

# 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 of the species *Pinus pinaster* and *Eucalyptus globulus* since the early 1900s; however, the long-term hydrologic 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 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 been no significant reduction in streamflow yield over either the entire test period, or during sub-record periods, despite large-scale afforestation. This lack of change is attributed to both the characteristics of the watershed and the nature of the land cover change. By contrast, a number of significant trends were found for baseflow index, which showed 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 are attributed to vegetation impacts on streamflow generating processes, both due to the species differences and to alterations in soil properties

1 (i.e. promoting water repellency of the topsoil). These results highlight the importance of  
2 considering both vegetation types/dynamics and watershed characteristic when assessing  
3 hydrologic impacts, in particular with respect to soil properties.

## 4 5 **1 Introduction**

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

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

25 Changes in forest cover can also modify hydrologic flow pathways by altering physical soil  
26 conditions (i.e. macroporosity) and forested areas tend to have higher infiltration rates, and  
27 hence groundwater recharge rates, than alternate land cover types (e.g. Bruijnzeel, 2004).  
28 Higher infiltration rates can help maintain baseflow during dry periods (e.g. Scott and Lesch,  
29 1997) and may also help mitigate storm-driven peak flows. However, this flood mitigation  
30 impact has been shown to be variable and can be over-ridden by other physical watershed  
31 characteristics during large flood events (Calder, 2005; Wahren et al., 2012).

1 While the general hydrologic impacts of forests at the watershed scale are fairly well  
2 understood, predicting the effects of a forest land cover change for a given watershed requires  
3 consideration of both physical site conditions and the specific vegetation types involved. In  
4 this respect, Andréassian (2004) identified several prerequisite conditions that need to be met  
5 in order to observe hydrologic impacts at the watershed scale. These include climatic (i.e.  
6 periods of hydrologic surplus / deficit), pedological (i.e. soil depth) and eco-physiological (i.e.  
7 forest age-dependence) conditions.

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

27 Besides transpiration, evaporation from canopy interception is an important component of  
28 water use by Mediterranean forests. Interception rates have been found to vary widely,  
29 depending on the tree species, canopy density, and climatic conditions. In central Portugal,  
30 interception rates of pine and eucalypt plantations have been found to be typically less than 20  
31 % of total rainfall. For *Pinus pinaster*, Ferreira (1996) reported interception rates of 15-18 %,  
32 while Valente et al. (1997) found rates of 17 %. For *Eucalyptus globulus*, both Ferreira and

1 Valente et al. (1997) observed lower rates, amounting to 10-14 % and 11 %, respectively. By  
2 contrast, much higher interception rates have been found for other tree species in the  
3 Mediterranean, with values near and even exceeding 50 %. For example, Scarascia-Mugnozza  
4 et al. (1988) found canopy interception rates of 68 % for a mature *Quercus cerris* forest,  
5 Iovino et al. (1998) found rates of 58 % for a mature *Pinus negra* forest, and Tarazona et al.  
6 (1996) observed rates of 48 % for a mature *Pinus sylvestris* forest.

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

26 Despite the well-documented potential for hydrologic impacts from afforestation in the  
27 Mediterranean region, there has been little investigation into the long-term effects in north-  
28 central Portugal. This is in part due to a lack of long-term streamflow records that include the  
29 pre-afforestation period. A notable exception to this lack of data is the Águeda watershed in  
30 the Caramulo Mountains, where streamflow data records are available from 1936 until the  
31 present.

1 Afforestation/deforestation studies typically focus on small paired watersheds, of which one  
2 has undergone fairly abrupt and well-recorded changes in land cover (e.g. Bosch and Hewlett,  
3 1982). By contrast, this study is conducted on a meso-scale watershed (404 km<sup>2</sup>), where  
4 afforestation has occurred in a progressive manner over a long period of time. Furthermore,  
5 the present study case lacks a nearby watershed which has a similarly long data record and  
6 also similar physical-environmental characteristics (or a land use history without similar land  
7 cover changes). The Águeda watershed also presents a major challenge for conducting an  
8 impact assessment based on hydrologic modeling, as there is insufficient spatial information  
9 available during the afforestation periods, and detailed maps of land cover for the study are  
10 lacking before 1990. Therefore, this study adopts an assessment approach that is data-driven  
11 and exploratory, examining the available hydro-meteorological data over the 75-year period  
12 from 1936 to 2010. This assessment is conducted not only over the entire period, but also  
13 within multiple (overlapping) sub-periods, and the temporal patterns for both annual and  
14 seasonal values are analyzed. The trends detected through robust time series analysis are then  
15 related to an approximated afforestation record, and related to the findings from previous  
16 field-based studies conducted in this area. Therefore, the objective of this study is to apply a  
17 trend-testing methodology to a long-term data set in a watershed which has undergone  
18 progressive afforestation over a 75-year period, to assess what significant trends/changes can  
19 be detected, and to relate these changes to the general afforestation pattern which has occurred  
20 there.

