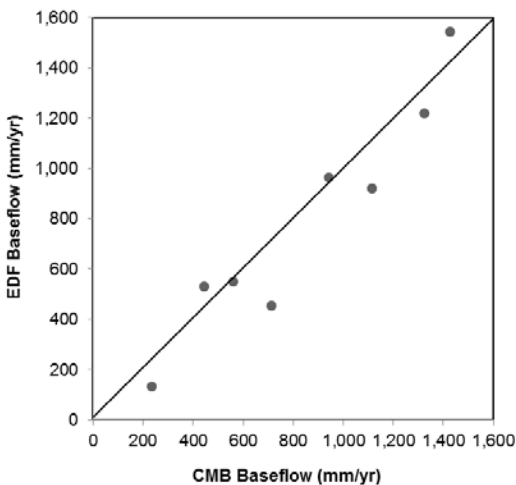
## **Review #1: J. Buttle**

Thank you for your general comments about the papers, and in particular for the detailed review of the paper in your supplementary material. We agree with nearly all of the edits suggested there, and have updated the paper based on your edits to reflect this.

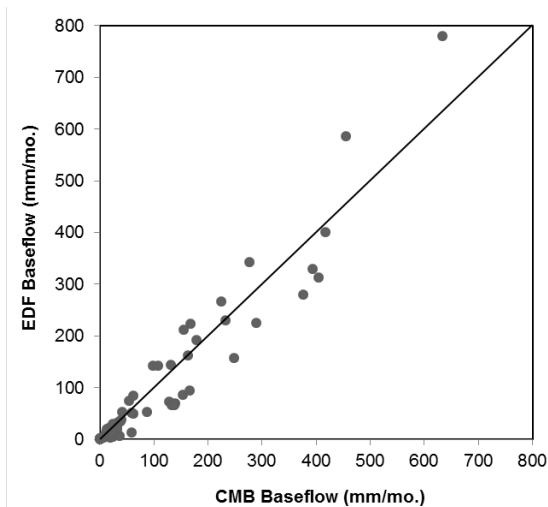
With respect to the specific comments, please see the following for our responses:

1. **12234/24-25:** *“present the results of the conductivity mass-balance work that were used to support the baseflow values obtained by the digital filter approach (a Figure plotting one vs. the other for the 2001-2009 period might suffice).”*

Below is a figure plotting the values from the two methods, the y-axis is the output from the Eckhardt digital filter (EDF Baseflow) and the x-axis is the Conductivity Mass-Balance (CMB Baseflow). The overlain black line is the one-to-one line. Both the annual and the monthly correlations were very high, with values of 0.958 and 0.956 respectively.

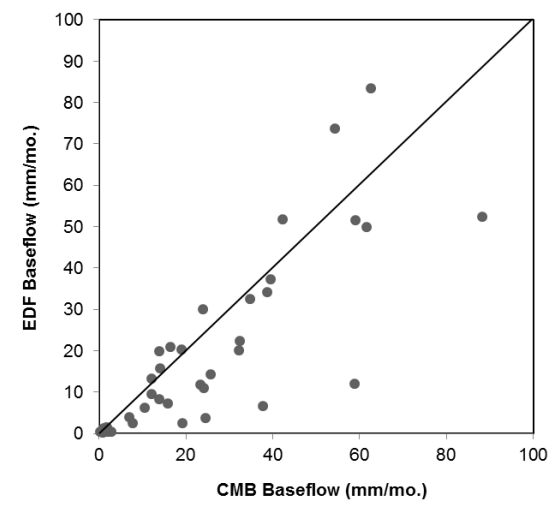


**Figure 1. Annual plot of CMB and EDF baseflow calculations methods, with an  $R^2 = 0.958$**



**Figure 2. Monthly plot of CMB and EDF baseflow calculations methods, with an  $R^2 = 0.956$**

In the monthly plot, there are a large number of months where the values were less than 100 mm, which are difficult to visualize in the plot including all data points. The plot below includes only the months where both values were less than 100 mm, to better show the relationship during drier months.



**Figure 3. Monthly plot of CMB and EDF baseflow calculations methods during months with less than 100 mm precipitation, with an  $r^2 = 0.83$ .**

This plot reveals that there is a greater difference in the estimates during the drier months (as compared to all months) although the Pearson's correlation coefficient of 0.83 still indicates a high level of correlation. As can be seen in the plot, the reduced correlation appears to be primarily due the higher estimates produced by the CMB method.

We are not certain what may account for these higher estimates with the CMB, as this aspect of the BFI estimates was not explored in depth (which is outside the objective of the study). However, a potential explanation could relate to the findings of Cartwright et al. (2014), which found over estimation from baseflow estimated by the chemical mass balance method during the early stages of high-discharge

events, that they attribute to the flushing of saline (and therefore more chemically similar) water at the start of an event. A similar flushing impact could account for the higher estimates here, although this is speculative, and may be accounted for by another factor. The current study did not find systematically higher annual estimations from the EDF method, which contrasts with the findings of Cartwright et al. (2014). This may indicate that there are different dominant hydrologic factors at work between the two sites, and given the differences in the characteristics of the sites, it is likely that there are less transient sources of water in the Agueda watershed when compared to the Cartwright study.

**2. 12239/8-9:** *“What are the actual values of tree densities in the plantations?”*

Based on (unpublished) forest plot assessments conducted in the study watershed, the average tree density values are:

- Eucalypt, unevenly spaced (<15 yrs old): 1,600 trees/ha
- Eucalypt, evenly spaced, terraces (<5 years old): 1,500 trees/ha
- Eucalypt, flat terrain (<5 yrs old): 2,600 trees/ha
- Pines, unevenly spaced (<30 yrs old): 500 trees/ha

**3. 12240/12:** *“In addition to more baseflow, baseflow comprised a larger fraction of total runoff.”*

Edits were made to the text to reflect the increase in the proportion of baseflow.

**4. 12241/6-10:** *“The authors could test this hypothesis (that soil hydrophobicity was responsible for the reduction in baseflow) by conducting a quickflow separation (using the Hewlett and Hibbert relation, or a similar separation method), and examining whether there has been any change in the number and magnitude of quickflow events and the ratio of quickflow to precipitation.”*

Using a quick-flow separation method such as the Hewlett and Hibbert relation would represent an alternative approach for assessing changes in streamflow characteristics in the study watershed. However, given that such methods are also based on division of the hydrograph data (similar to the baseflow separation we have applied), we are uncertain how this could be used to test the SWR hypothesis.

The findings of this study are interesting to consider with respect to the four key factors Hewlett and Hibbert’s list as driving the separation of quick and slow flow (McDonnell, 2009). Of the four, the average soil mantle depth or depth to a relatively impermeable layer is considered the most critical, followed by slope, and then the frequency / intensity of precipitation events. The fourth factor is land-use, which they consider to be superimposed on the effects of the other factors.

In the Agueda watershed, the first three of these factors can be considered to be relatively stable over the 75 year test period, while the fourth (land-cover) has changed substantially. Based on these factors, a corresponding change in the quick / slow flow proportion of streamflow would therefore be reasonable to expect. We see this impact in our baseflow trend analysis during the Eucalypt afforestation period, which

we attribute to the changes in soil properties (i.e. SWR) induced by Eucalypts (as observed in the SWR field tests conducted in the study watershed).

5. **12241/12-14:** *“Should the order of this argument be reversed? I would have thought that a delay in breaking soil water repellency would lead to a longer recovery of soil moisture levels, since water would continue to move laterally over the surface of hydrophobic soils.”*

This is a good point, as the two processes reinforce each other (i.e. a delay in soil wetting will lead to a delay in breaking SWR, which will make soil wetting more difficult). However, plot studies in this watershed have shown that high SWR does not entirely prevent soil wetting, as not all rainfall is converted to overland flow, regardless of how repellent the soil is. This is particularly important during large frontal storm systems, with persistent rainfall occurring over days or weeks, which will increase the soil moisture regardless of high SWR. Therefore, overall SWR is more dependent on soil moisture levels remaining low, than soil moisture levels are kept low due to SWR. However, we have modified the text to better explain the connection between these processes.

6. **Table 2:** *“Include baseflow amounts.”*

This has been added.

7. **Figure 6:** *“This should also include the baseflow quantity data and trend results.”*

Figure 6 is not intended to show all of the results, but only those that are most relevant for the discussion of the main findings. The full results from all variables, test periods, and trends are included in the supplementary material. We decided to present the results in this manner to keep the amount of material more manageable for the reader, as the full results provide a lot of data which unnecessary for understanding the key findings of the study.

## **References**

Cartwright, I., Gilfedder, B., and Hofmann, H. (2014). Contrasts between estimates of baseflow help discern multiple sources of water contributing to rivers. *Hydrol. Earth Syst. Sci.* 18, 15–30.

McDonnell, J.J. (2009). Hewlett, J.D. and Hibbert, A.R. 1967: Factors affecting the response of small watersheds to precipitation in humid areas. In Sopper, W.E. and Lull, H.W., editors, *Forest hydrology*, New York: Pergamon Press, 275--90. *Progress in Physical Geography* 33, 288–293.

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## **Review #2**

Thank you for your detailed and thoughtful review of the paper. Please see our response to your specific comments below.

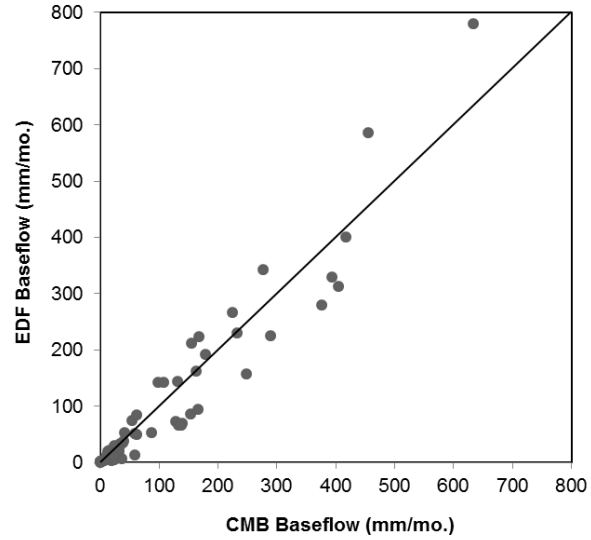
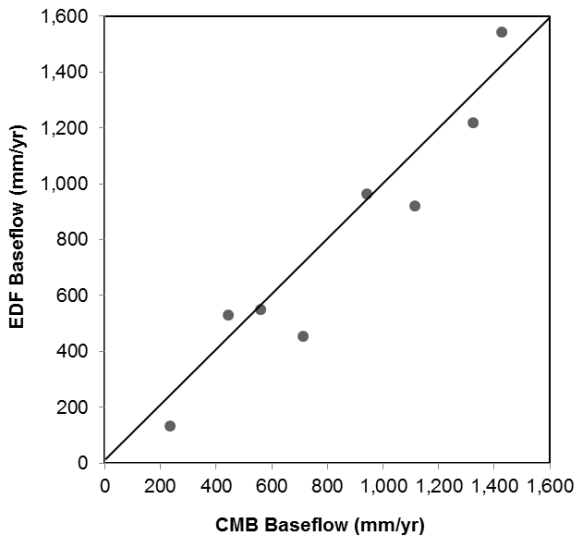
1. *“The authors adopted the ratio of annual runoff to annual precipitation to do this. However, this is a crude approach because any change in precipitation/runoff relationship will occur at a much shorter time-step and the effect will be largely masked at an annual level. Therefore, for the study to provide credible results, I would have expected the effect of precipitation on runoff to be removed in a more credible way.”*

We agree that changes in the rainfall-runoff ratio can be masked at the annual time scale, and indeed this ratio was also tested over 4-month periods (the “seasonal” test periods). These periods were selected to reflect the seasonal dynamic of the watershed, which should better reflect the shorter time-periods where the runoff ratio may have changed. Monthly time periods were considered in the preliminary analysis as well, however due to the temporal lag between precipitation events and streamflow response the ratios did not have much utility (i.e. many months had more streamflow than precipitation, due to the carry-over from the previous month). Therefore, we selected the 4-month periods for analysis as a temporal period which is long enough to provide stable precipitation/streamflow ratios, while being able to capture sub-annual streamflow dynamics.

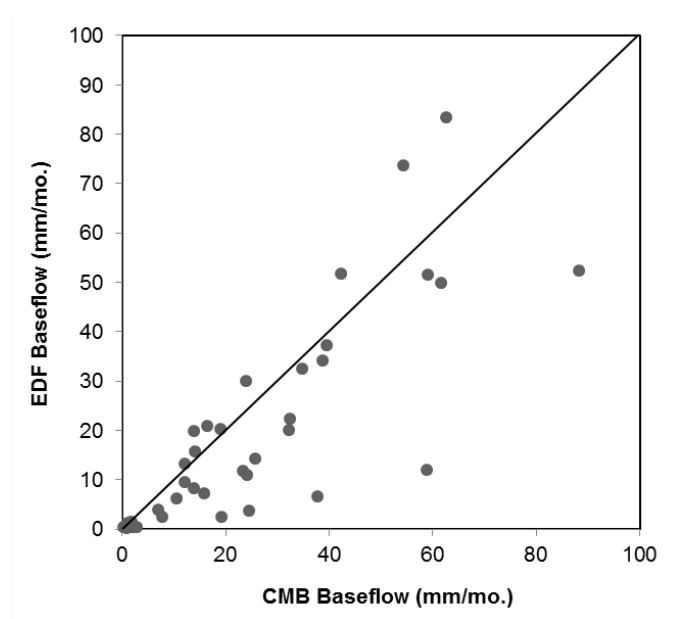
2. *“The interpretation of the baseflow trends needs further consideration. A recent paper in HESS by Cartright et al. (2014) is pertinent. For the watershed analysed by Cartright et al., they showed that estimates of baseflow from the local minimum and recursive digital filters (including the Eckhardt filter adopted by the authors) are higher than those based on chemical mass balance using Cl calculated from continuous electrical conductivity measurements. This suggests that baseflow computed using a digital filter is made up of local riparian groundwater (including bank storage) that has a short storage delay time plus the more regionally based groundwater with a much longer storage delay time. The interplay between these two baseflow components may explain some of the features of the BFI trends observed in Figure 6. I would suggest the authors examine this aspect in relation to the Agueda watershed.”*

Thank you for the reference to the Cartright paper; this is an interesting comparison of the different methods of estimating baseflow. As indicated by the paper, it is possible that the recursive digital filter method provides an over-estimate of baseflow, due to the aggregation of different sources of delayed flow.

To assess this over there period where we have data for both sources, figures 1 - 3 can be considered, where the y-axis is the output from the Eckhardt digital filter (EDF Baseflow) and the x-axis is the Conductivity Mass-Balance (CMB Baseflow). The overlain black line is the one-to-one line. For the annual time scale the correlation 0.958 (figure 1), the monthly was 0.956 (figure 2).



In the monthly plot there are a large number of months where the values were less than 100 mm, which are difficult to visualize in the first plot. Figure 3 includes only the months where both values were less than 100 mm, to better show the relationship during drier months.



This plot reveals that there is a greater difference in the estimates during the drier months (as compared to all months) although the Pearson's correlation coefficient of 0.83 still indicates a high level of correlation. As can be seen in the plot, the reduced correlation appears to be primarily due the higher estimates produced by the CMB method.

We are not certain what may account for these higher estimates with the CMB, as this aspect of the BFI estimates was not explored in depth (which is outside the objective of the study). However, a potential explanation could relate to the findings of Cartwright et al. (2014), which found over estimation from baseflow estimated by the chemical mass balance method during the early stages of high-discharge

events, which they attribute to the flushing of saline (and therefore more chemically similar) water at the start of an event. A similar flushing impact could account for some of the higher estimates here, although this is speculative, and may be accounted for by another factor which the authors are not aware of. The current study also did not find systematically higher annual estimations from the EDF method, which contrasts with the findings of Cartwright et al. (2014). This may indicate that there are different dominant hydrologic factors at work between the two sites, notably that there may be less transient sources of water in the Águeda watershed when compared to the Cartwright study.

These figures do indicate that there is a difference between the BFI estimates of the two methods, and there are indications of a positive bias of the CMB method during low months, and from this analysis, we cannot assess which method provides a more accurate estimate of BFI.

However, for the purposes of this study, the accuracy of the method of estimating the BFI is a secondary consideration to the data availability to utilize an approach, and the stability of the estimations from the method selected. As the CMB data is only available for a short period of time, relative to the 75 year period being considered, it is not a viable method for conducting the trend tests needed for this study. By contrast, the EDF method provides a consistent method of estimating the baseflow across the entire 75 year period, since it is strictly based on the hydrograph data. Therefore, while a chemical mass balance approach (such as that tested by Cartright) may provide a more accurate baseflow ratio, there is no data available to support this method over the data period considered in this study.

**3. P12224, L6:** *I think 7 should read 70.*

This seems to have been a type-setting error. It should be 75 (1936 to 2010).

**4. P12226, Ls28 - 29:** *After “20%” add ‘of total rainfall’. Delete “of total rainfall” from the next line.*

Change made as suggested.