## 21 **2 Methods**

### 22 **2.1 Watershed Description**

23 The Águeda watershed is located in the Caramulo Mountains of north-central Portugal, east of  
24 the coastal city of Aveiro (Fig. 1). From the streamflow gauging point Ponte Águeda, the  
25 watershed area is approximately 404 km<sup>2</sup>. The Águeda River is a left bank tributary to the  
26 Vouga River, which terminates at the coastal wetland of the Ria de Aveiro lagoon. This  
27 region of Portugal is categorized as a wet Mediterranean climate zone, with pronounced  
28 seasonal differences in temperature and precipitation between dry summer and wet winter  
29 seasons (Fig. 2). The Serra do Caramulo Mountains, which forms the source area of the  
30 Águeda river network, receives a substantial amount of annual rainfall, which can range from  
31 1 000 to 2 500 mm/yr. The bedrock in the watershed consists primarily of a mix of schist and  
32 granite at higher elevations, with sedimentary rock formations present at lower elevations.

1 Topographically, the landscape is dominated by steep hill-slopes with stony and shallow soils,  
2 which have a long history of anthropogenic impacts.

3 The north-central region of Portugal has undergone substantial land cover/use changes over  
4 the past centuries, which have fundamentally altered the vegetative landscape. From the  
5 1800s until the 1980s, the region had a general trend towards both increased agricultural and  
6 forest land cover, with reductions in natural vegetation types, which was primarily due to the  
7 adoption of fertilizers and mechanization, as well as the abolition of feudal land systems  
8 (Estêvão, 1983; GPPAA, 2004; Jones et al., 2011). The period between 1930 and 1980 saw  
9 particularly rapid afforestation, due to incentives from the establishment of related  
10 government regulations and subsidies.

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

20 Portugal has a very high rate of wildfire events, which has significant impacts on post-fire  
21 hydrologic functioning, and is an important factor driving land-cover/use change in this  
22 region. Figure 3 shows the burned area of the Águeda watershed from 1975 to 2010, which  
23 illustrates the high frequency of wildfire and post-fire hydrologic impacts in the study site  
24 (Instituto da Conservação da Natureza e das Florestas, 2014). Over this period a total of 30  
25 790 hectares burned, with some single years having wildfire over more than 10 % of the  
26 watershed, such as 1986 and 1995. Wildfires can have significant hydrologic impacts in both  
27 the short term (e.g. by decreasing infiltration and enhancing runoff generation) and in the  
28 long-term (e.g. by altering vegetation cover and therefore evapotranspiration potential), and in  
29 addition they have been a major contributing factor promoting land-owners to convert from  
30 pine to eucalyptus plantations in the study region.

31 This region-wide trend of the afforestation of shrubland with *Pinus pinaster*, followed by a  
32 secondary transition from *Pinus pinaster* to *Eucalyptus globulus* plantations, is representative

1 of the land cover changes in the Águeda watershed, as well as in the Vouga basin as a whole.  
2 From this regional pattern, and from forestry maps of the Serra do Caramulo Mountains  
3 (Rego, 2001), a general afforestation timeline for the Águeda watershed during the period of  
4 investigation can be approximated, which is summarized in Table 1.