**5. P12226, L28 -12227, L6:** *These percentages are not useful unless the mean annual precipitation is provided for each case.*

We agree that providing the MAP would give greater context to these reported findings. This section was substantially updated, and now reads as:

“With respect to *Pinus pinaster*, Ferreira (1996) reported interception rates of 15-18 % in the Águeda watershed of north-central Portugal (the current study site, mean precipitation  $\approx$  1700 mm/yr), while Valente et al. (1997) found similar rates of 17 % in a drier region of central Portugal (mean precipitation  $\approx$  600 mm/yr). For *Eucalyptus globulus*, both Ferreira and Valente et al. (1997) observed lower rates, amounting to 10-14 % and 11 %, respectively. By contrast, much higher interception rates have been found for other tree species in different parts of the Mediterranean, with values near and even exceeding 50 %. For example, Scarascia-Mugnozza et al. (1988) found canopy interception rates of 68 % for a

mature *Quercus cerris* forest in central Italy (mean precipitation 1006 mm/yr), Iovino et al., (1998) found rates of 58 % for a mature *Pinus negra* forest in southern Italy (mean precipitation 1179 mm/yr), and Tarazona et al. (1996) observed rates of 48 % for a mature *Pinus sylvestris* forest in northern Spain (mean precipitation 895 mm/y, 1253 mm/yr during the study period).”

**6. P12228, Ls16-17:** Delete “analyzes” and add after Value ‘are analysed’.

Change made as suggested.

**7. P12230, L26:** “Corine Land Cover” requires an appropriate reference.

Citation added.

**8. P12233, L15:** “streamflow/precipitation”. Should this not be ‘annual streamflow/annual precipitation’.

These values are not necessarily annual since this actually refers to both the annual and the seasonal time periods. This drew attention that the “mm/yr” designation after the other values is not correct, because this also refers to the seasonal data. This section has been completely re-written as:

“Over the time periods shown in Fig. 4, the trend testing was conducted for over both annual and seasonal time periods. The seasonal breakdown selected corresponds with the prevailing precipitation patterns of the study site, which consists of: the “Wet Season” from October to January when the largest amount of precipitation occurs, the “Transitional Season” from February to May when precipitation rates are reduced, and the “Dry Season” from June to September when precipitation is lowest. Due to gaps in the streamflow record (discussed in section 2.2), six years of data were unavailable for the trend testing at the annual and seasonal time periods the hydrologic years 1999/2000 through 2002/03, and the hydrologic years 1954/55 and 1975/76 were unavailable for the annual and transitional season. In addition, the trend tests were not conducted during the “Dry Period” for streamflow (and therefore also baseflow), due to the uncertain data quality during these months.”

**9. P12238, L5:** Reword – replace “well below” with ‘less than’.

Change made as suggested.

**10. P12238, Ls15-23:** It would be helpful if the authors had compared their results with those from similar catchments elsewhere. There are approximately 190 separate land use impact studies reported in Bosch & Hewlett (1982), Brown et al. (2005) and Farley et al. (2005). It is likely that



*some of these would be from catchments that have similar climate and physical features as in the Agueda watershed.*

This is a good suggestion, and would help to put the findings of this study into a broader context. We have looked over the land-use impact meta-analysis studies for cases with similar climate and physical features to the Agueda watershed, and this section has been substantially re-written to reflect this.

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## **Review #3**

### **General comments**

1. *“the paper examines trends in precipitation and streamflow variables separately but the key question is really has the catchment response changed. It is well known that there is a strong relationship between rainfall and runoff at the annual timescale, so the question of the paper should really be expressed as “has the rainfall-runoff relationship changed?” I think the authors should analyse this relationship in addition to the analyses they have conducted as this relationship captures the effect of internal catchment dynamics. As an illustration of this issue, there is a positive trend in streamflow from 1946-1970 that corresponds to an almost significant ( $p$  value = 0.11) positive trend in rainfall for the same period. The streamflow increase may just reflect a rainfall increase, rather than any internal change in the catchment. Looking at the rainfall-runoff relationship would help by controlling for rainfall changes.”*

In this study, we have used the term ‘streamflow quantity’ to define the total amount of streamflow (the depth), and ‘streamflow yield’ to define the ratio of streamflow to precipitation. In the literature, the terms streamflow and runoff are frequently used interchangeably, however we decided to use the term streamflow rather than runoff to avoid confusion with the process of surface runoff (i.e. overland flow). To better clarify the terms used and the variables tested in the study, the following text and table have been added to the manuscript:

“After the streamflow gaps were filled, the ratio of precipitation which becomes streamflow was calculated, to allow potential changes in the streamflow-precipitation relationship to be assessed. This ratio is defined in this study as the “streamflow yield” ( $Q_{yld}$ ), which is calculated by dividing total streamflow by total precipitation, with the period of summation determined by the period being considered (i.e. the annual or the seasonal ratio).”

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### **Hydrometeorological Variables**

<b>Variable</b>	<b>Description</b>	<b>Data Source</b>	<b>Unit</b>
P	Precipitation	SNIRH Gauge Data	mm
T	Temperature	IPMA Gauge Data	°C
PET	Potential Evapotranspiration	Thornthwaite Equation	mm
Q	Streamflow Quantity	SNIRH Gauge Data	mm
$Q_{yld}$	Streamflow Yield	$\sum Q_{mm} / \sum P$	%
BF	Baseflow Quantity	Recursive Digital Filter	mm
BFI	Baseflow Index	$\sum BF_{mm} / \sum Q_{mm}$	%

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2. *“there is little consideration of the overall water balance setting and some contradictions are implied in what is presented. Table 2 and Section 3.2 imply the long-term evapotranspiration is about 1180mm/a. While the potential evapotranspiration (PET) is not provided, this would seem to be a large fraction of the PET, suggesting little constraint on soil water availability. However the soils are said to be very shallow and there is little rain in summer when PET is high, so there should be a substantial effect of soil water stress. These two things seem hard to reconcile and currently detract from the overall confidence in the results and the hydrologic interpretations. I think a more thorough discussion of the hydrological setting and water balance is needed, including (but by no means limited to) presentation of PET information.”*

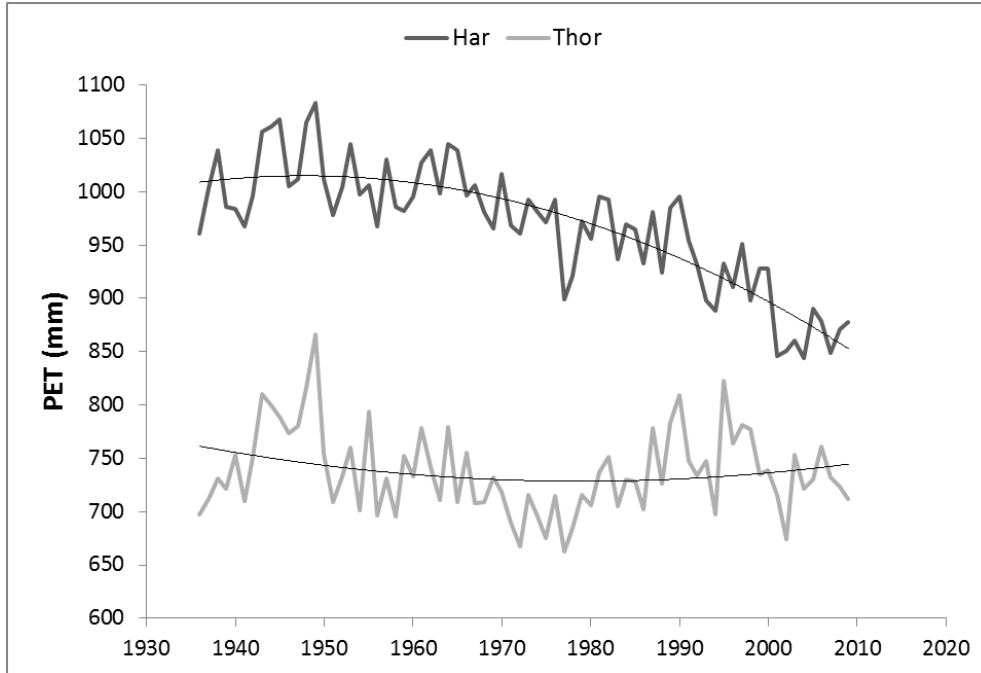
The main issue to consider with respect to the water balance is that the data used in this study was selected on the basis of their long term consistency, rather than their suitability for reconciling the water balance. To clarify this decision, some background on the precipitation and potential evapotranspiration data we have used is worth discussing.

First, the rainfall gauge we have used for this study (Campia) is located in the uplands of the Agueda watershed, and given its relative high elevation within the watershed, it is a high estimate for watershed scale precipitation. Regardless, this gauge was the only option available for the trend testing, since it is the only gauge with a data record as far back as the streamflow gauge data. But while the amount of precipitation recorded by Campia is not representative of the overall watershed, we are confident that it is capturing most rainfall events, given its good correlations with the nearby gauges of Varzielas” ( $r^2 = 0.82$ ) and “Barragem de Castelo Burgães ( $r^2 = 0.79$ ). To get an idea of a more representative value, a co-author on the current study is conducting an eco-hydrological modeling study in the same site, which is using spatially distributed watershed-scale precipitation values in the range of 1,200 to 1,400 mm per year over the period of 1980 - 2000 (the current study is 1,787).

With respect to PET, we have made estimates across the same data record, and included it into the trend testing and summary statistic. However, we were very limited on which methods we could use for estimating PET, as there was no way to meet the data requirements Penman–Monteith over the entire data record, and there are severe problems with the values estimated by the Hargreaves equation. The problem with the Hargreaves estimates is due to its sensitivity to the difference between maximum and minimum temperature. These measures are not consistent over the long-term in our watershed, both because the methods used to measure them have changed over time, and that the regressions needed to fill gaps are less reliable than for average temperature. We therefore utilized the Thornthwaite equation, which only needs average temperature, as we have much more confidence in the consistency of these values across the data record.

However, when we compare the PET calculations over the data record, we see that the Thornthwaite values are far lower than Hargreaves across the entire record (see figure below). The sharp downward trend in Hargreaves values shows the temporal inconsistency of this method, as we are confident that this trend is a data artifact, rather than a true trend. This is because: the known data issues previously

mentioned, that this trend has not been reported in any previous climate assessments (and would be difficult to miss), and that the pattern in our Thornthwaite output matches well with the findings from the SIAM 2 climate report (a benchmark climate study in Portugal). Therefore, the Thornthwaite values are our only option for the trend-testing, despite that the values appear to be far too low. To give an idea of a more reasonable range of PET values, the previously mentioned modeling study has found values in the range of 900 - 1,200 mm per year (the current study is 732 mm/yr).



So if we consider the median values in the study watershed, it is indeed difficult to reconcile a reasonable water balance (see table below, which includes the PET data).

Median Values: 1936 - 2010								
Season	Months	P (mm)	T (°C)	PET (mm)	Q (mm)	Q <sub>yld</sub> (%)	BF (mm)	BFI (%)
Wet	Oct - Jan	965	11.7	145	301	30 %	149	55 %
Transitional	Feb - May	626	12.6	198	281	43 %	184	63 %
Dry	Jun - Sep	193	19.3	390	NA	NA	NA	NA
Annual	All*	1 787	14.7	732	565	36 %	320	59 %

However, to compare the values in this study against the current modeling work, the table below shows the annual study values, and the different high and low end values of P and PET in the modeling study being undertaken (Q is set to 600 to compensate for the missing dry season flows). When the values

which are more watershed-scale representative are used, the ratio of ET to PET is in the range of 50% - 89%, which is much more realistic than the number that can be concluded from the current study.

<b>Scenario</b>	<b>P</b>	<b>Q</b>	<b>ET</b>	<b>PET</b>	<b>ET / PET</b>
<b>Study Values</b>	1787	600	1187	732	<b>162%</b>
<b>Low P, Low PET</b>	1200	600	600	900	<b>67%</b>
<b>Low P, High PET</b>	1200	600	600	1200	<b>50%</b>
<b>High P, High PET</b>	1400	600	800	1200	<b>67%</b>
<b>High P, Low PET</b>	1400	600	800	900	<b>89%</b>

Therefore, while the long-term values we have in this study are not suitable for calculating a realistic water balance, we are confident in their reliability for the purposes of this study (long-term trend testing). This issue was not addressed in the current paper, as we found this added too much further detail to the study without assisting in the interpretation of the findings. The issue of water balance in Agueda will instead be dealt with in the upcoming modeling paper (to be submitted to Geoderma).

3. *“the paper has a major problem in the application of the statistical testing. Only 9% of the 240 tests conducted were significant. A 95% confidence level was used, hence you expect at least 5% of the tests to be significant. That is, more than half the positive results might be due to chance alone. The methodology needs to control for multiple testing using Bonforoni corrections or a more sophisticated method such as the False Discovery Ratio approach of Benjamini and Hochberg (1995).”*

The lack of correction for the FCR was a definite oversight in the original trend-testing approach. To address this, we have applied the Benjamini–Hochberg–Yekutieli procedure, and updated the results of the study to reflect this.

The following text was added to the methodology to explain the procedure:

“When conducting multiple simultaneous hypothesis tests, it is also necessary to correct for the false discovery rate (FDR) due to multiple comparisons. FDR corresponds to the expected proportion of incorrectly rejected null hypotheses, and therefore a method is needed to reduce the chance of receiving false-positive results (i.e. type I error). A number of different methods can be applied to control for FDR, however given the overlapping time periods examined in this study, a method is needed which can deal with FDR under the assumption of positive dependence. Therefore, the Benjamini–Hochberg–Yekutieli procedure was applied to the trend-testing output from each individual ‘analysis set’ (Benjamini and Yekutieli, 2001). An analysis set corresponds to a group of tests which are expected to exhibit mutual positive dependence, which is the case for the 12 overlapping test periods over which each hydrometeorological variable was tested for the different annual and seasonal periods (i.e. the periods in figure 4).”

### Specific comments

4. *“The term “streamflow yield” is used throughout the paper for “runoff coefficient”. Generally streamflow yield refers to runoff depth (what the authors refer to as runoff quantity). I would suggest using “runoff coefficient”.”*

Please see the response to the first general comment.

5. *“In the abstract give some indication of the pattern of landuse change over time.”*

The abstract has been substantially changed, and now provides more specific information on the LC-change.

6. **12226, L 3-8.** *Very long sentence. Break it up.*

This section been largely re-written, and should be more clear.

7. **12228, L10-15.** *“This gave me the impression little was known of the patterns of change over time but later more detail is given. Also could a better record be constructed from 1974 onwards via Landsat images?”*

The details provided later in the manuscript describe the general pattern of land-cover change for the North-Central region as a whole. However, within the study watershed itself, there is not enough detailed past (from existing maps, planning documents, etc.) to know the past land-cover with much spatial or temporal accuracy. Using Landsat to create historical land-use/cover maps for the post-1974 period is an interesting idea, and one that we have considered as well. However, even with creation of these maps a gap of 38 years (1936 to 1974) would remain, during which no spatial data is available. Post-1974 maps may be created in this watershed for further hydrologic modeling work which is planned at this site; however this data was not necessary for the approach used in the current study (although if available would be a good complimentary data source).

8. **12229, L14.** *“What are the typical depths of the “shallow” soils.”*

A bit more information was added here: “Topographically, the landscape is dominated by steep hill-slopes with stony and shallow soils (<0.5m), which have a long history of anthropogenic impacts. These shallow soil were characterized by Ferreira et al. (2000) as stony, sandy Loam, weakly structured Umbric Leptosols.”

9. **12229, L19.** *“Say what the “natural” vegetation types are here.”*

This sentence now specifies that this refers to Matos shrublands and mixed forests.

**10. 12230.** *“There is an extensive literature on fire effects from California, Australia, and Mediterranean countries. It might be worth providing a brief summary in the introduction and drawing on the broader literature.”*

While the hydrologic impact of fire is an important topic in Mediterranean regions, the current study is more concerned with the long-term impacts of wildfire as a driver of land-cover change. Therefore, we have re-ordered the section indicated to better reflect our emphasis, and added a reference to Shakesby (2011) for a review of (short-term) fire impacts in the Mediterranean. This section now reads as:

“Wildfire is another important factor in land cover/use change in Portugal, which has some of the highest rates of wildfire in Europe. Figure 3 shows the burned area of the Águeda watershed from 1975 to 2010, during which a total of 30 790 hectares burned, with some single years having wildfire over more than 10 % of the watershed (i.e. 1986 and 1995; Instituto da Conservação da Natureza e das Florestas, 2014). Wildfire can have significant short-term impacts on hydrologic functions, such as decreased infiltration and increased surface runoff / erosion (Shakesby, 2011). In addition to these short-term impacts, wildfire can have potential long-term impacts by resulting in changes in vegetation type. Wildfire has been a major driver of land-cover change in north-central Portugal in this respect, by promoting land-owners to convert from pine to eucalyptus plantations in the post-fire period.”

Shakesby, R. A.: Post-wildfire soil erosion in the Mediterranean: Review and future research directions, *Earth-Science Reviews*, 105(3–4), 71–100, doi:10.1016/j.earscirev.2011.01.001, 2011.

**11. 12231, L10.** *“Has the consistency of the rainfall record been checked, e.g. by double mass curve analysis?”*

The recording agency (SNIRH) provides a rating of the reliability of the data (in a range between 5 and 15), which is generated from double mass curve analysis and other tests as well. For the Campia rainfall data the value given is “14”, which is ranked as “highly reliable”.

The text regarding the precipitation data has been updated to include this: “The SNIRH provides a reliability ranking for the data in the range of 5 – 15, for which Campia is ranked “14, highly reliable”.”

**12. 12231, L23.** *“What was done when <5% was missing but the logarithmic decay wasn’t used?”*

To clarify this, the text was modified to the following:

“In addition, a number of smaller streamflow gaps occurred throughout the daily streamflow dataset. When they occurred during periods with little or no precipitation, the gaps were filled by fitting a logarithmic decay curve to the streamflow recession. If gaps occurred during a precipitation event, then this approach was not applied and the gaps were left in the data record. If the number of gaps was greater

than 5 % of the record, then the entire period was removed from analysis, which was the case for the years 1954/55 and 1975/76.”