5 The current land cover in Águeda watershed reflects this large-scale transition towards  
6 eucalyptus forests. According to the Corine Land Cover classification of 2006, approximately  
7 44 % of the watershed was covered by broad-leaved forest, which primarily consisted of  
8 eucalyptus (Corine Land Cover, 2010). Other land cover types with significant areal coverage  
9 in 2006 include: 22 % mixed forest (mostly mixed stands of eucalypt and pine), 13 %  
10 transitional woodland-shrub (mostly post-fire recovery, or regrowth after clear-cutting), and 7  
11 % coniferous forest, which mainly consisted of *Pinus pinaster* (Fig. 1).

## 12 **2.2 Hydrometeorological Data**

13 Daily precipitation and streamflow records for the Águeda watershed were compiled from  
14 hydrological year 1935/36 (i.e. Oct 1st 1935 to Sep 30th 1936) until hydrological year  
15 2009/10 from the ‘Sistema Nacional de Informação de Recursos Hídricos’ (SNIRH, 2013).  
16 Precipitation data were compiled from the rain-gauge “Campia”, which consists of 24 h  
17 rainfall totals collected at 9:00 each day. Data gaps occurred with the greatest frequency  
18 between 1997 and mid-2003, which were filled by linear regression with the nearby rain-  
19 gauges “Varzielas” ( $r^2 = 0.82$ ) and “Barragem de Castelo Burgães” ( $r^2 = 0.79$ ).

20 Streamflow data consisted of daily average discharge measurements from the gauging station  
21 “Ponte Águeda”. This station was operational from June 1935 until the end of September  
22 1990, and was then reactivated in October 1999. Streamflow for the interim period (1990/91  
23 until 1998/99) was estimated by linear regression with the upstream gauges “Ribeiro” ( $r^2 =$   
24  $0.76$ ) and “Ponte Redonda” ( $r^2 = 0.75$ ). However, the streamflow estimates from the  
25 hydrologic years of 1999/2000 through 2002/03 were eliminated from the dataset, due to  
26 concerns about the data quality and, in particular, the absence of an adequate stage-discharge  
27 curve during this period.

28 In addition, a number of smaller streamflow gaps occurred throughout the streamflow dataset.  
29 When they occurred in periods with little or no precipitation, they were filled by fitting a  
30 logarithmic decay curve to the streamflow recession. Where this method was not possible,  
31 and the result was that more than 5 % of daily values were missing, then the entire

1 hydrological year was removed from analysis, which was the case for the years 1954/55 and  
2 1975/76. Finally, data for the driest months of the year (i.e. June to September) during the  
3 period before 1963 and after 2004 had very high uncertainty, due to unreported and variably  
4 occurring impoundments of streamflow during these months. Therefore, these four months  
5 were removed from the streamflow analysis for all years, to keep the inter-annual  
6 comparisons consistent.

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

### 18 **2.3 Thiel-Sen / Mann-Kendall Trend Testing Approach**

19 To examine the magnitude and significance of potential trends in the time-series, a multi-step  
20 trend-testing approach was applied, following the general approach presented in Yue et al.  
21 (2002). This approach first determined the magnitude (i.e. slope) of any potential trend in the  
22 data using the non-parametric Thiel-Sen slope estimator (Sen, 1968). This value was  
23 determined by selecting the median slope among the set generated between all sample points.  
24 This method also estimates the 95 % confidence intervals of the true slope, based on the set of  
25 slopes from sample points, which provides a measure of uncertainty of the median Thiel-Sen  
26 value. If a potential trend was detected by the Thiel-Sen test (i.e. a non-zero slope), then the  
27 data were processed using the ‘Trend Free Pre-whitening’ procedure of Yue et al. (2002).  
28 This step aimed to reduce the over-estimation of significance which can occur in time-series  
29 data that exhibit positive serial correlation, as is typically the case for streamflow time-series  
30 data.



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

6 For every data set, this trend testing procedure was applied over 12 time periods with varying  
7 starting dates and lengths (Fig. 4). The longest period contains the entire 75-year data record  
8 (1936-2010), followed by two periods of 50 years, three periods of 35 years, and six periods  
9 of 25 years. These periods were selected to thoroughly sample the potential range of years,  
10 while still allowing enough years of data to produce a robust significance test. Figure 4  
11 provides an overview of the testing periods, and their temporal correspondence with the  
12 afforestation periods listed in Table 1.