### **Technical corrections**

**13. 12224, L6.** *70 years not 7 years*

This has been corrected to 75 years (1936 – 2010).

**14. 12230, L25.** *Should be “....in the Águeda....”*

Change made.

**15. 12231, L22.** *Not clear what logarithmic means – do you mean traditional linear reservoir i.e. fitting on a semi-log plot?*

We used traditional linear reservoir with a semi-log fitting, which we have added in brackets to specify: “When they occurred during periods with little or no precipitation, the gaps were filled by fitting a logarithmic decay curve (traditional linear reservoir with a semi-log fitting) to the streamflow recession.”

**16. 12234, L22.** *Change to “..... results obtained....”*

Change made.

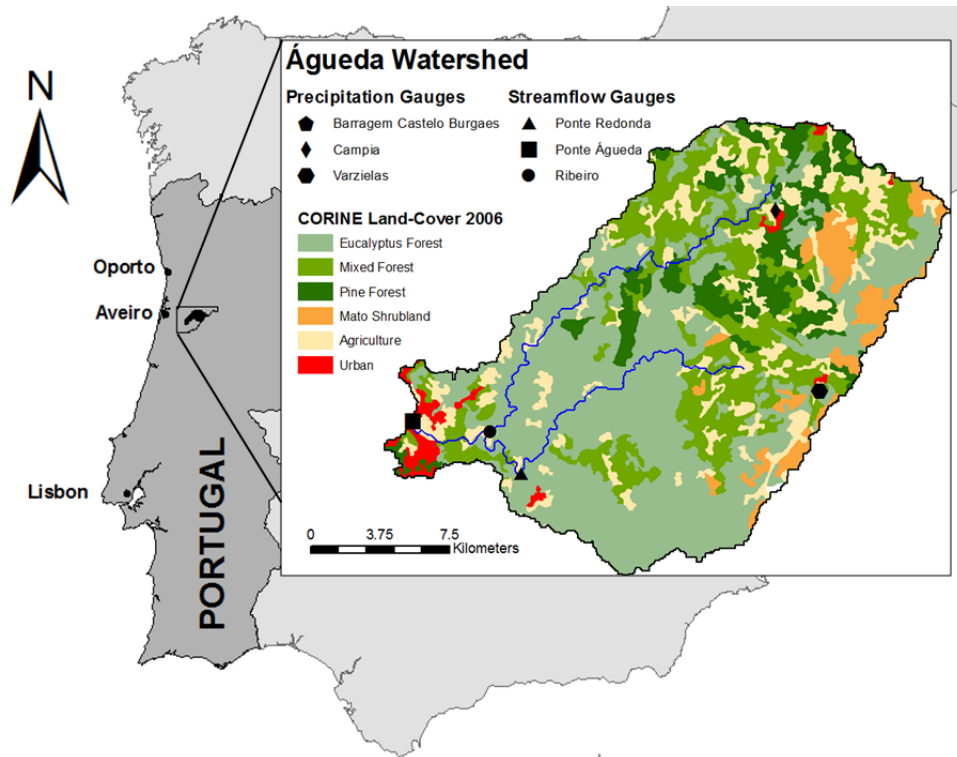
**17. 12240, L26.** *Change “expectedly” to “expected”*

Change made.

**18. Figure 1.** *The colours can't all be differentiated. This needs improvement.*

The watershed map has been simplified and focused on the land cover/use relevant to the study. Please see the new map below.





19. Figure 3. The y-axis labels are reversed.

Fix made.

## **Review #4**

### **General comments**

1. *'I don't think that the posed research question (afforestation impacts on hydrology) is answered clearly, let alone directly, by the presented results. Instead, the paper used many lines of arguments and hypotheses to indirectly attribute decreasing trends in baseflow variables to that in precipitation, while no-trends in streamflow were explained by a seemingly stretched logic of soil-water repellency. At the end, the stretched deductive reasoning (eliminating possible causes step-by-step) provided conclusions, which may or may not be true. Therefore, the findings presented in this study are largely conjectural, rather than being inferential in nature.'*

We believe that this study work does provide clear results on the topic of afforestation impacts on hydrology. With respect to streamflow, there is a clear lack of a significant effect, and given that this finding does not agree with the general finding of afforestation studies, we propose a plausible explanation (based on the watershed characteristic and the “prerequisite conditions” proposed by Andréassian ).

With respect to the observed trends in baseflow, we have proposed an explanation based on the known historical land-cover/uses, combined with knowledge from field observations conducted in the watershed. And while the argument is necessarily speculative, given that we cannot confirm this hypothesis with past field data, we feel that providing a plausible explanation has value in pointing towards further research direction which could test this hypothesis (e.g. paired-catchment study with explicit measurement of evaporation, sap flow or eddy cov).

However, we agree that these lines of argument were not stated clearly enough in the text, and there were too many side-lines of argument that made the interpretation difficult. To address this, we have substantially reworked the discussion section to make it more clear and direct, and focus on the main argument.

2. *The overall trends in the hydrologic variables are likely to be the combined outcomes of the long-term changes in both climatic and land use/cover regimes. The authors acknowledge this for baseflow variables in the discussion. However, although the authors state in the Introduction that the eucalyptus is known to have a higher ET than that of pines, I am really surprised that the long-term trends in temperature (as a surrogate for ET) were not analyzed and synthesized with those of the flow variables. Instead, the authors sort of dismiss the possible trends in ET arguing that the plants' root zones are shallower than the water table depth!*

The lack of assessment of PET was a major oversight in the original manuscript, and we have conducted additional analysis to assess the long-term trends in PET, which is now integrated throughout the paper. The issue of rooting depth (and therefore water consumption capacity) has to do with the depth of the soils as a limiting factor, not the potential rooting depth of the plants (this point has been rewritten to clarify).

3. *The paper justifies the use of trend testing, compared to hydrologic modeling citing the lack of data and knowledge on the complexity in soil geomorphology over the entire study period. I have hard*

*time to accept this argument. I believe a well calibrated and validated model with current data can be used to answer the land use/cover impact question posed here by conducting a proper sensitivity analysis. I don't think that the trend testing approach needs to be justified as done in this paper. Instead, the data driven method can be justified as a complementary approach to the largely physically based watershed hydrologic modeling.*

The watershed certainly could be modeled with the available data for the more recent periods (currently underway by a co-author) or historically using a non-spatially explicit model. However, the type of long-term analysis of the historical data record which we were interested in examining could not be modeled without historical land cover maps, and this is being looked into as potential future work. However, the manuscript may be “over-justifying” the methodological approach selected, which does not add anything to the findings from the current paper. Both sections have been re-written, and the unnecessary modeling references have been removed.

### **Specific & Technical Comments**

**8. Abstract, line 6:** *“7 years of data” should be revised to “75 years: : :”*

Correction made.

**9. Section 2.3:** *The results of Mann-Kendall test could vary if there were too many missing data-years. Please state the number of missing data that you allowed for the different variables.*

The years where there were gaps is written in section 2.2, however to make it clear in this section, the following text was added to the end of section 2.3:

*“Due to gaps in the streamflow record (discussed in section 2.2), the hydrologic years 1999/2000 through 2002/03 were unavailable for the trend testing for both the annual and seasonal time periods, and the hydrologic years 1954/55 and 1975/76 were unavailable for the annual and transitional season.”*

**10. Page 12235, lines 21-23:** *Please include the negative (-) sign before the trend magnitudes.*

Negative signs added.

**11. Page 12236, lines 5-6:** *It is unclear what is meant by the first clause of this last sentence: “These results indicated that the trend in streamflow yield during this period was fairly consistent across the year..”. Most periods didn't show any significant trends; the one period that showed trend should have a single Theil-Sen slope value by default!*

When referring to the consistency across the year, this is referring to the values stated in the previous sentence (i.e. annual: +0.78 %/yr; wet season: +0.77 %/yr; transitional season: +0.74 %/yr). This is simply to point out that the annual trend was a product of a similar magnitude increase during both the wet and the transitional seasons. By contrast, most of the significant annual trends in baseflow were due to changes only in the wet season.

However, as this sentence is unclear and simply re-states the information in the previous sentence, it has been removed.

**12. Page 12236, line 17:** *Should be “wet” instead of “west”.*

Correction made.

**13. Page 12237, lines 9-11:** *The following sentence does not make sense: “This could have led to longer recovery times for soil moisture during the resumption of the wet season, which could have amplified soil water repellency during this period (both in terms of the duration and severity)”. Shouldn’t the logic be the other way around?*

A similar point was raised by reviewer #1. Our response is as follows:

“This is a good point, as the two processes are certainly self-reinforcing, i.e. that a delay in soil wetting would lead to a delay in breaking SWR which would lead to a delay in soil wetting. However, it is important to note that high SWR does not entirely prevent soil wetting, and that plot studies here have shown that only part of the rainfall is converted to overland flow, regardless of how repellent the soil is. This is particularly important during large frontal storm systems, with persistent rainfall occurring over days or weeks, which will increase the soil moisture regardless of high SWR. Therefore, soil moisture is likely less impacted by SWR than the breakdown of SWR is on the soil moisture levels. However, we have modified the text to better reflect that these processes are self-reinforcing.”

**14. Section 4.3: Except up to line 15 (page 12240),** *the entire section is about conjecture rather than inferences based on the presented results. It must be substantially revised by mainly focusing the inferences.*

**15. Page 12241, lines 8-10:** *The following clause does not make sense to me: “: : :leading to an increase in quick flow (particularly via fast sub-surface flow from macropore infiltration) and the rapid conversion of precipitation into runoff”*

**16. Page 12241, lines 11-12:** *The following sentence is incorrect, according to Fig. 6: “Notably, the significant reductions in BFI were confined to the wet period, with only one exception”*

**17. Page 12241, lines 11-23:** *The presented logic and the entire paragraph, starting with an inaccurate statement (line 11-12), do not make sense. Please substantially revise or remove.*

This entire section has been substantially rewritten and simplified.

**18. Page 12242, lines 23-26:** *The last sentence of this paragraph is vague. It does not contribute any new information, and should be removed.*

This sentence has been removed.

**19. Page 12243, lines 1-20:** *The entire paragraph is full of conjectures with grandiose statements that are not really supported by the presented results. I recommend that the authors rewrite this paragraph, if they really want to include a second paragraph in the Conclusions, by following the second half of their Abstract.*

The conclusion has been substantially rewritten to focus on the presented results.

**20.** *Although the Table 2 presents statistics of observations for the dry months (June- Sept), the corresponding hydro-climatic trends were not presented due to unreliable data. This may confuse some readers.*

The data during the dry months was only unreliable with respect to streamflow (due to the variable impoundments), and therefore in table 2 these values are listed as NA. By contrast, there were no issues with the precipitation or temperature data during this period, so they were left in. We do see how it may be confusing to the reader that this information is included, while the streamflow / baseflow information is not. However, we decided it was worth keeping this data in the table to illustrate the seasonal characteristics of the watershed to the reader.

# Time-Series Analysis of the Long-Term Hydrologic Impacts of Afforestation in the Águeda Watershed of North-Central Portugal

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## Abstract

The north-central region of Portugal has undergone significant ~~afforestation~~land-cover change since the early 1900s, with large-scale replacement of ~~the species~~natural vegetation types with plantation forests. This transition consisted of an initial conversion primarily to *Pinus pinaster* and, followed by a secondary transition to *Eucalyptus globulus* ~~since the early 1900s;~~ however, ~~the long-term~~. This land-cover change is likely to have altered the hydrologic functioning of this region; however these potential impacts ~~of this land cover change~~ are not fully understood. To contribute to a better understanding of the potential hydrologic impacts of this land cover change, this study examines the temporal trends in 75 years of data from the Águeda watershed (part of the Vouga Basin) over the period of 1936 to 2010. ~~Meteorological and hydrological records were analysed~~A number of hydrometeorological variables were analyzed using a combined Thiel-Sen / Mann-Kendall trend testing approach, to assess the magnitude and significance of patterns in the observed data. These trend tests indicated that there ~~had~~have been no significant ~~reduction~~reductions in streamflow ~~yield~~ over either the entire test period, or during sub-record periods, despite the large-scale afforestation which ~~had taken place~~has occurred. This lack of change in streamflow is attributed to both the specific characteristics of the watershed and ~~the nature of the~~ land cover change. By contrast, a

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number of significant trends were found for baseflow index, ~~which showed with~~ positive trends in the early data record (primarily during *Pinus pinaster* afforestation), followed by a ~~reversal to~~ negative trends later in the data record (primarily during *Eucalyptus globulus* afforestation). These ~~changes trends~~ are attributed to land-use and vegetation impacts on streamflow generating processes, both due to ~~the~~ species differences and to alterations in soil properties (i.e. ~~promoting infiltration capacity. soil~~ water repellency ~~of the topsoil~~). These results highlight the importance of considering both vegetation types/dynamics and watershed characteristic when assessing hydrologic impacts, in particular with respect to soil properties.

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## 1 Introduction

Water resource management is inherently tied to watershed-scale land ~~use and land cover~~ dynamics, and proper management requires understanding how changes in land cover/use will impact hydrological processes (~~Calder, 2005~~); (Calder, 2005). A key land cover type ~~in this respect~~ are forests, as changes in forest cover have the potential to significantly affect watershed-scale hydrologic processes, particularly by altering interception, evaporation, and streamflow ~~and water availability~~. Changes in water availability due to afforestation/deforestation are driven by several factors controlling the water consumption of different vegetation species, in particular, canopy interception and evapotranspiration rates, which are typically higher in tree species than in shrub and herbaceous species (~~Calder, 1998~~); (Calder, 1998).

~~Meta-analyses of paired catchments studies have found that deforestation typically leads to an increase in streamflow and that afforestation results in a decrease water availability (e.g. Bosch and Hewlett, 1982; Brown et al., 2005). In a global synthesis of afforestation studies, Farley et al. (2005) found that afforestation of grasslands or shrublands will lead, on average, to reductions of one third to two thirds of streamflow, with these reductions occurring rapidly after planting (i.e. within the first 5 years) and reaching their maximum between 15 to 20 years. Overall, however, the hydrologic response to afforestation is less consistent than the response to deforestation; this has been attributed to the greater variability in land cover after afforestation than following deforestation (i.e. the effects of transitional species and/or changes in forest physiology; Andréassian, 2004).~~

~~Changes in forest cover can also modify hydrologic flow pathways by altering physical soil conditions (i.e. macroporosity) and forested areas tend to have higher infiltration rates, and~~

1 ~~hence groundwater recharge rates, than alternate land cover types (e.g. Bruijnzeel, 2004).~~  
2 ~~Higher infiltration rates can help maintain baseflow during dry periods (e.g. Scott and Lesch,~~  
3 ~~1997) and may also help mitigate storm driven peak flows. However, this flood mitigation~~  
4 ~~impact has been shown to be variable and can be over-ridden by other physical watershed~~  
5 ~~characteristics during large flood events (Calder, 2005; Wahren et al., 2012).~~

6 Meta-analyses of paired catchments studies have found that afforestation typically results in  
7 decreased streamflow while deforestation typically leads to increased streamflow (e.g. Bosch  
8 and Hewlett, 1982; Brown et al., 2005). However, the hydrologic response to deforestation is  
9 in general more consistent than the response to afforestation. This difference may be due to  
10 higher variability in land cover following afforestation compared to deforestation, and the  
11 effects of different transitional species and/or changes in forest physiology (Andréassian,  
12 2004). In a global synthesis of afforestation studies, Farley et al., (2005) found that  
13 afforestation of grasslands or shrublands will lead, on average, to reductions of one-third to  
14 two-thirds of streamflow, with these reductions occurring rapidly after planting (i.e. within  
15 the first 5 years) and reaching their maximum reduction 15 to 20 years following planting.

16 Changes in forest cover can also impact hydrologic processes by altering physical soil  
17 conditions, for example by reducing soil bulk density, increasing macro-porosity, or changing  
18 soil water repellency. Forested areas tend to have higher infiltration and groundwater recharge  
19 rates than alternate land cover types (e.g. Bruijnzeel, 2004). Higher infiltration rates will  
20 increase soil moisture levels, and therefore increase water availability as well as streamflow  
21 during dry periods (e.g. Scott and Lesch, 1997). The increased infiltration capacity of forested  
22 areas may also help mitigate storm-driven peak flows, and therefore reduce potential flood  
23 damage; however, this effect may be subordinate to other watershed characteristics,  
24 particularly during severe flooding events (Calder, 2005; Wahren et al., 2012).

25 While the ~~general~~ hydrologic impacts of forests at the watershed scale are ~~fairly~~generally well  
26 understood, predicting the effects of ~~a~~ forest land ~~cover~~ change for a ~~given~~specific watershed  
27 requires consideration of both ~~the~~ physical site conditions and ~~the specific~~ vegetation types  
28 involved. In this respect, ~~Andréassian (2004)~~Andréassian (2004) identifiedidentifies several  
29 prerequisite conditions that need to be met in order to observe hydrologic impacts at the  
30 watershed scale. These include climatic (i.e. periods of hydrologic surplus / deficit),  
31 pedological (i.e. soil depth) and eco-physiological (i.e. forest age-dependence) conditions.