13 Over the time periods shown in Fig. 4, the trend testing was conducted for aggregated  
14 “annual” and “seasonal” values of precipitation (mm), streamflow quantity (mm), streamflow  
15 yield (streamflow/precipitation), baseflow quantity (mm), and baseflow index  
16 (baseflow/streamflow). The seasonal breakdown selected corresponds with the prevailing  
17 precipitation patterns of the study site, which consists of: the “Wet Season” from October to  
18 January when the largest amount of precipitation occurs, the “Transitional Season” from  
19 February to May when precipitation rates are reduced, and the “Dry Season” from June to  
20 September when precipitation is lowest. As stated previously however, the trend tests were  
21 not conducted during the “Dry Period” for streamflow (and therefore also baseflow), due to  
22 the uncertain data quality during these months.

23

## 24 **3 Results**

### 25 **3.1 Summary of the Seasonal Breakdown**

26 To characterize the hydrometeorological conditions of the three seasons, the median  
27 temperature, precipitation, streamflow quantity, streamflow yield, and baseflow index values  
28 over the study period are presented in Table 2. They clearly reveal the strong seasonality in  
29 precipitation patterns, with distinctly lower amounts during the dry season. During the wet  
30 and transitional periods, streamflow quantities are similar. However, both streamflow yield  
31 and baseflow index are higher during the transitional period, which reflects the sustained

1 streamflow carried over from the wet season precipitation and the lower proportion of  
2 streamflow coming directly from precipitation events.

### 3 **3.2 Analysis of the Elimination of the Dry Season Streamflow**

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

### 10 **3.3 Assessment of the Baseflow Calculations**

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

### 19 **3.4 Thiel-Sen / Mann-Kendall Trend Testing Results**

20 The results for the Thiel-Sen/Mann-Kendall trend tests for precipitation (mm), streamflow  
21 yield (streamflow/precipitation), and baseflow index (baseflow/streamflow) are presented by  
22 Fig. 6, while the full results for all variables are provided in the supplementary material. For  
23 the precipitation data, two significant trends were identified at the annual time-scale. The first  
24 concerned the 50-year period from 1961 to 2010, with a trend of  $-13.8$  mm/yr. The second  
25 concerned the 35-year period from 1976 to 2010 and corresponded to a decrease of  $-16.6$   
26 mm/yr. With respect to the seasonal analysis, no significant trends were found for the wet  
27 season, as opposed to four significant trends during the transitional season. All four  
28 significant trends corresponded to decreases in precipitation, i.e. of  $4.8$  mm/yr over the entire  
29 75-year data record from 1936 to 2010,  $7.9$  mm/yr. trend over the 50 years from 1961 to

1 2010, 11.3 mm/yr. trend over the 35 years from 1976 to 2010, and 14.3 mm/yr trend over the  
2 25-year period from 1976 to 2000. These trends indicate that there was an overall trend  
3 towards a decline in precipitation from February to May during the study period, and that this  
4 tendency was strongest during the period's final part.

5 For the streamflow quantity data, a single significant trend of  $-0.9$  mm/yr was found during  
6 the 50 year period from 1961 to 2010, which also corresponds with a period of a significant  
7 decrease in precipitation ( $-4.9$  mm/yr). With respect to streamflow yield data, a single  
8 positive trend was found for the annual data as well as for both the wet and transitional  
9 season. All three trends occurred during the 25-year period from 1946 to 1970, and  
10 corresponded to similar rates of increase (annual:  $+0.78$  %/yr; wet season:  $+0.77$  %/yr;  
11 transitional season:  $+0.74$  %/yr). These results indicated that the trend in streamflow yield  
12 during this period was fairly consistent across the year, although no assessment can be made  
13 about the dry season.