1 Understanding the hydrologic impacts of land cover/use change, and in particular  
2 afforestation, is an important topic in the European Mediterranean region, given the  
3 significant land cover changes that have occurred over its long history of human habitation  
4 which has left only an estimated 4.7 % of primary vegetation unaltered (Geri et al., 2010), and  
5 given the widespread concerns over potential future water shortages due to changing climatic  
6 conditions (Giorgi and Lionello, 2008). Some of the most significant land cover/use changes  
7 in recent decades have been rural abandonment, a decrease in traditional agricultural/pastoral  
8 activities, and an increase in the homogeneous cover of forest plantations (Geri et al., 2010;  
9 Serra et al., 2008). These land cover changes have also taken place in the north-central region  
10 of Portugal, where traditional rural agrosilvopastoral activities have been widely replaced by  
11 plantations of the tree species *Pinus pinaster* and *Eucalyptus globulus* (Jones et al., 2011;  
12 Moreira et al., 2001). Both of these tree species have the potential to substantially reduce  
13 water availability. Bosch and Hewlett (1982) estimated that pine and eucalypt forests caused  
14 an average decrease of over 40 mm/yr in water yield per 10 % change in land cover, while  
15 Farley et al. (2005) found that afforestation with pines and eucalypts led to reductions in  
16 streamflow of 40 % ( $\pm 3$  %) and 75 % ( $\pm 10$  %), respectively. Rodríguez-Suárez et al. (2011)  
17 found that afforestation with *Eucalyptus globulus* caused a drop in water table depth as well  
18 as a decrease in streamflow during the summer period, which they attributed to the higher  
19 transpiration capacity of the eucalypt plantations than the original crop lands.

20 Besides transpiration, evaporation from canopy interception is an important component of  
21 water use by Mediterranean forests. Interception rates have been found to vary widely,  
22 depending on the tree species, canopy density, and climatic conditions. In central Portugal,  
23 interception rates of pine and eucalypt plantations have been found to be typically less than 20  
24 %. For *Pinus pinaster*, Ferreira (1996) reported interception rates of 15–18 % of total rainfall,  
25 while Valente et al. (1997) found rates of 17 %. For *Eucalyptus globulus*, both Ferreira and  
26 Valente et al. (1997) observed lower rates, amounting to 10–14 % and 11 %, respectively. By  
27 contrast, much higher interception rates have been found for other tree species in the  
28 Mediterranean, with values near and even exceeding 50 %. For example, Scarascia Mugnozza  
29 et al. (1988) found canopy interception rates of 68 % for a mature *Quercus cerris* forest,  
30 Iovino et al. (1998) rates of 58 % for a mature *Pinus nigra* forest, and Tarazona et al. (1996)  
31 rates of 48 % for a mature *Pinus sylvestris* forest.

1 A further hydrologic change related to afforestation in north-central Portugal is its impact on  
2 soil water repellency (SWR), as both pine and eucalyptus tree species can promote SWR in  
3 the topsoil due to the considerable amount of resins, waxes, and aromatic oils contained in  
4 their organic matter (Benito and Santiago, 2003; Doerr and Thomas, 2000; Doerr et al., 2000;  
5 Ferreira et al., 2000, 2005; Keizer et al., 2005a, 2005b). SWR is a key factor in triggering land  
6 degradation processes due to reductions in infiltration capacity and increased overland flow  
7 (Doerr et al., 2000; Shakesby et al., 2000; Benito and Santiago, 2003; Keizer et al., 2005b).  
8 While SWR is often associated in many regions with post fire soil conditions, Doerr et al.  
9 (1996) demonstrated that in the Águeda watershed, SWR is a widespread characteristic of  
10 both burned and unburned soils during dry periods, in particular for stands of *Eucalyptus*  
11 *globulus*. Santos et al. (2013) examined temporal patterns in topsoil hydrophobicity in the  
12 Águeda watershed between July 2011 and June 2012, in unburnt pine as well as eucalypt  
13 plantations. Their findings suggested that the breakdown of SWR following dry summer  
14 conditions occurs from the top down under pine, and from the bottom up under eucalypt.  
15 Unpublished results indicated that this contrast reflected varying infiltration patterns, with  
16 infiltration occurring as slow matrix flow under pine sites as opposed to much faster  
17 macropore flow under eucalypt.

18 The European Mediterranean region has undergone significant land cover changes over its  
19 long history of human habitation, which has left only an estimated 4.7 % of primary  
20 vegetation unaltered (Geri et al., 2010). These land cover changes are likely to have altered  
21 hydrologic processes at multiple scales, and the impacts of these changes are often not well  
22 understood. Gaining a better understanding of these past changes is critical for predicting the  
23 impact of future land-cover changes, particularly given widespread concerns over potential  
24 water shortages in this region due to changing temperature and rainfall regimes (Giorgi and  
25 Lionello, 2008). Some of the most significant land cover/use changes observed in the  
26 European Mediterranean region in recent decades have been: increased rural abandonment, a  
27 decrease in traditional agricultural/pastoral activities, and widespread planting of fast-growing  
28 tree species (Geri et al., 2010; Serra et al., 2008).

29 These regional trends are representative of the changes which have taken place in north-  
30 central Portugal, where traditional rural agrosilvopastoral activities have been widely replaced  
31 by plantations of the tree species *Pinus pinaster* and *Eucalyptus globulus* (Jones et al., 2012;  
32 Moreira et al., 2001). Both of these tree species have relatively high consumptive water

1 demand and the potential to substantially reduce local water availability. Bosch and Hewlett  
2 (1982) estimated that pine and eucalypt forests cause an average decrease of over 40 mm/yr in  
3 water yield per 10 % change in land cover, while Farley et al. (2005) reported that  
4 afforestation with pines and eucalypts lead to reductions in streamflow of 40 % ( $\pm$  3 %) and  
5 75 % ( $\pm$  10 %), respectively. Rodríguez-Suárez et al. (2011) found that afforestation with  
6 *Eucalyptus globulus* caused a drop in water table depth as well as a decrease in streamflow  
7 during the summer period, which they attributed to the higher transpiration capacity of the  
8 eucalypt plantations compared to the original crop lands.

9 In addition to consumptive water use through transpiration, evaporation from canopy  
10 interception is an important component of water use by Mediterranean forests. Interception  
11 rates have been found to vary widely in this region, depending on the tree species, canopy  
12 density, and climatic conditions. With respect to *Pinus pinaster*, Ferreira, (1996) reported  
13 interception rates of 15-18 % in the Águeda watershed of north-central Portugal (mean  
14 precipitation  $\approx$  1700 mm/yr), while (Valente et al., 1997) found similar rates of 17 % in a  
15 drier region of central Portugal (mean precipitation  $\approx$  600 mm/yr). For *Eucalyptus globulus*,  
16 both Ferreira (1996) and Valente et al. (1997) observed lower rates, amounting to 10-14 %  
17 and 11 %, respectively. By contrast, much higher interception rates have been found for other  
18 tree species in different parts of the Mediterranean, with values near and even exceeding 50  
19 %. For example, Scarascia-Mugnozza et al. (1988) found canopy interception rates of 68 %  
20 for a mature *Quercus cerris* forest in central Italy (mean precipitation 1006 mm/yr), Iovino et  
21 al. (1998) found rates of 58 % for a mature *Pinus negra* forest in southern Italy (mean  
22 precipitation 1179 mm/yr), and Tarazona et al. (1996) observed rates of 48 % for a mature  
23 *Pinus sylvestris* forest in northern Spain (long-term mean precipitation of 895 mm/y, 1253  
24 mm/yr during the study period).

25 A further hydrologic factor relevant to afforestation in north-central Portugal is the potential  
26 for impacts on soil water repellency (SWR). Both pine and eucalyptus tree species can  
27 promote SWR in the topsoil due to the considerable amount of resins, waxes, and aromatic  
28 oils contained in their organic matter (Benito and Santiago, 2003; Doerr and Thomas, 2000;  
29 Ferreira et al., 2000; Keizer et al., 2005a, 2005b). SWR is a key factor in triggering land  
30 degradation processes due to reductions in infiltration capacity and increased overland flow  
31 (Benito and Santiago, 2003; Doerr and Thomas, 2000; Keizer et al., 2005b; Shakesby et al.,  
32 2000). While in many regions SWR is associated primarily with post-fire soil conditions,

1 Doerr et al. (1996) demonstrated that SWR is a widespread characteristic of both burned and  
2 unburned soils in the Águeda watershed during dry periods, in particular for stands of  
3 *Eucalyptus globulus*. Santos et al. (2013) examined temporal patterns in topsoil  
4 hydrophobicity in the Águeda watershed between July 2011 and June 2012 in unburnt pine  
5 and eucalypt plantations. Their findings suggested that the breakdown of SWR following dry  
6 summer conditions occurs through different mechanisms in the pine and eucalypt stands. In  
7 the pine stands, SWR breakdown occurred from the top-down (i.e. vertically downwards),  
8 while in the eucalypt stands, breakdown occurred from the bottom-up (i.e. vertically  
9 upwards). Unpublished results indicated that this contrast reflected varying infiltration  
10 patterns, with infiltration occurring relatively slowly (i.e. matrix flow) in pine stands, as  
11 opposed to much faster (i.e. macropore flow) in eucalypt stands. This contrast in infiltration  
12 patterns appeared to be a product of SWR induced alterations in flow pathways.

13 Despite the well-documented potential for hydrologic impacts from afforestation in the  
14 Mediterranean region, there has been little investigation into the long-term effects in north-  
15 central Portugal. This is in part due to a lack of long-term streamflow records that ~~include the~~  
16 ~~pre-afforestation period, allow for historical analyses.~~ A notable exception to this lack of data  
17 is the Águeda watershed in the Caramulo Mountains, where streamflow data records are  
18 available from 1936 until the present.

19 Afforestation/deforestation studies typically focus on small paired watersheds, of which one  
20 has undergone fairly abrupt and well-recorded changes in land cover (e.g. Bosch and Hewlett,  
21 ~~1982). By contrast, this study is conducted on a meso scale watershed (404 km<sup>2</sup>), where~~  
22 ~~afforestation has occurred in a progressive manner over a long period of time. Furthermore,~~  
23 ~~the present study case lacks a nearby watershed which has a similarly long data record and~~  
24 ~~also similar physical environmental characteristics (or a land use history without similar land~~  
25 ~~cover changes). The Águeda watershed also presents a major challenge for conducting an~~  
26 ~~impact assessment based on hydrologic modeling, as there is insufficient spatial information~~  
27 ~~available during the afforestation periods, and detailed maps of land cover for the study are~~  
28 ~~lacking before 1990. Therefore, this study adopts an assessment approach that is data driven~~  
29 ~~and exploratory, examining the available hydro-meteorological data over the 75 year period~~  
30 ~~from 1936 to 2010. This assessment is conducted not only over the entire period, but also~~  
31 ~~within multiple (overlapping) sub periods, and analyzes the temporal patterns for both annual~~  
32 ~~and seasonal values. The trends detected through robust time series analysis are then related~~

1 ~~to an approximated afforestation record, and related to the findings from previous field-based~~  
2 ~~studies conducted in this area. Therefore, the objective of this study is to apply a trend-testing~~  
3 ~~methodology to a long-term data set in a watershed which has undergone progressive~~  
4 ~~afforestation over a 75-year period, to assess what significant trends/changes can be detected,~~  
5 ~~and to relate these changes to the general afforestation pattern which has occurred there.~~ Bosch  
6 ~~and Hewlett, 1982). By contrast, this study is conducted on a meso-scale watershed (404~~  
7 ~~km<sup>2</sup>), where afforestation has occurred progressively over an extended period of time.~~  
8 ~~Furthermore, the present study case lacks a nearby watershed to serve as a paired site, which~~  
9 ~~has a similarly long data record, similar physical-environmental characteristics, or a land use~~  
10 ~~history without similar land cover changes (to serve as a control site).~~

11 To assess the hydrologic impacts of afforestation in the Águeda watershed, this study  
12 therefore adopts a data-driven and exploratory approach, which conducts multiple trend  
13 analyses on the 75-years of hydrometeorological data available from 1936 to 2010. This  
14 assessment is conducted over the entire data record as well as over multiple (overlapping)  
15 sub-periods for both annual and seasonal trends. The significant trends detected through this  
16 analysis are then considered with respect to the regional afforestation trends, and discussed in  
17 the context of previous field-studies conducted in this watershed. Therefore, the objective of  
18 this study is to apply a trend-testing methodology to a long-term data set in a watershed which  
19 has undergone progressive afforestation over a 75-year period, to assess what significant  
20 trends can be detected, and to relate these changes to the afforestation which has occurred  
21 there.

## 22 **2 Methods**

### 23 **2.1 Watershed Description**

24 The Águeda watershed is located in the Caramulo Mountains of north-central Portugal, east of  
25 the coastal city of Aveiro (Fig. 1). From the streamflow gauging point of Ponte Águeda, the  
26 watershed area is approximately 404 km<sup>2</sup>. The Águeda River is a left bank tributary to the  
27 Vouga River, which terminates at the coastal wetland of the Ria de Aveiro lagoon. This  
28 region of Portugal is categorized as a wet Mediterranean climate zone, with pronounced  
29 seasonal differences in temperature and precipitation between dry summer and wet winter  
30 seasons (Fig. 2). The Serra do Caramulo Mountains, which forms the source area of the  
31 Águeda river network, receives a substantial amount of annual rainfall, which can range from

1 1 000 to 2 500 mm/yr. ~~The bedrock in the watershed consists primarily of a mix of schist and~~  
2 ~~granite at higher elevations, with sedimentary rock formations present at lower elevations.~~  
3 ~~Topographically, the landscape is dominated by steep hill slopes with stony and shallow soils,~~  
4 ~~which have a long history of anthropogenic impacts.~~ Topographically the landscape is  
5 dominated by steep hill-slopes with stony and shallow soils (< 0.5 m), which have a long  
6 history of anthropogenic impacts. These shallow soil were characterized by Ferreira et al.  
7 (2000) as stony, sandy loam, weakly structured Umbric Leptosols.

8 ~~The north~~ North-central ~~region of~~ Portugal has undergone substantial land cover/use changes  
9 over the past centuries, which have fundamentally altered the vegetative landscape ~~of this~~  
10 region. From the 1800s until the 1980s, the region had a general trend towards both increased  
11 agricultural and forest land cover, with reductions in natural vegetation types, ~~which (e.g.~~  
12 Matos shrublands and mixed forests). This trend was primarily ~~due to~~ driven by the adoption  
13 of fertilizers and mechanization, as well as the abolition of feudal land systems ~~(Estêvão,~~  
14 1983; GPPAA, 2004; Jones et al., 2011). ~~(Estêvão, 1983; Jones et al., 2011; Silva et al., 2004).~~  
15 The period between 1930 and 1980 saw particularly rapid afforestation, due to incentives  
16 from the establishment of related government regulations and subsidies.

17 A key driver was the enactment of legislation in 1938 which encouraged afforestation of areas  
18 classified as “uncultivated/wasteland”, which often consisted of areas of matos (shrublands),  
19 mountain ranges, and sand dunes ~~(Coelho et al., 1995; Estêvão, 1983; Ferreira et al., 2010;~~  
20 GPPAA, 2004; Jones et al., 2011). ~~The primary species planted during this earlier period was~~  
21 *Pinus pinaster*; ~~however beginning in the 1970s, *Eucalyptus globulus* became the preferred~~  
22 species due to its faster growth and higher profitability for use in the paper pulp industry.  
23 During this period, eucalypt plantations began to replace pine forests as these were harvested,  
24 as well as being widely introduced into remaining areas of shrublands and in recently burned  
25 areas (Jones et al., 2011). ~~(Coelho et al., 1995; Estêvão, 1983; Ferreira et al., 2010; Jones et~~  
26 al., 2011; Silva et al., 2004). ~~The primary species planted during this earlier period was *Pinus*~~  
27 *pinaster*, and beginning in the 1970s *Eucalyptus globulus* became the preferred species due to  
28 its faster growth and higher profitability for use in the paper pulp industry. During this period,  
29 eucalypt plantations began to replace pine forests as these were harvested, as well as being  
30 widely introduced into remaining areas of shrublands and in recently burned areas (Jones et  
31 al., 2011).

1 In this respect, wildfire is an important factor when considering land cover and hydrological  
2 processes in this region, particularly given the widespread occurrence of wildfires in Portugal.  
3 Figure 3 shows the burned area of the Águeda watershed from 1975 to 2010, which illustrates  
4 the high frequency of wildfire and post-fire hydrologic impacts in the study site (Instituto da  
5 Conservação da Natureza e das Florestas, 2014). Over this period a total of 30 790 hectares  
6 burned, with some single years having wildfire over more than 10 % of the watershed, such as  
7 1986 and 1995. Wildfires can have significant hydrologic impacts in both the short term (e.g.  
8 by decreasing infiltration and enhancing runoff generation) and in the long term (e.g. by  
9 altering vegetation cover and therefore evapotranspiration potential), and in addition they  
10 have been a major contributing factor promoting land owners to convert from pine to  
11 eucalyptus plantations in the study region.

12 Wildfire is another important factor in land cover/use change in Portugal, which has some of  
13 the highest rates of wildfire in Europe. Figure 3 shows the burned area of the Águeda  
14 watershed from 1975 to 2010, during which a total of 30 790 hectares burned, with some  
15 single years having wildfire over more than 10 % of the watershed (i.e.1986 and 1995;  
16 Instituto da Conservação da Natureza e das Florestas, 2014). Wildfire can have significant  
17 short-term impacts on hydrologic functions in the study region, such as decreased infiltration  
18 and increased surface runoff / erosion (Malvar et al., 2011; Prats et al., 2012; Shakesby et al.,  
19 1993). In addition to these short-term impacts, wildfire can have potential long-term impacts  
20 by promoting changes in vegetation type. Wildfire has been a major driver of land-cover  
21 change in north-central Portugal in this respect, by allowing land-owners to convert from pine  
22 to eucalyptus plantations in the post-fire period.

23 This region-wide trend of the afforestation of shrubland with *Pinus pinaster*, followed by a  
24 secondary transition from *Pinus pinaster* to *Eucalyptus globulus* plantations, is representative  
25 of the land cover changes in the Águeda watershed, as well as in the Vouga basin as a whole.  
26 From this regional pattern, and from forestry maps of the Serra do Caramulo Mountains  
27 (Rego, 2001), a general afforestation timeline for Vouga basin as a whole, and for the Águeda  
28 watershed in particular. From this regional pattern, and from afforestation maps of the Serra  
29 do Caramulo Mountains (Rego, 2001), a general timeline of land-cover change in the Águeda  
30 watershed during the period of investigation can be approximated, which is summarized in  
31 Table 1.

1 The current land cover in the Águeda watershed reflects this large-scale transition towards  
2 eucalyptus forests. According to the Corine Land Cover classification of 2006, approximately  
3 ~~44 % of the watershed was covered by broad leaved forest, which primarily consisted of~~  
4 ~~eucalyptus.~~ 46 % of the watershed was covered by broad-leaf forest - which is predominantly  
5 eucalyptus (Corine Land Cover, 2010). Other land cover types with significant areal coverage  
6 in 2006 include: 22 % mixed forest (mostly mixed stands of eucalypt and pine), ~~13 %~~  
7 ~~transitional woodland shrub (mostly post fire recovery, or regrowth after clear cutting), and 7~~  
8 ~~% coniferous forest, which mainly consisted of *Pinus pinaster* (Fig.14 % agriculture, 10 %~~  
9 ~~pine forest, 6 % mato shrubland, 2 % urban, and 1% grasslands (Fig. 1).~~

## 10 2.2 Hydrometeorological Data

11 ~~Daily precipitation and streamflow~~ Hydrometeorological records for the Águeda watershed  
12 were compiled from hydrological year 1935/36 (i.e. Oct 1st 1935 to Sep 30th 1936) until  
13 hydrological year 2009/10 ~~from the ‘Sistema Nacional de Informação de Recursos Hídricos’~~  
14 ~~(SNIRH, 2013).~~ Precipitation data were compiled from the rain-gauge “Campia”, which  
15 consists of 24 h rainfall totals collected at 9:00 each day., for the variables: precipitation,  
16 temperature, potential evapotranspiration, streamflow quantity, streamflow yield, baseflow  
17 quantity, and baseflow index. Table 2 provides an overview of the hydrometeorological  
18 variables used in this study.

19 Precipitation data were obtained from the rain-gauge “Campia”, of the ‘Sistema Nacional de  
20 Informação de Recursos Hídricos’ (SNIRH, 2013), which consists of 24 hour rainfall totals  
21 collected at 9:00 each day. The SNIRH provides a reliability ranking for the data in the range  
22 of 5 – 15, for which Campia is ranked as 14 (highly reliable). Data gaps occurred with the  
23 greatest frequency between 1997 and mid-2003, which were filled by linear regression with  
24 the nearby rain-gauges “Varzielas” ( $r^2 = 0.82$ ) and “Barragem de Castelo Burgães” ( $r^2 = 0.79$ ).

25 ~~Streamflow data consisted of daily average discharge measurements from the gauging station~~  
26 ~~“Ponte Águeda”.~~ Temperature data was compiled using data from the gauge “Campia” of the  
27 Instituto Portugues do Mar e Atmosfera (IPMA, 2014). When data for “Campia” was not  
28 available, the time-series gaps were filled using linear regression with the temperature gauge  
29 “Coimbra” ( $r^2 = 0.93$ ) which is part of the Global Historical Climate Network available at the  
30 National Climatic Data Center (NCDC). Using the mean monthly temperature ( $^{\circ}\text{C}$ ) from this  
31 time-series, potential evapotranspiration (PET) was estimated using the Thornthwaite



1 equation (1948). The Thornthwaite equation was utilized rather than more sophisticated  
2 equations (e.g. Hargreaves, Penman–Monteith), as there is insufficient data available over the  
3 entire time-series to calculate PET using the Penman–Monteith equation, and the estimates  
4 using the Hargreaves equation were unreliable, due to the reliance of this method on a stable  
5 measure of minimum and maximum temperature (which was not available at this site).

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6 Streamflow data consists of daily average discharge measurements from the gauging station  
7 “Ponte Águeda” of the ‘Sistema Nacional de Informação de Recursos Hídricos’ (SNIRH,  
8 2013). This station was operational from June 1935 until the end of September 1990, and was  
9 then reactivated in October 1999. Streamflow for the interim period (1990/91 until 1998/99)  
10 was estimated by linear regression with the upstream gauges “Ribeiro” ( $r^2 = 0.76$ ) and “Ponte  
11 Redonda” ( $r^2 = 0.75$ ). However, the streamflow estimates from the hydrologic years of  
12 1999/2000 through 2002/03 were eliminated from the dataset, due to concerns about the low  
13 data quality and, in particular, owing to the absence of an adequate stage-discharge curve  
14 during this period.

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15 In addition, a number of smaller streamflow gaps occurred throughout the daily streamflow  
16 dataset. When they occurred ~~in~~during periods with little or no precipitation, ~~they~~the gaps were  
17 filled by fitting a logarithmic decay curve (traditional linear reservoir with a semi-log fitting)  
18 to the streamflow recession. ~~Where~~-If gaps occurred during a precipitation event, then this  
19 method approach was not possible, applied, and the ~~result~~gaps were left unfilled. If the number  
20 of gaps was ~~that more~~greater than 5 % of ~~daily values were missing~~the total record, then the  
21 entire ~~hydrological year~~period was removed from analysis, which was the case for the  
22 hydrologic years 1954/55 and 1975/76. Finally, data for the driest months of the year (i.e.  
23 June to September) during the period ~~from~~ before 1963 and after 2004 had very high  
24 uncertainty, due to unreported and variably occurring impoundments of streamflow during  
25 these months. Therefore, ~~these~~this four ~~months were~~month period had to be removed from  
26 the streamflow analysis for ~~all year~~the entire data record, to keep the inter-annual  
27 comparisons consistent. ~~After the streamflow gaps were filled, the ratio of precipitation which~~  
28 becomes streamflow was calculated, to allow potential changes in the streamflow-  
29 precipitation relationship to be assessed. This ratio is defined as the “streamflow yield”,  
30 which is the total streamflow divided by total precipitation, with the period of summation  
31 determined by the period being considered (i.e. the annual or the seasonal ratio).

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1 ~~The final data set utilized in this study included a time-series of baseflow derived from the~~  
2 ~~daily streamflow data. Baseflow corresponds to the portion of streamflow which does not~~  
3 ~~come directly from a precipitation event, and can be used as a proxy of the sustained~~  
4 ~~streamflow contribution from slow flow. For this study, baseflow was calculated using the~~  
5 ~~Eckhardt digital filter (Eckhardt, 2008), via the “Web-based Hydrograph Analysis Tool” (Lim~~  
6 ~~et al., 2005). The relative proportion of baseflow from each day of streamflow was estimated,~~  
7 ~~which were then aggregated to the time periods used for analysis. To assess the baseflow~~  
8 ~~time-series calculated using the Eckhardt digital filter, a supplementary data set from 2001 to~~  
9 ~~2009 was also utilized, which calculates baseflow contribution using conductivity data from~~  
10 ~~the SNIRH streamflow data using the ‘Conductivity Mass Balance Method’ (Stewart et al.,~~  
11 ~~2007)~~

12 The final data set utilized in this study is a baseflow time-series calculated with the Eckhardt  
13 digital filter (Eckhardt, 2005) using the daily streamflow dataset. Baseflow corresponds to the  
14 portion of streamflow which does not come directly from a precipitation event, and can be  
15 used as a proxy of the sustained streamflow contribution from slow-flow. The relative  
16 proportion of baseflow from each day of streamflow was estimated, which was then  
17 aggregated to the time periods used for analysis. To assess the baseflow time-series calculated  
18 using the Eckhardt digital filter, a supplementary data set from 2001 to 2009 was also utilized,  
19 which calculates baseflow contribution using conductivity data from the SNIRH streamflow  
20 data using the ‘Conductivity Mass-Balance Method’ (Stewart et al., 2007).

### 21 **2.3 Thiel-Sen / Mann-Kendall Trend Testing Approach**

22 ~~To examine the magnitude and significance of potential trends in the time series, a multi-step~~  
23 ~~trend testing approach was applied, following the general approach presented in Yue et al.~~  
24 ~~(2002). This approach first determined the magnitude (i.e. slope) of any potential trend in the~~  
25 ~~data using the non-parametric Thiel-Sen slope estimator (Sen, 1968). This value was~~  
26 ~~determined by selecting the median slope among the set generated between all sample points.~~  
27 ~~This method also estimates the 95 % confidence intervals of the true slope, based on the set of~~  
28 ~~slopes from sample points, which provides a measure of uncertainty of the median Thiel-Sen~~  
29 ~~value. If a potential trend was detected by the Thiel-Sen test (i.e. a non-zero slope), then the~~  
30 ~~data was processed using the ‘Trend-Free Pre-whitening’ procedure of Yue et al. (2002). This~~  
31 ~~step aimed to reduce the over-estimation of significance which can occur in time-series data~~  
32 ~~that exhibit positive serial correlation, as is typically the case for streamflow time-series data.~~

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1 To examine the magnitude and significance of potential trends in the hydrometeorological  
2 time-series, a multi-step trend-testing approach was applied, following the general approach  
3 presented in (Yue et al., 2002). This approach first determines the magnitude (i.e. slope) of  
4 any potential trend in the data using the non-parametric Thiel-Sen slope estimator (Sen,  
5 1968). This value is determined by calculating the median slope among the set generated  
6 between all sample points. This method also estimates the 95 % confidence intervals of the  
7 true slope, based on the set of slopes from the sample points, which provides a measure of  
8 uncertainty of the median Thiel-Sen value. If a potential trend is detected by the Thiel-Sen  
9 test (i.e. a non-zero slope), then the data is processed using the ‘Trend Free Pre-whitening’  
10 procedure of (Yue et al., 2002). This step reduces the over-estimation of significance which  
11 can occur in time-series data that exhibits positive serial correlation, as is typically the case  
12 for streamflow time-series data.

13 After the “Trend Free Pre-whitening procedure”, a Mann-Kendall test was applied to assess  
14 the statistical significance of any non-zero slope identified by the Thiel-Sen test. The Mann-  
15 Kendall test is a widely used, rank-based significance test, where the null hypothesis is that  
16 there is no trend in the observed series (Helsel, 1993). Statistical significance was determined  
17 using an  $\alpha$  value of 0.05. data (Helsel, 1993). For this study, statistical significance was  
18 determined using an  $\alpha$  value of 0.05.

19 For every data set each hydrometeorological variable, this trend testing procedure was applied  
20 over 12 different time periods with varying starting/end dates and lengths (Fig. 4). The  
21 longest period tested contains the entire 75-year data record (hydrologic year 1936-2010),  
22 followed by two periods of 50 years, three periods of 35 years, and six periods of 25 years.  
23 These overlapping periods were selected of different lengths aim to thoroughly sample the  
24 potential range of years, while still allowing enough years of data to produce a robust  
25 significance test. within each test period (i.e. a minimum of 25 years), Figure 4 provides an  
26 overview of the testing periods, and their temporal correspondence with the afforestation  
27 periods listed in Table 1.

28 When conducting multiple simultaneous hypothesis tests, it is necessary to correct for the  
29 false discovery rate (FDR). FDR corresponds to the expected proportion of incorrectly  
30 rejected null hypotheses, and therefore a method is needed to reduces the chance of receiving  
31 false-positive results (i.e. type I errors). A number of different methods can be applied to  
32 control for FDR, however given the overlapping time periods examined in this study, a

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1 method is needed which can deal with FDR under the assumption of positive dependence.  
2 Therefore, the Benjamini–Hochberg–Yekutieli procedure was applied to the trend-testing  
3 output from each individual ‘analysis set’ (Benjamini and Yekutieli, 2001). An analysis set  
4 corresponds to a group of tests which are expected to exhibit mutual positive dependence,  
5 which in this case are the 12 overlapping periods over which each hydrometeorological  
6 variable was tested for the different annual and seasonal periods (i.e. Fig. 4 for a given  
7 variable and period).

8 Over the time periods shown in Fig. 4, the trend testing was conducted for aggregated  
9 “annual” and “seasonal” values of precipitation (mm/yr), streamflow quantity (mm/yr),  
10 streamflow yield (streamflow/precipitation), baseflow quantity (mm/yr), and baseflow index  
11 (baseflow/streamflow) over both annual and seasonal time periods. The seasonal breakdown  
12 selected corresponds with the prevailing precipitation patterns of the study site, which  
13 consists of: the “Wet Season” from October to January when the largest amount of  
14 precipitation occurs, the “Transitional Season” from February to May when precipitation  
15 rates are reduced, and the “Dry Season” from June to September when precipitation is  
16 lowest. As stated previously however Due to gaps in the streamflow record (discussed in  
17 section 2.2), the hydrologic years 1999/2000 through 2002/03 were unavailable for the trend  
18 testing for both the annual and seasonal time periods, and the hydrologic years 1954/55 and  
19 1975/76 were unavailable for the annual and transitional season.. In addition, the trend tests  
20 were not conducted during the “Dry Period” for streamflow (and therefore also baseflow), due  
21 to the uncertain data quality during these months.

### 23 **3 Results**

#### 24 **3.1 Summary of the Seasonal Breakdown**

25 To characterize the hydrometeorological conditions of the three seasons, seasons’ used in this  
26 study; the median temperature, precipitation, streamflow quantity, streamflow yield, and  
27 baseflow index values over of the hydrometeorological variables during the study period are  
28 presented in Table 2. They clearly reveal3. This summary shows the strong seasonality in  
29 precipitation patterns climatic pattern in the watershed, with distinctly lower amounts  
30 occurring during the dry season. During the contrasting precipitation, temperature, and  
31 potential evapotranspiration values between seasons. With respect to streamflow, the values

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1 ~~are similar during the wet and transitional periods, streamflow quantities are similar.~~  
2 ~~However, seasons, however,~~ both streamflow yield and baseflow index are higher during the  
3 transitional ~~period~~season, which reflects the sustained streamflow carried over from the wet  
4 season precipitation, and the lower proportion of streamflow coming directly from  
5 precipitation events.

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### 6 **3.2 Analysis of the Elimination of the Dry Season Streamflow**

7 As discussed in the data section, the months of June to September had to be removed from all  
8 streamflow analyses, due to uncertainty related to unrecorded seasonal impoundments during  
9 this part of the year. To quantify the percentage of streamflow that this excluded from the  
10 analysis, an assessment was made over the years when streamflow impoundments did not  
11 occur (45 % of years). During these years, approximately 6.5 % of streamflow occurred  
12 between the months of June to September (Fig. 5, monthly mean values presented).

### 13 **3.3 Assessment of the Baseflow Calculations**

14 ~~To provide a check on the baseflow values estimated with the Eckhardt digital filter~~  
15 ~~(Eckhardt, 2008), the obtained results were compared against baseflow values calculated~~  
16 ~~using conductivity data from 2001 to 2009 with the 'Conductivity Mass-Balance Method'~~  
17 ~~(Stewart et al., 2007). At a monthly time scale, the two baseflow data sets were strongly~~  
18 ~~correlated (Pearson's correlation coefficient of 0.96), which indicates that the Eckhardt~~  
19 ~~method agreed well with the more empirical Conductivity Mass-Balance Method. This in~~  
20 ~~itself does not confirm the accuracy of the baseflow values utilized, but it does indicate their~~  
21 ~~consistency over the study period, and thus their suitability for time series analysis.~~

22 To provide a check on the baseflow values estimated with the Eckhardt digital filter  
23 (Eckhardt, 2005), the results were compared against baseflow values calculated using  
24 conductivity data from 2001 to 2009 with the 'Conductivity Mass-Balance Method' (Stewart  
25 et al., 2007). At the monthly time-scale, the two baseflow data-sets have a Pearson's  
26 correlation coefficient of 0.96 for all months (Fig. 6a), and 0.83 for months with less than 100  
27 mm of baseflow (Fig. 6b), which indicates that the Eckhardt method agreed well with the  
28 more empirical Conductivity Mass-Balance Method. This in itself does not confirm the  
29 accuracy of the baseflow values utilized, but it does indicate their consistency over the study  
30 period, and thus their suitability for the time-series trend analysis.

### 3.4 Thiel-Sen / Mann-Kendall Trend Testing Results

The results for the Thiel-Sen / Mann-Kendall trend tests are provided by Fig. 6 and Tables A1 through A5 in the appendix. Figure 6 provides visualization for a selection of time series the variables with the most noteworthy findings, while the tables in the appendix provide the results (i.e. precipitation, temperature, potential evapotranspiration, streamflow yield, and baseflow index) are presented by Fig. 7. The full test results for all periods and variables analyzed. In Fig. 6 the individual time-series charts are divided vertically by the variable considered (i.e. precipitation, streamflow yield, or baseflow index), and horizontally by the time of the year tested (i.e. annual, wet season, or transitional season). The different "Afforestation Periods" (P1, P2, E1, E2; cf. Table 1) are indicated in the charts by the dotted vertical lines. Within each chart, periods with a significant trend were indicated by a dashed line overlain on the time series data. hydrometeorological variables and test periods are provided in the supplementary material.