14 For the baseflow quantity data, significant negative trends were found for the annual data and  
15 the transitional season during the 50 year period from 1961 to 2010; with values of  $-6.1$   
16 mm/yr and  $-3.3$  mm/yr respectively (this also corresponds with a negative precipitation trend  
17 period). By contrast, the baseflow index data (BFI) showed the greatest number of significant  
18 trends of the variables considered, with a total of ten over the different periods of analysis.  
19 Over the 35-year period from 1936 to 1970, the annual data revealed an increase of  $+0.16$   
20 %/yr., whereas the wet season data showed an increase of  $+0.28$  %/yr. During the following  
21 35-year test period from 1956 to 1990, by contrast, there was a significant negative trend in  
22 the annual BFI data of  $-0.22$  %, and in the wet season BFI data of  $-0.19$  %/yr. Similar  
23 significant trends were found for the 25 year test periods, with increases of  $0.31$  %/yr for the  
24 annual data from 1946 to 1970 and  $0.25$  % for the wet season data from 1936 to 1960.  
25 Significant trends were detected for the period of 1966 to 1990, corresponding to decreases of  
26  $0.46$  %,  $0.33$  %, and  $0.35$  % in the annual, wet and transitional season data, respectively.

## 27 **4 Discussion**

### 28 **4.1 Precipitation Trends**

29 The precipitation data showed negative trends over much of the data period, which indicates  
30 that this study was conducted during a period with slightly reduced precipitation, although the  
31 climate remains very wet, with an aridity index range from 1.0 to greater than 1.5 (SNIRH,

1 2013). This downward trend was primarily due to reductions during the transitional season  
2 (February to May), and not during the wet season. According to projected climate change  
3 impacts for this region, this trend may be representative of future regional trends as well,  
4 which anticipate a decrease in rainfall by as much as 40 % by the end of the 21st century  
5 (Nunes et al., 2008).

6 A further consideration is that these reductions in precipitation during the transitional season  
7 could have impacted soil moisture levels in the dry season, which receives little additional  
8 precipitation input. This could have led to longer recovery times for soil moisture during the  
9 resumption of the wet season, which could have amplified soil water repellency during this  
10 period (both in terms of the duration and severity).

## 11 **4.2 Streamflow Trends**

12 The streamflow data revealed only one significant negative trend for quantity and none for  
13 yield over the periods tested, despite the large-scale afforestation that occurred in the test  
14 watershed. In addition, the single negative trend with respect to quantity corresponds to a  
15 significant negative trend in precipitation, and can therefore be attributed to a response to the  
16 reduction in precipitation input rather than to land cover change. Overall therefore, the results  
17 of this study do not support the general finding that afforestation tends to reduce streamflow  
18 (e.g. Bosch and Hewlett, 1982; Brown et al., 2005; Farley et al., 2005). However, this does  
19 not imply that this finding contradicts the complete findings of these studies, which also  
20 include examples where afforestation had either a positive or negligible impact on  
21 streamflow. Rather, this study supports the assertion of Andréassian (2004) that there are  
22 prerequisite soil, climatic, and physiological conditions that must be present in order to  
23 observe hydrologic impacts at the watershed scale.

24 With respect to soil conditions, it is likely that the characteristics of the soils of the Águeda  
25 watershed are a key factor in the lack of a reduction in streamflow. Under conditions of well-  
26 developed soils, the deeper rooting depths of trees will give greater access to soil moisture,  
27 allowing for more transpiration, resulting in higher water consumption. However, the soils of  
28 the Águeda watershed tend to be fairly shallow, being frequently less than a meter in depth,  
29 and are often as shallow as 20-30 cm (Santos et al., 2013). These depths are less than the  
30 maximum rooting depth of shrub species, as well as of pine and eucalypt, and therefore are  
31 likely to be a constraint to deep rooting for both species (Canadell et al., 1996). In addition,

1 the schist and granite bedrock in this watershed is relatively impermeable and not easily  
2 penetrated by tree roots, which restricts the access of tree species to groundwater reserves as  
3 well. Therefore, the capability of tree species to access deeper soil moisture than other  
4 vegetation types is likely much less relevant in this watershed than it would be in a site with  
5 deeper soils. In this case, the most important soil related factor in water consumption appears  
6 to be the low moisture storage capacity of the soils, and therefore the potential impact of  
7 higher water consumptive capacity of tree species is severely offset.

8 A second factor which could explain the lack of reductions in streamflow is the  
9 Mediterranean climatic regime of the study area. In all Mediterranean-type climates, the  
10 period of peak sunlight and temperature, and therefore potential evapotranspiration, is out of  
11 phase with the maximum precipitation period. Given the low amount of summer precipitation,  
12 and the shallowness of soils in this watershed, there will typically be little soil water available  
13 for summer evapotranspiration (David et al., 1997; Doerr and Thomas, 2000). In this regard,  
14 the climatic conditions of the study site might have an amplifying effect on the impacts of the  
15 shallow soils, by further reducing the potential impacts of the higher evapotranspiration  
16 potential of trees in this study site.

17 With respect to physiological conditions, the specific land cover changes observed in the  
18 Águeda watershed might also be a factor in the lack of an observed reduction in streamflow.  
19 One of the primary drivers of increased consumptive water use by tree species is their  
20 typically high canopy interception capacity (Domingo et al., 1994; Scarascia-Mugnozza et al.,  
21 1988; Tarazona et al., 1996). In the study watershed however the rates appear to be  
22 comparatively low for pine and eucalypt species (Coelho, 2008; Ferreira, 1996; Valente et al.,  
23 1997). At the same time, the interception capacity of Mediterranean shrublands can be  
24 relatively high. Garcia-Estringana et al. (2010) found that Mediterranean shrub species can  
25 have interception capacities similar to those of forests. In addition, interception rates are  
26 particularly high in shrublands growing in dense stands (Llorens and Domingo, 2007). These  
27 characteristics apply to the ‘matos’ shrubland which was the most common natural vegetation  
28 type in Águeda watershed prior to pine afforestation, as it has a relatively high leaf-area index  
29 and the tendency to grow in very dense stands (Asner et al., 2003). By contrast, given the  
30 poor soil conditions of the study site, the densities of the tree plantations are not as high as  
31 they could be on well-developed soils. Therefore, the land cover/use change from shrubland

1 to pine/eucalypt forest might not have resulted in large changes in either transpiration rates or  
2 canopy interception rates.

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

11 Although these findings indicate that there have been few significant reductions in streamflow  
12 during the wet, transitional, or annual time scales, negative trends may have occurred during  
13 the dry summer period, when the impact of tree species on soil moisture could be greatest.  
14 Unfortunately, given the limitation in the streamflow data (i.e. the summer streamflow  
15 impoundments), it was impossible to assess what the impacts of afforestation during the dry  
16 period. Therefore, no comparison could be made with the findings of Rodríguez-Suárez et al.  
17 (2011), who found dry season reductions in water table and streamflow discharge.

### 18 **4.3 Baseflow Trends**

19 For baseflow quantity (mm/yr), the only negative trends were found during the 50 year period  
20 from 1961 to 2010. However, as with the streamflow data this period corresponds with a  
21 negative precipitation trend period, and can therefore be attributed to the same cause. For  
22 baseflow index (BFI), no significant trend was found over the entire data record (1936-2010),  
23 but interestingly, numerous significant trends existed within the shorter periods. The general  
24 pattern in BFI was a positive trend during the P1 and P2 periods, followed by a negative trend  
25 from the middle of the P2 period through the E1 period. The P1/P2 periods correspond with a  
26 period of pine afforestation, which also showed the only significant positive trend in  
27 streamflow yield. This may indicate modifications in hydrologic flow pathways and/or soil  
28 moisture levels (i.e. higher soil moisture levels allowing for a higher proportion of baseflow)  
29 during this period. With respect to changes in flow pathways, an increase in baseflow index  
30 could indicate that there is less overland flow and fast subsurface flow (i.e. via macropores),  
31 and more water entering the soil matrix via infiltration. Given that previous studies have

1 shown that hydrophobic soil conditions can be promoted by pine species (Keizer et al., 2005b;  
2 Santos et al., 2013), pine afforestation would not necessarily be expected to increase BFI.  
3 However, the initial conversion to pine forests could have a positive impact on infiltration  
4 rates, especially due to ground preparation and planting operations breaking up the repellent  
5 topsoil layer and creating sinks for overland flow. With time, and in particular with soil and  
6 vegetation recovery, the repellent top soil layer would then become re-established,  
7 accounting for the reversal of the BFI trend in the later part of the P2 period. Also, the typical  
8 hydrologic impact of pine afforestation of reducing soil moisture due to higher consumptive  
9 water usage (e.g. Bosch and Hewlett, 1982) would not lead to a positive trend in BFI.  
10 However, as discussed previously, due to the shallow soils of the Águeda watershed, and  
11 expectedly similar water consumptive demands of matos shrubland and pine forest, this  
12 response is unlikely to occur in this study site. Again, the positive trend in baseflow in this  
13 period could also indicate that the immature pine forests consume less water than the previous  
14 land cover, leading to higher levels of soil moisture.