For the precipitation data, ~~two~~three significant trends were identified at the annual time scale. The first concerned the 50 year period from 1961 to 2010, with a trend of  $-13.8$  mm/yr. The second concerned the 35 year period from 1976 to 2010 and corresponded to a decrease of  $-16.6$  mm/yr. With respect to the seasonal analysis, no significant trends were found for the wet season, as opposed to four significant trends during the transitional season. All four significant trends corresponded to decreases in precipitation, i.e. of  $4.8$  mm/yr over the entire 75 year data record from 1936 to 2010,  $-7.9$  mm/yr trend over the 50 years from 1961 to 2010,  $-11.3$  mm/yr trend over the 35 years from 1976 to 2010, and  $-14.3$  mm/yr trend over the 25-year period from 1976 to 2000. These trends indicate that there was an overall trend towards a decline in a pattern of decreasing precipitation from totals during the transitional season (February to May) starting during the study P2 land-cover period, and that this tendency was strongest during the period's final part. pattern continued through the E1 and E2 land-cover periods (cf. Table 1).

Three significant trends were also found for potential evapotranspiration (PET) during the transitional season: a  $-0.8$  mm/yr trend over the 50 years from 1936 to 1985, a  $-1.3$  mm/yr trend over the 25 years from 1956 to 1980, and a  $1.7$  mm/yr trend over the 25-year period from 1976 to 2000. Therefore the PET data shows a pattern of negative trends throughout the P1, P2, and into the E1 land-cover periods, which reverses and becomes positive during the E1 period and into the E2 land-cover period (cf. Table 1).

1 For the streamflow data record, no significant trends were found for either streamflow  
2 quantity or streamflow yield. No significant trends were found for baseflow quantity either,  
3 however a number of significant trends were found for baseflow index (BFI). For the annual  
4 test period, four significant trends were found in total: including significant positive trends of  
5 0.16%/yr for the 35 year period from 1936 to 1970 and of 0.31%/yr for the 25 year period  
6 from 1946 to 1970; and negative trends of -0.22%/yr for the 35 year period from 1956 to  
7 1990 and a -0.46%/yr trend for the 25 year period from 1966 to 1990. Two significant trends  
8 were found for BFI during the wet season: a 0.28%/ yr trend for the 35 year period from 1936  
9 to 1970 and a -0.33%/yr trend for the 25 year period from 1966 to 1990. Therefore, the BFI  
10 data showed an overall pattern of positive trends during the P1 and P2 land-cover periods,  
11 which reverse to negative trends during the P2 period and throughout the E1 land-cover  
12 period (cf. Table 1).

13  
14 ~~**4 Discussion**For the streamflow quantity data, a single significant trend of -~~  
15 ~~**0.9 mm/yr was found during the 50 year period from 1961 to 2010, which**~~  
16 ~~**also corresponds with a period of a significant decrease in precipitation (-**~~  
17 ~~**4.9 mm/yr).**~~

#### 18 4.1 Streamflow Trends

19 ~~With respect to streamflow yield data, a single positive trend was found for the annual data as~~  
20 ~~well as for both the wet and transitional season. All three trends occurred during the 25 year~~  
21 ~~period from 1946 to 1970, and corresponded to similar rates of increase (annual: +0.78 %/yr;~~  
22 ~~wet season: +0.77 %/yr; transitional season: +0.74 %/yr). These results indicated that the~~  
23 ~~trend in streamflow yield during this period was fairly consistent across the year, although no~~  
24 ~~assessment can be made about the dry season.~~

25 ~~For the baseflow quantity data, significant negative trends were found for the annual data and~~  
26 ~~the transitional season during the 50 year period from 1961 to 2010; with values of -6.1~~  
27 ~~mm/yr and -3.3 mm/yr respectively (this also corresponds with a negative precipitation trend~~  
28 ~~period). By contrast, the baseflow index data (BFI) showed the greatest number of significant~~  
29 ~~trends of the variables considered, with a total of ten over the different periods of analysis.~~  
30 ~~Over the 35 year period from 1936 to 1970, the annual data revealed an increase of +0.16~~  
31 ~~%/yr., whereas the wet season data showed an increase of +0.28 %/yr. During the following~~

1 35-year test period from 1956 to 1990, by contrast, there was a significant negative trend in  
2 the annual BFI data of  $-0.22\%$ , and in the wet season BFI data of  $-0.19\%/yr$ . Similar  
3 significant trends were found for the 25-year test periods, with increases of  $0.31\%/yr$  for the  
4 annual data from 1946 to 1970 and  $0.25\%$  for the wet season data from 1936 to 1960.  
5 Significant trends were detected for the period of 1966 to 1990, corresponding to decreases of  
6  $0.46\%$ ,  $0.33\%$ , and  $0.35\%$  in the annual, wet and transitional season data, respectively. The  
7 streamflow trend tests revealed that there were no significant trends for either quantity or  
8 yield over any of the periods tested (Fig. 7). These results therefore contrast with the overall  
9 pattern found in meta-analysis studies dealing with the hydrologic impacts of  
10 afforestation/deforestation, which indicate that afforestation tends to reduce streamflow (e.g.  
11 Bosch and Hewlett, 1982; Brown et al., 2005; Farley et al., 2005). However, there are a  
12 number of individual cases within these meta-analyses studies which show contrasting trends  
13 to the overall pattern. These cases are difficult to directly compare to the current study  
14 however, as most were conducted at the plot to micro-catchment scale, which underwent  
15 relatively rapid land-cover change. By contrast, this study was conducted on a  $404\text{ km}^2$   
16 watershed, which underwent relatively gradual land-cover change over a 75 year period. In  
17 this case, any potential changes in hydrologic processes are likely to be far more diffuse and  
18 difficult to detect, when compared to the paired catchment studies.

19 Despite this limitation, some comparisons can be made to sites with similar site conditions, in  
20 terms of having winter-dominant precipitation and shallow soils. Across a number of  
21 catchments with winter-dominant rainfall, Brown et al. (2005) found that afforestation led to  
22 much larger proportional reductions in summer flows compared to winter flows, which they  
23 attributed to the afforestation-induced changes in interception and evapotranspiration. Among  
24 these catchments, those of Gallart et al. (2001) and Lewis et al. (2000) demonstrated the  
25 importance of soil depth in controlling the hydrological response of Mediterranean mountain  
26 catchments in the Pyrenees and California, respectively. Other studies with somewhat similar  
27 site conditions (i.e. Bari et al., 1996; Van Lill et al., 1980) were conducted at very different  
28 temporal and spatial scales than the present study, making comparisons to their findings  
29 difficult. In spite of the lack of comparable studies for direct comparison, the absence of a  
30 marked reduction in streamflow was an unexpected finding, given the scale of afforestation in  
31 the Águeda watershed.



1 A potential explanation for this lack of observed impact could be the presence of offsetting  
2 climatic trends over the same period. Either an increase in water availability due to higher  
3 precipitation (P) and / or a reduction in atmospheric demand due to lower potential  
4 evapotranspiration (PET) could compensate for any land-cover induced changes. While no  
5 significant trends were found for either P or PET at the annual time scale, or during the wet or  
6 dry seasons, significant trends were found during the transitional season, which may have  
7 impacted water availability.

8 With respect to increasing water availability during the transitional season, negative trends in  
9 PET were found from 1936 to 1985 and from 1956 to 1980 (Fig 7). These trends occur  
10 primarily during the periods of pine afforestation (P1, P2) and partially during the transition  
11 to eucalyptus (E1; Cf. Table 1). The trends in PET would lead to a reduction in atmospheric  
12 demand during this period, and therefore could be responsible for offsetting an increase in  
13 consumptive demand that occurred from afforestation.

14 With respect to reductions in water availability during the transitional season, negative trends  
15 in P were found from 1961 to 2010, 1976 to 2010, and 1976 to 2000; and a positive trend in  
16 PET was found from 1976 to 2000 (Fig. 7). These trends indicate movement toward a  
17 relatively more arid environment, which could therefore lead to a reduction in water  
18 availability. However, no corresponding trends in streamflow were found during this period.  
19 This lack of change is particularly noteworthy given that these trends occurred during the  
20 eucalyptus afforestation periods (E1, E2; Cf. Table 1), which would also be expected to  
21 increase consumptive demand, and would therefore amplify, rather than offset, an increase in  
22 atmospheric demand.

23 Given the lack of significant climate trends at the annual time scale, and the contrasting  
24 findings during the transitional season, offsetting climatic trends do not appear to be an  
25 adequate explanation for the overall lack of observed streamflow changes in the Águeda  
26 watershed. However, given that the observed climate trends occurred during the transitional  
27 season, there may have been streamflow impacts during the (following) dry season. This can  
28 only be speculated on however, since no assessment can be made on streamflow during the  
29 dry season, due to the limitations in the streamflow data (i.e. the summer streamflow  
30 impoundments). Therefore, no comparison could be made with the findings of Rodríguez-  
31 Suárez et al. (2011), who found dry season reductions in the water table and streamflow  
32 discharge following afforestation with eucalyptus; or to Brown et al. (2005) which found that

1 afforestation led to much larger proportional reductions in summer flows compared to winter  
2 flows.

3 An alternate explanation for the lack of streamflow change could relate to the specific  
4 characteristics of the watershed, which may make it less responsive to changes in forest land-  
5 cover than is typical. With respect to watershed characteristics, (Andréassian, 2004) identifies  
6 several prerequisites conditions necessary

## 7 **4 Discussion**

### 8 **4.1 Precipitation Trends**

9 ~~The precipitation data showed negative trends over much of the data period, which indicates~~  
10 ~~that this study was conducted during a period which the watershed became a small degree~~  
11 ~~drier, although the climate remains very wet, with an aridity index range from 1.0 to greater~~  
12 ~~than 1.5 (SNIRH, 2013). Interestingly, this downward trend was primarily due to reductions~~  
13 ~~during the transitional season (February to May), and not during the wet season. According to~~  
14 ~~projected climate change impacts for this region, this trend may be representative of future~~  
15 ~~regional trends as well, which anticipate a decrease in rainfall by as much as 40 % by the end~~  
16 ~~of the 21st century (Nunes et al., 2008):~~

17 ~~A further consideration is that these reductions in precipitation during the transitional season~~  
18 ~~could have impacted soil moisture levels in the dry season, during which there is little~~  
19 ~~additional precipitation input. This could have led to longer recovery times for soil moisture~~  
20 ~~during the resumption of the wet season, which could have amplified soil water repellency~~  
21 ~~during this period (both in terms of the duration and severity). This is discussed further in the~~  
22 ~~section on potential impacts on then baseflow index.~~

#### 23 **4.21.1 Streamflow Trends**

24 ~~The streamflow data revealed only one significant negative trend for quantity (mm/yr) and~~  
25 ~~none for yield over the periods tested, despite the large-scale afforestation that occurred in the~~  
26 ~~test watershed. In addition, the single negative trend with respect to quantity corresponds with~~  
27 ~~a significant negative trend in precipitation, and can therefore be attributed to a response to~~  
28 ~~the reduction in precipitation input rather than to land cover change. Overall therefore, the~~  
29 ~~results of this study do not support the general finding that afforestation tends to reduce~~  
30 ~~streamflow (e.g. Bosch and Hewlett, 1982; Brown et al., 2005; Farley et al., 2005). However,~~

1 ~~this does not imply that this finding contradicts the complete findings of these studies, which~~  
2 ~~also include examples where afforestation had either a positive or negligible impact on~~  
3 ~~streamflow. Rather, this study supports the assertion of Andréassian (2004) that there are~~  
4 ~~prerequisite soil, climatic, and physiological conditions that must be present in order to~~  
5 ~~observe hydrologic impacts at the watershed scale.~~

6 to observe hydrologic impacts, including soil, climatic, and eco-physiological factors.

7 With respect to soil conditions, ~~it is likely that~~ the characteristics of the soils of the Águeda  
8 watershed are may be a key factor in the lack of a reduction in streamflow. Under conditions  
9 of well-developed soils, the deeper rooting depths of trees will give greater access to soil  
10 moisture, allowing for more transpiration, resulting in higher water consumption. However,  
11 the soils of the Águeda watershed tend to be fairly shallow, being ~~frequently typically~~ less  
12 than a 1 meter in depth, deep and ~~are~~ often as shallow as 20-30 cm (Santos et al., 2013). (Santos  
13 et al., 2013). These depths are well below less than the maximum rooting depth of ~~shrub~~  
14 ~~species, as well as of~~ pine and eucalypt tress, and therefore are likely to be a constraint to  
15 deep rooting for both species (Canadell et al., 1996). (Canadell et al., 1996). In addition, the  
16 schist and granite bedrock in this watershed is relatively impermeable and not easily  
17 penetrated by tree roots, which restricts the access of tree species to groundwater reserves as  
18 well. Therefore, the capability of ~~tree species the fast-growing pine and eucalypt trees~~ to  
19 access deeper sources of soil moisture than ~~other vegetation types the original shrub and slow-~~  
20 growing tree species is likely much less relevant in this watershed than it would be in a  
21 site location with deeper soils. In ~~this the~~ case of the Águeda watershed, the most important  
22 soil related factor in water consumption appears to be the low moisture storage capacity of the  
23 soils, ~~and therefore severely off-setting~~ the potential impact of widespread planting of trees  
24 with higher water consumptive capacity ~~of tree species is severely offset.~~

25 ~~A second factor which could explain the lack of reductions in streamflow is the~~  
26 ~~Mediterranean climatic regime of the study area. In all Mediterranean type climates, the~~  
27 ~~period of peak sunlight and temperature, and therefore potential evapotranspiration, is out of~~  
28 ~~phase with the maximum precipitation period. Given the low amount of summer precipitation,~~  
29 ~~and the shallowness of soils in this watershed, there will typically be little soil water available~~  
30 ~~for summer evapotranspiration (David et al., 1997; Doerr and Thomas, 2000). In this regard,~~  
31 ~~the climatic conditions of the study site might have an amplifying effect on the impacts of the~~

1 shallow soils, by further reducing the potential impacts of the higher evapotranspiration  
2 potential of trees in this study site.

3 ~~With respect to physiological conditions, the specific land cover changes observed in the~~  
4 ~~Águeda watershed might also be a factor in the lack of an observed reduction in streamflow.~~  
5 ~~One of the primary drivers of increased consumptive water use by tree species is their~~  
6 ~~typically high canopy interception capacity (Domingo et al., 1994; Scarascia Mugnozza et al.,~~  
7 ~~1988; Tarazona et al., 1996). In the study watershed however, the rates appear to be~~  
8 ~~comparatively low for pine and eucalypt species (Coelho, 2008; Ferreira, 1996; Valente et al.,~~  
9 ~~1997). At the same time, the interception capacity of Mediterranean shrublands can be~~  
10 ~~relatively high. Garcia-Estringana et al. (2010) found that Mediterranean shrub species can~~  
11 ~~have interception capacities similar to those of forests. In addition, interception rates are~~  
12 ~~particularly high in shrublands growing in dense stands (Llorens and Domingo, 2007). These~~  
13 ~~characteristics apply to the ‘matos’ shrubland which was the most common natural vegetation~~  
14 ~~type in Águeda watershed prior to pine afforestation, as it has a relatively high leaf area index~~  
15 ~~and the tendency to grow in very dense stands (Asner et al., 2003). By contrast, given the~~  
16 ~~poor soil conditions of the study site, the densities of the tree plantations are not as high as~~  
17 ~~they could be on well developed soils. Therefore, the land cover/use change from shrubland~~  
18 ~~to pine/eucalypt forest might not have resulted in large changes in either transpiration rates or~~  
19 ~~canopy interception rates.~~

20 Therefore, the Águeda watershed does not meet any of the three prerequisites identified by  
21 Andréassian (2004) for observing afforestation driven hydrologic impacts at the watershed  
22 scale. In fact, one of the few significant trends found in streamflow was an increase in yield  
23 during the 25 year period of 1946 to 1970. This period corresponds with the end of the P1  
24 period and the entirety of the P2 period, during which significant replacement of matos  
25 shrublands by *Pinus pinaster* occurred. This suggests that *Pinus pinaster* had a lower  
26 consumptive water demand than the previous land cover types, which could be related to the  
27 relative young age of the newly planted pines, relative to well established shrublands.

28 Although these findings indicate that there have been little significant reductions in  
29 streamflow during the wet, transitional, or annual time scales, negative trends may have  
30 occurred during the dry summer period, when the impact of tree species on soil moisture  
31 could be greatest. Unfortunately, given the limitation in the streamflow data set (i.e. the  
32 summer streamflow impoundments), it was impossible to assess what the impacts of

1 ~~afforestation were during the dry period. Therefore, no comparison could be made with the~~  
2 ~~findings of Rodríguez Suárez et al. (2011), who found dry season reductions in water table~~  
3 ~~and streamflow discharge.~~

4 A second factor which could contribute to the lack of reductions in streamflow is the  
5 Mediterranean climate regime of the study area. In all Mediterranean-type climates, the period  
6 of peak sunlight and temperature, and therefore potential evapotranspiration, is out of phase  
7 with the maximum precipitation period (Brown et al., 2005). Given the low amount of  
8 summer precipitation, and the shallowness of soils in this watershed, there will typically be  
9 little soil water available for summer evapotranspiration (David et al., 1997; Doerr and  
10 Thomas, 2000). In this regard, the climatic conditions of the Águeda catchment may have an  
11 amplifying effect on the impacts of the shallow soils, by further reducing the higher  
12 evapotranspiration potential of fast-growing trees species.

13 With respect to eco-physiological conditions, the specific land-cover changes in the Águeda  
14 watershed may also be a factor in the lack of an observed reduction in streamflow. One of the  
15 primary drivers of increased consumptive water use by tree species is their typically high  
16 canopy interception capacity (Domingo et al., 1994; Scarascia-Mugnozza et al., 1988;  
17 Tarazona et al., 1996). In the Águeda watershed, however, the interception rates appear to be  
18 comparatively low for pine and eucalypt species (Coelho et al., 2008; Ferreira, 1996; Valente  
19 et al., 1997), while the interception capacity of Mediterranean shrublands can be relatively  
20 high. Garcia-Estringana et al. (2010) found that Mediterranean shrub species can have  
21 interception capacities similar to those of forests. In addition, interception rates are  
22 particularly high in shrublands growing in dense stands (Llorens and Domingo, 2007). These  
23 characteristics apply to the 'matos' shrubland that was the most common vegetation type in  
24 the Águeda watershed prior to pine afforestation, as it has a relatively high leaf-area index and  
25 the tendency to grow in very dense stands (Asner et al., 2003). By contrast, given the poor  
26 soil conditions of the study site, the densities of the tree plantations are not as high as they  
27 could be on well-developed soils. Average tree density from unpublished plot assessments put  
28 the density of unevenly spaced eucalyptus stands (< 15 yr old) at 1 600 trees/ha, of evenly  
29 spaces eucalyptus stands on terraces (< 5 years old) at 1,500 trees/ha, of eucalyptus on flat  
30 terrain (< 5 yr old) at 2,600 trees/ha, and of unevenly spaced pines (< 30 yr old) at 500  
31 trees/ha. Therefore, the land cover/use change from shrubland to pine/eucalypt forest might  
32 not have resulted in large changes in either transpiration rates or canopy interception rates.

1 Therefore, the Águeda watershed does not meet the prerequisites conditions identified by  
2 Andréassian (2004) for observing afforestation-driven streamflow changes at the watershed  
3 scale. Given this lack of prerequisites conditions, and the absence of offsetting climate trends  
4 as an alternative explanation, the streamflow findings of this study appear to be primarily a  
5 function of watershed characteristics, with soil properties as the most important factor.

#### 6 **4.34.2 Baseflow Trends**

7 ~~For~~ No significant trends were founds for baseflow quantity (mm/yr), the only BF) over any  
8 of the periods or seasons tested. However a number of trends were found for baseflow index  
9 (BFI), for both the annual data and the wet season data, which includes both positive and  
10 negative trends over different parts of the data record.

11 Positive trends in BFI were found during the 50 year period from 1961-1936 to 2010.  
12 However, as with the streamflow data this period corresponds with a negative precipitation  
13 trend period, and can therefore be attributed to the same cause. For baseflow index (BFI), no  
14 significant trend was found over 1970 for the entire data record (1936-2010), but  
15 interestingly, numerous significant trends existed within the shorter test periods. The general  
16 pattern in BFI was a positive trend during annual data and the wet season, and from 1946 to  
17 1970 for the annual data (Fig. 7). These trends correspond with the pine afforestation land-  
18 cover periods P1 and P2 periods, followed (Cf. Table 1). These trends could be an indication  
19 that the pine afforestation promoted slower flow pathways, by a negative trend from the  
20 middle of the P2 period through increasing the E1 period. The P1/P2 periods correspond with  
21 a period of pine afforestation, which also showed the only significant positive trend in  
22 streamflow yield. This may indicate modifications in hydrologic flow pathways and/or soil  
23 moisture levels (i.e. higher soil moisture levels allowing for more baseflow) during this  
24 period. With respect to changes in flow pathways, an increase in baseflow index could  
25 indicate that there is less overland flow and fast subsurface flow (i.e. via macropores), and  
26 more amount of water entering the soil matrix via infiltration. Given, and reducing surface  
27 flow and fast subsurface flow (i.e. via macropores). However, given that previous studies in  
28 Águeda watershed have shown that hydrophobic found soil water repellent (SWR) conditions  
29 can be promoted by at pine species (Keizer et al., 2005b; Santos et al., 2013) stands (during dry  
30 periods), pine afforestation would not necessarily normally be expected to increase BFI.  
31 However, the matrix infiltration in this location (Keizer et al., 2005a, 2005b; Santos et al.,  
32 2013). However, the land-cover state during the initial conversion to pine forests could were

1 significantly different from the state during these studies, which may have led to a more  
 2 positive impact on infiltration rates, especially. This is due to the ground preparation and  
 3 planting operations used, which would have the effect of breaking up the repellent topsoil  
 4 layer and creating sinks for overland flow. With, both of which would promote infiltration.  
 5 This effect would be reduced over time, and eventually SWR would recover in particular with  
 6 soil and vegetation recovery, the repellent top soil layer would then become re-established,  
 7 accounting stands.

8 Negative BFI trends were found from 1956 to 1990 for the reversal of annual data, and from  
 9 1966 to 1990 for the wet season (Fig. 7). This corresponds with the BFI trend in the later early  
 10 part of the P2 period. Also, the typical hydrologic impact of pine afforestation of reducing soil  
 11 moisture due to higher consumptive water usage (e.g. Bosch and Hewlett, 1982) would not  
 12 lead to a positive trend in BFI. However, as discussed previously, due to the shallow soils of  
 13 the Águeda watershed, and expectedly similar water consumptive demands of matos  
 14 shrubland and pine forest, this response is unlikely to occur in this study site. Again, the  
 15 positive trend in baseflow in this period could also reflect that the immature pine forests  
 16 actually have less water consumption than the previous land cover, leading to higher levels of  
 17 soil moisture.

18 The negative trends in BFI occurred during the second half of the P2 period and during the E1  
 19 period land-cover period, and the entirety of the first eucalyptus afforestation period (E1, Cf.  
 20 Table 1). Therefore, the strongest negative trend in BFI corresponded with trends occur during  
 21 the period when *Pinus pinaster* plantations had reached greater maturity and (after logging)  
 22 were being rapidly replaced with *Eucalyptus globulus*. Reductions The reductions in baseflow  
 23 during this period could may therefore be attributed related to hydrophobic high rates of soil  
 24 conditions from water repellency (SWR) in the established pine pine stands and/or from the  
 25 newly planted established eucalypt stands, leading. An increase in SWR could lead to an  
 26 increase in quick flow (particularly via fast sub-surface flow from macropore infiltration),  
 27 and the lead to more rapid conversion of precipitation into runoff streamflow.

28 The temporal correspondence between the significant trends in BFI and land cover changes  
 29 which could affect hydrologic flow pathways indicate there may be a relationship between  
 30 afforestation and changes in baseflow index in the Águeda watershed. These findings are  
 31 further supported by field studies conducted in the watershed, which show the strong impact  
 32 of SWR in pine and (particularly) eucalyptus stands on hydrologic flow pathways (Santos et

1 al., 2013). However, given that there is no field data available to verify the site conditions  
2 during the time of the observed trends, the attribution of the changes in BFI to land-cover  
3 change is necessarily speculative. To test this hypothesis, further field studies would be  
4 needed to examine baseflow dynamics under land-cover conditions which replicate the  
5 historic conditions.

## 6

## 7 **5 Conclusions**

8 ~~Notably, the significant reductions in BFI were confined to the wet period, with only one~~  
9 ~~exception. This might indicate that soil moisture levels were taking longer to recover at the~~  
10 ~~onset of the wet season, leading to a delay in the time needed to break soil water repellency.~~  
11 ~~By contrast, during the transitional season, soil moisture levels were typically high after the~~  
12 ~~wet season (which was also reflected in the higher baseflow during this period), and soil water~~  
13 ~~repellency would have largely disappeared by this point in the year. In this regard, a negative~~  
14 ~~trend in BFI during the wet season could also be related to the negative trends seen for~~  
15 ~~precipitation during the transitional period. These rainfall reductions would be expected to~~  
16 ~~lower soil moisture at the onset of the dry season, resulting in even drier soil conditions at the~~  
17 ~~start of the wet season. In this manner, the afforestation with eucalypt and the decrease in~~  
18 ~~precipitation during the transitional period could have compounding impacts on the BFI~~  
19 ~~trends during the wet season.~~

### 20 **4.4 — Pine vs. Eucalypt Afforestation**

21 ~~From~~ This study did not detect statistically significant – negative or positive – trends in  
22 streamflow quantity or yield in the Águeda watershed of north-central Portugal over the 75  
23 year period examined, despite the large scale afforestation with *Pinus pinaster* and later  
24 *Eucalyptus globulus* which has taken place there. While these findings differ from the general  
25 conclusion of afforestation/deforestation meta-analysis studies, such as Bosch and Hewlett  
26 (1982), Brown et al. (2005), and Farley et al. (2005), they do support the assertion of  
27 Andréassian (2004) that there are requisite climatic, pedological, and eco-physiological  
28 watershed conditions that are necessary to observe hydrologic impacts at the watershed scale.  
29 These conditions are not present in the Águeda watershed, and the lack of soil moisture  
30 holding capacity is likely the primary controlling factor.



1 With respect to baseflow trends, the initial conversion from more natural land-cover types  
2 (i.e. matos shrublands, mixed forests) to pine plantations appears to have had a significant –  
3 initial – positive impact on baseflow index, while the substitution of pine plantations by  
4 eucalypt plantations had a negative impact on baseflow index. The positive trends are  
5 attributed to the impact of the site preparation methods applied during the initial pine planting  
6 on soil infiltration capacity, while the negative baseflow trends are attributed to the onset of  
7 soil water repellency (SWR) under the mature pine and eucalypt stands. Therefore, from the  
8 standpoint of promoting well-regulated streamflow (i.e. higher baseflow) the impacts of the  
9 afforestation with pine ~~were appear~~ generally positive, while those of re-/afforestation with  
10 eucalypts were generally negative. ~~This agrees with the popular perception that eucalyptus~~  
11 ~~species diminish the availability of water for human usage.~~

12 However, it is important to stress that the pine and eucalypt planting in the study catchment  
13 took place on dissimilar types of land cover. Pines were primarily replacing naturally  
14 occurring shrublands, ~~while eucalypts were primarily substituting~~ which was followed by the  
15 ~~replacement of the~~ planted pines ~~by eucalypts~~. Therefore, a direct comparison between the  
16 impacts of widespread planting with pine or with eucalypt cannot be drawn from this study.  
17 ~~Nonetheless, the general pattern in the detected trends suggested that the conversion from~~  
18 ~~matos shrubland to pine forests had significant impacts on hydrologic processes, at least~~  
19 ~~initially, while the conversion from pines to eucalypts did not~~In addition, these baseflow  
20 ~~findings are based on a statistical / historical analysis, with no field data available for~~  
21 ~~validation. To further test this hypothesis, field studies would be needed to examine baseflow~~  
22 ~~dynamics under different land-cover conditions replicating the historic conditions.~~

## 23 **51 Conclusions**

24 ~~This study did not detect statistically significant –negative or positive– trends in streamflow~~  
25 ~~or index in the Águeda watershed of north central Portugal over the 75 year period examined~~  
26 ~~(i.e. the entire data record), despite of large scale afforestation with *Pinus pinaster* and later~~  
27 ~~*Eucalyptus globulus* which has taken place there. However, this study did uncover significant~~  
28 ~~trends in the examined variables over the sub-record periods, and that these trends correspond~~  
29 ~~with impacts attributed to the changing land cover/use patterns over these periods. The lack of~~  
30 ~~negative trends in streamflow can be explained by the specific climatic, pedological, and eco-~~  
31 ~~physiological conditions of the watershed. From the two major conversions in land cover/use,~~  
32 ~~the widespread planting of pine trees in matos shrublands had a significant (initial) impact on~~

1 baseflow, while the substitution of pine plantations by eucalypt plantations had a negative  
2 impact on baseflow. These findings agree well with the results of previous studies in this  
3 region of Portugal; however, they contrast with the general pattern of findings from  
4 afforestation/deforestation meta-analyses. As such, the present case study highlights the  
5 importance of considering both the specific attributes of a study area and the nature of the  
6 land cover/use change, when assessing the hydrologic impacts of changes in forest cover.

7 A common goal of water resource management is to improve the ability of hydrologic models  
8 to predict the effects of land cover/use changes on hydrological processes. In this respect, our  
9 findings point towards the importance of soil depth as a key factor controlling the soil  
10 moisture holding capacity at the watershed scale, as well as of soil parameters controlling  
11 (macro) porosity related to rooting patterns and infiltration. In the Águeda watershed, as in  
12 many locations, the available data on soil properties are very poor and even a semi-detailed  
13 map of soil types does not exist for large parts of the area. Therefore, an improved  
14 understanding of watershed scale soil variability is needed to move forward with hydrologic  
15 modeling efforts in this location. A second important consideration regarding improved model  
16 predictions is the need to provide a representation of the soil water repellency dynamics in  
17 this watershed, and the mechanisms controlling the establishment and breakdown of these  
18 conditions (e.g. soil moisture levels controls, top-down or bottom-up breaking of repellency).  
19 Without representing these processes, it is unlikely that the hydrologic response of this  
20 watershed could be represented in a physically based model with an adequate degree of  
21 predictive accuracy and/or uncertainty. Developing this predictive capacity for this region will  
22 remain an important research topic for improving land and water resource management, as  
23 socio-economic and climate projections for this region predict further expansion of forested  
24 land cover and the continued prevalence of wildfire (Jacinto et al., 2013), highlighting the  
25 need to understand their impacts on regional water resources.

## 26

### 27 **Appendix A: Trend Testing Results**

28 The full results of the trend testing are provided by the following tables. The results for  
29 precipitation are provided by Table A1, for streamflow quantity (mm/yr) and yield  
30 (streamflow/precipitation) by Tables A2 and A3, and for baseflow quantity and index  
31 (baseflow/streamflow) by Tables A4 and A5. All tables include the trend test results of the  
32 twelve test periods for all variables considered. In the table headers, the value "T.S. Trend"

1 provides the Thiel-Sen slope line, which shows the annual trend value. The “Lower / Upper  
2 Bound” provide the bounds of the 95 % confidence interval of the true value of the T.S. trend.  
3 The “M.K. Sig.” provides the Mann Kendall significance value, with a value less than 0.05  
4 indicating a significant trend. Test results where a significant trend was found are highlighted  
5 in grey in all tables.

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Table 1. Summary Land-cover periods and dominant afforestation trends in Águeda watershed from 1935 to 2010.

<u>Land-Cover Period-Code</u>	<u>Time Period</u>	<u>Dominant Afforestation Trend</u>
P1	1935 - 1950	Large scale replacement of shrubland with <i>Pinus pinaster</i> .
P2	1950 - 1970	Continuing afforestation with <i>Pinus pinaster</i> , but at a slower rate.
E1	1970 - 1990	Rapid reforestation with <i>Eucalyptus globulus</i> (particularly post '86 wildfire), replacement of <i>Pinus pinaster</i> .
E2	1990 - 2010	Relatively stable forested area, with continued replacement of <i>Pinus pinaster</i> with <i>Eucalyptus globulus</i> .

Table 2. Season and annual median values of T = teperature (°C); P = precipitation (mm/yr); Q = streamflow; Q<sub>yield</sub> = streamflow yield (streamflow/precipitation); BFI = baseflow index (baseflow/streamflow) in Águeda watershed from 1936–2010.

Table 2. Summary of hydrometeorological variables.

<u>Hydrometeorological Variables</u>			<u>Median</u>	<u>Unit</u>
<u>Variable</u>	<u>Descriptio n</u>	<u>Data Source</u>		
SeasonP	<u>Precipitatio nMonths</u>	<u>T (°C)SNIRH Gauge Data</u>	<u>P mm/yr</u>	
WetT	<u>JanTemper ature Feb MayPotenti</u>	<u>11.7IPMA Gauge Data</u>	<u>965°C</u>	
TransitionalPET	<u>al Evapotrans piration</u>	<u>12.6Thornthwaite Equation</u>	<u>626mm</u>	
DryQ	<u>Jun SepStreamf</u>	<u>19.3SNIRH Gauge Data</u>	<u>193mm</u>	NA NA

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low  
Quantity  
All-Stream  
Flow Yield

Annual Q<sub>Yld</sub>      44.7ΣQ<sub>mm</sub> / ΣP      1.787%

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BF      Baseflow      Recursive Digital Filter      mm  
Quantity

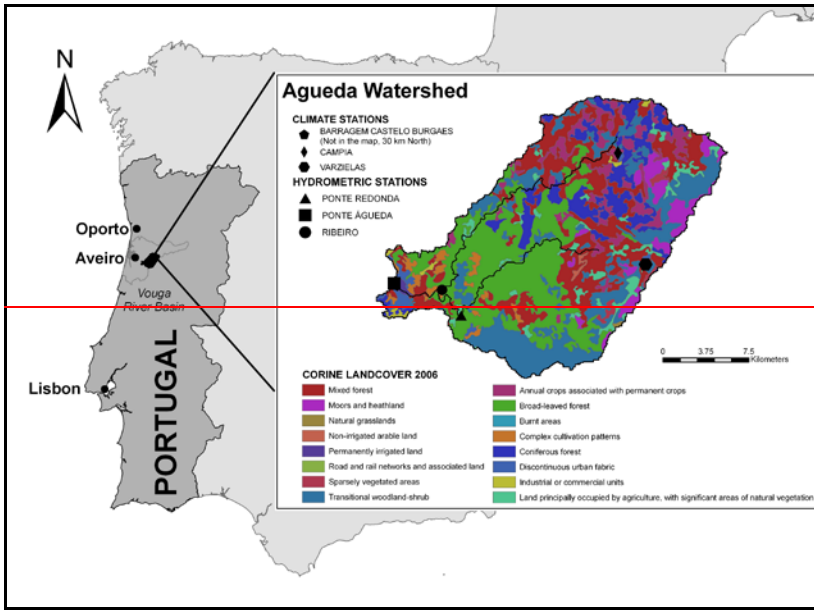
BFI      Baseflow      ΣBF<sub>mm</sub> / ΣQ<sub>mm</sub>      %  
Index

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2

1 Table 3. Seasonal and annual median values of the hydrometeorological variables in Águeda  
 2 watershed from 1936 - 2010.

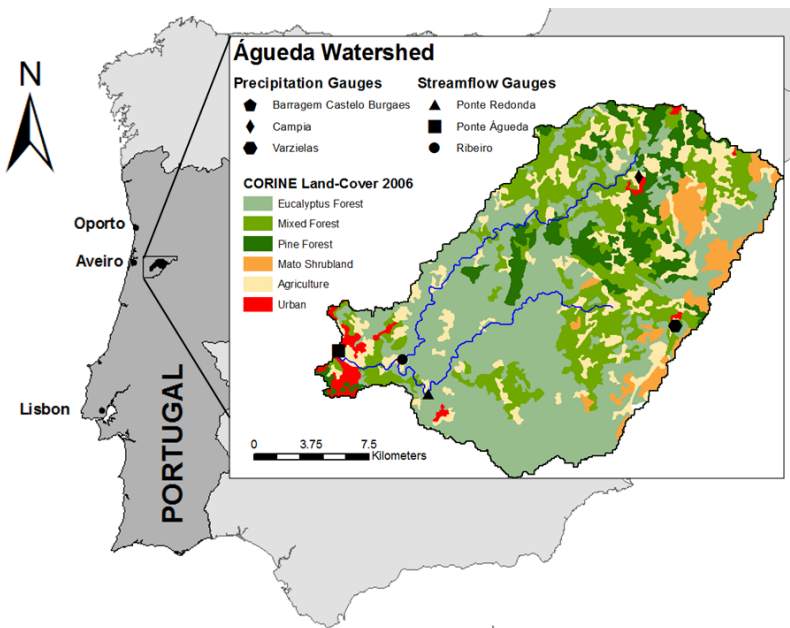
<u>Median Values: 1936 - 2010</u>								
<u>Season</u>	<u>Months</u>	<u>P (mm)</u>	<u>T (°C)</u>	<u>PET (mm)</u>	<u>Q (mm)</u>	<u>Q<sub>yield</sub> (%)</u>	<u>BF (mm)</u>	<u>BFI (%)</u>
<u>Wet</u>	<u>Oct - Jan</u>	<u>965</u>	<u>11.7</u>	<u>145</u>	<u>301</u>	<u>30 %</u>	<u>149</u>	<u>55 %</u>
<u>Transitional</u>	<u>Feb - May</u>	<u>626</u>	<u>12.6</u>	<u>198</u>	<u>281</u>	<u>43 %</u>	<u>184</u>	<u>63 %</u>
<u>Dry</u>	<u>Jun - Sep</u>	<u>193</u>	<u>19.3</u>	<u>390</u>	<u>NA</u>	<u>NA</u>	<u>NA</u>	<u>NA</u>
<u>Annual</u>	<u>All*</u>	<u>1 787</u>	<u>14.7</u>	<u>732</u>	<u>565</u>	<u>36 %</u>	<u>320</u>	<u>59 %</u>

3 \* The months of June to September are not included for Q (mm<sup>4yr</sup>), Q<sub>yield</sub> (%), Q<sub>yield</sub> (%), BF (mm), and BFI (%).  
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**Figures**



6



Figure 1. Map Location and Land-Cover of the Águeda watershed.

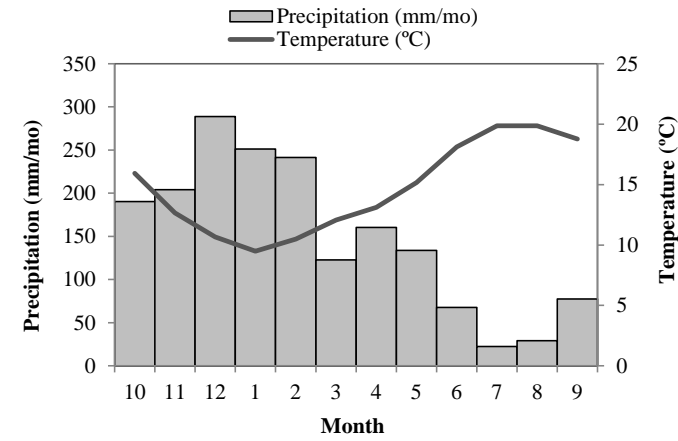
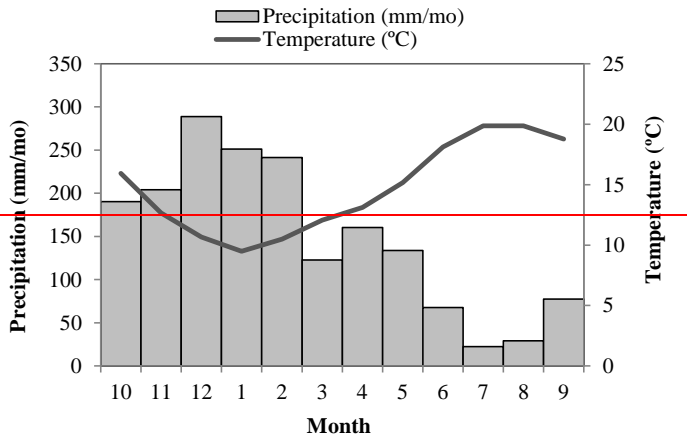
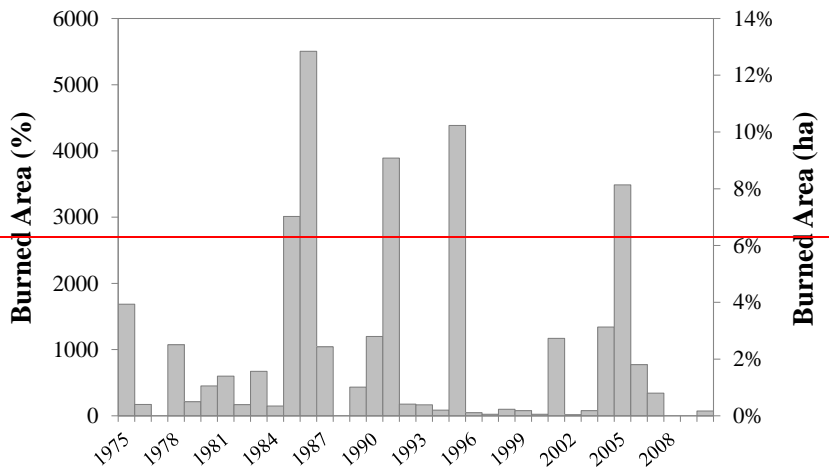


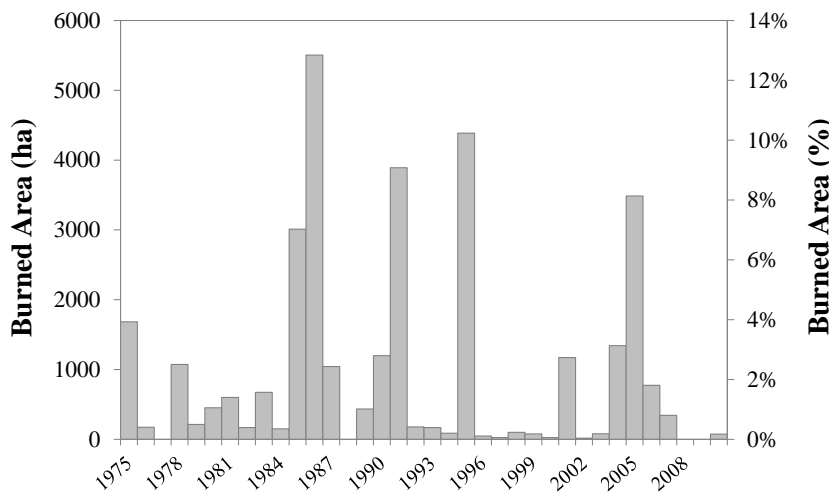
Figure 2. Average monthly precipitation and temperature in the Águeda watershed from 1971 to 2000.

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3 Figure 3. Burned arearea in the Águeda watershed from 1975 to 2010; total watershed area is  
4 404 km<sup>2</sup>.

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Timeline	1935	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005										
Afforestation Period	P1			P2			E1			E2															
75 yr Trend Test	1936 to 2010																								
50 yr Trend Tests	1936 to 1985										1961 to 2010														
35 yr Trend Tests	1936 to 1970						1956 to 1990																		
25 yr Trend Tests	1936 to 1960				1946 to 1970					1956 to 1980						1966 to 1990				1976 to 2000			1986 to 2010		

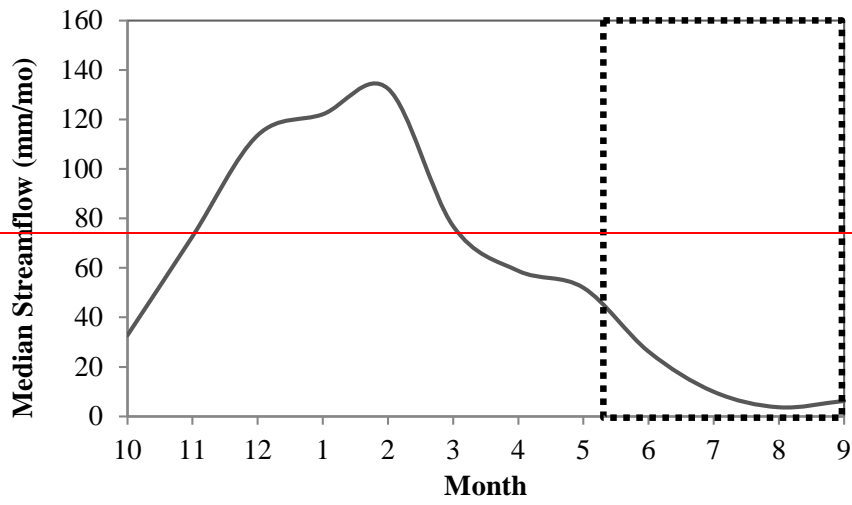
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Timeline	1935	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005										
Afforestation Period	P1			P2			E1			E2															
75 yr Trend Test	1936 to 2010																								
50 yr Trend Tests	1936 to 1985										1961 to 2010														
35 yr Trend Tests	1936 to 1970						1956 to 1990																		
25 yr Trend Tests	1936 to 1960				1946 to 1970					1956 to 1980						1966 to 1990				1976 to 2000			1986 to 2010		

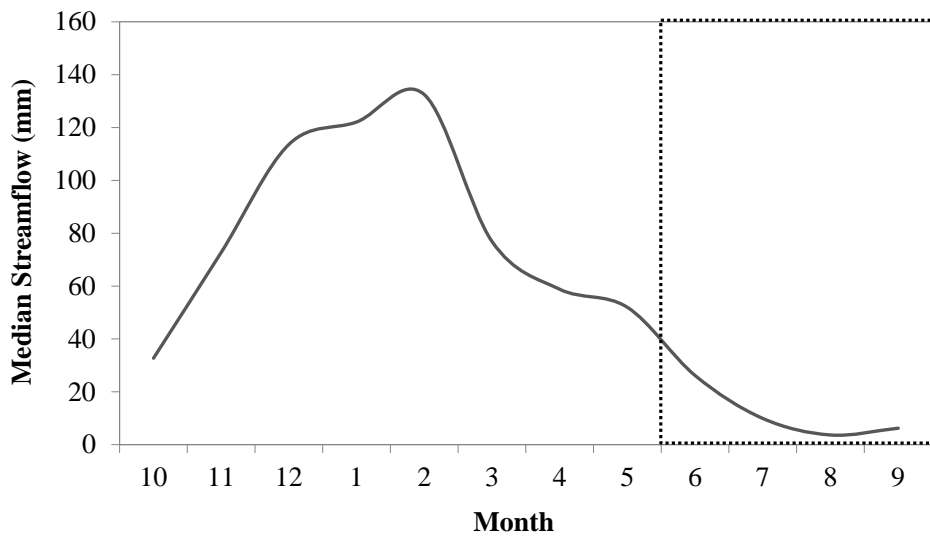
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Figure 4. Timeline of the trend-testing periods and their correspondence with the different afforestation periods.

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3 Figure 5. Monthly ~~means of mean~~ streamflow during the years without seasonal  
4 ~~impoundment. The impoundments; the~~ boxed off period (June - September)  
5 ~~represents indicates~~ the period removed from the streamflow and baseflow analysis.

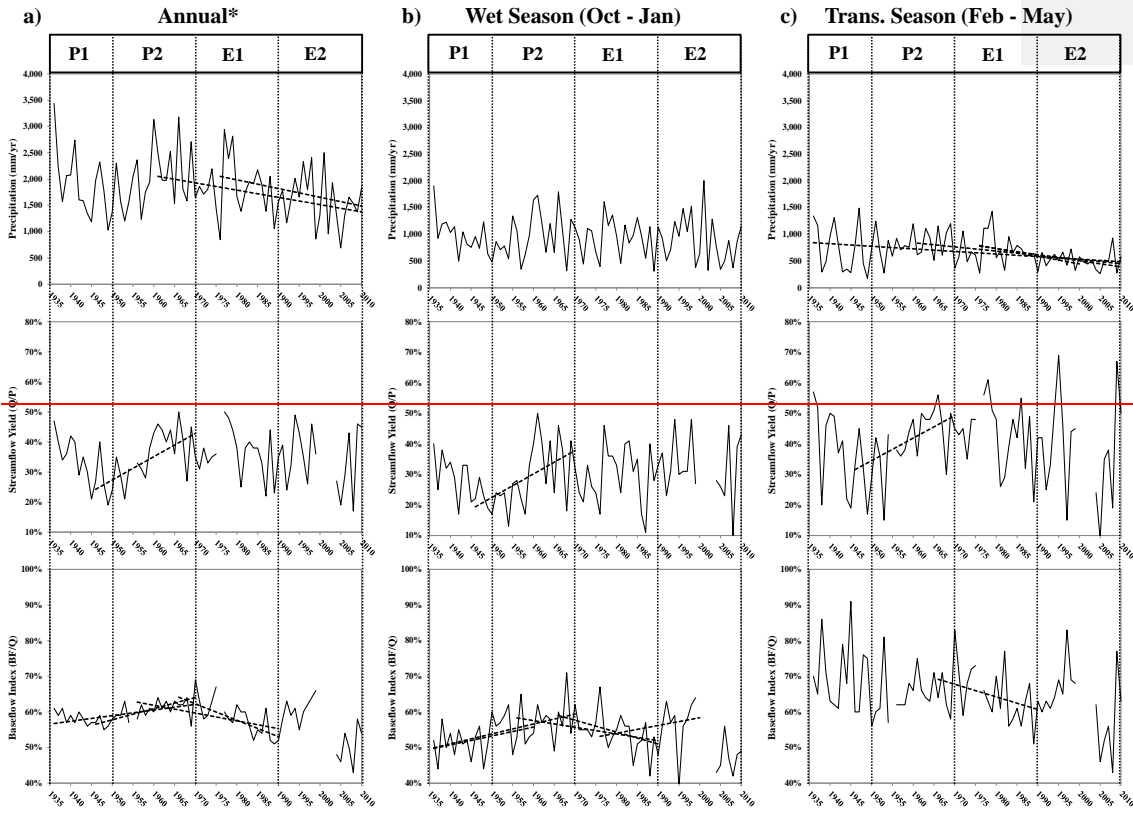
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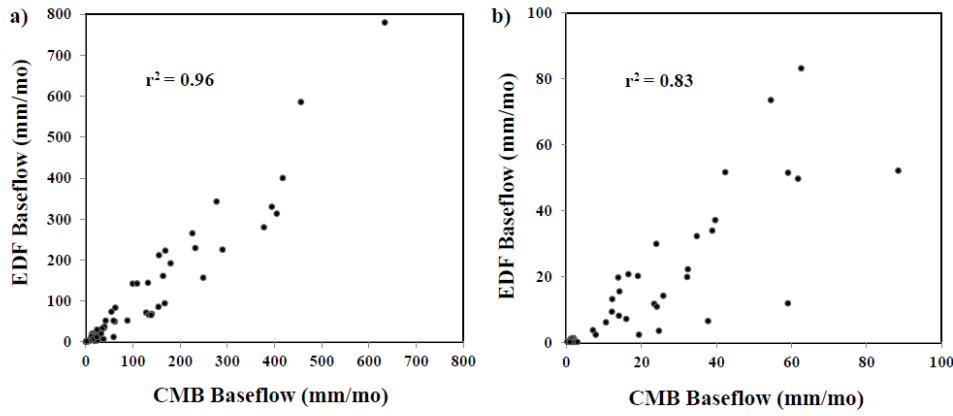
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Figure

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1 Figure 6. Monthly plots of baseflow from the Conductivity Mass-Balance (CMB) and  
2 Eckhardt digital filter calculations; 5a includes all months ( $r^2 = 0.96$ ) and 5b includes months  
3 with less than 100 mm of baseflow ( $r^2 = 0.83$ ).

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Figure 7. Summary of the trend testing results, with the afforestation periods (P1, P2, E1, E2: cf. Table 1) overlain for comparison. Significant trends are indicated with dashes lines ~~(the full test results are given in Appendix A).~~

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