15 The negative trends in BFI occurred during the second half of the P2 period and during the E1  
16 period. Therefore, the strongest negative trend in BFI corresponded with the period when  
17 *Pinus pinaster* plantations reached greater maturity and (after logging) were being rapidly  
18 replaced with *Eucalyptus globulus*. Reductions in baseflow during this period could be  
19 attributed to hydrophobic soil conditions from the established pines and/or from the newly  
20 planted eucalypt stands, leading to an increase in quick flow (particularly via fast sub-surface  
21 flow from macropore infiltration) and the rapid conversion of precipitation into runoff.

22 Significant reductions in BFI were confined to the wet period, with only one exception. This  
23 might indicate that soil moisture levels were taking longer to recover at the onset of the wet  
24 season, leading to a delay in the time needed to break soil water repellency. This process is  
25 also likely to be self-reinforcing, since a delay in breaking SWR will also delay soil wetting.  
26 However, given that some water will enter the soil even under conditions of high SWR  
27 (particularly during prolonged storm events), the breakdown of SWR is likely to be more  
28 dependent on soil moisture conditions than vice-versa. By contrast, during the transitional  
29 season, soil moisture levels were typically high after the wet season (which was also reflected  
30 in the higher baseflow during this period), and soil water repellency would have largely  
31 disappeared by this point in the year. In this regard, a negative trend in BFI during the wet  
32 season could also be related to the negative trends seen for precipitation during the

1 transitional period. These rainfall reductions would be expected to reduce soil moisture at the  
2 onset of the dry season, resulting in even drier soil conditions at the start of the wet season. In  
3 this manner, the afforestation with eucalypt and the decrease in precipitation during the  
4 transitional period could have compounding impacts on the BFI trends during the wet season.

#### 5 **4.4 Pine vs. Eucalypt Afforestation**

6 From the standpoint of promoting well-regulated streamflow (i.e. higher baseflow) the  
7 impacts of the afforestation with pine were generally positive, while those of re-/afforestation  
8 with eucalypts were generally negative. This agrees with the popular perception that  
9 eucalyptus species diminish the availability of water for human usage. However, it is  
10 important to stress that the pine and eucalypt planting in the study catchment took place on  
11 dissimilar types of land cover. Pines were primarily replacing naturally occurring shrublands,  
12 which was followed by the replacement of the planted pines by eucalypts. Therefore, a direct  
13 comparison between the impacts of widespread planting with pine or with eucalypt cannot be  
14 drawn from this study. Nonetheless, the general pattern in the detected trends suggested that  
15 the conversion from matos shrubland to pine forests had significant impacts on hydrologic  
16 processes, at least initially, while the conversion from pines to eucalypts did not.

#### 17 **5 Conclusions**

18 This study did not detect statistically significant – negative or positive – trends in streamflow  
19 quantity or yield in the Águeda watershed of north-central Portugal over the 75 year period  
20 examined (i.e. the entire data record), despite of large scale afforestation with *Pinus pinaster*  
21 and later *Eucalyptus globulus* which has taken place there. However, this study did uncover  
22 significant trends in the examined variables over the sub-record periods, and that these trends  
23 correspond with impacts attributed to the changing land cover/use patterns over these periods.  
24 The lack of negative trends in streamflow can be explained by the specific climatic,  
25 pedological, and eco-physiological conditions of the watershed. From the two major  
26 conversions in land cover/use, the widespread planting of pine trees in matos shrublands had a  
27 significant – initial – impact on baseflow, while the substitution of pine plantations by  
28 eucalypt plantations had a negative impact on baseflow. These findings agree with the results  
29 of previous studies in this region of Portugal; however, they contrast with the general pattern  
30 of findings from afforestation/deforestation meta-analyses. As such, the present case study  
31 highlights the importance of considering both the specific attributes of a study area and the



1 nature of the land cover/use change, when assessing the hydrologic impacts of changes in  
2 forest cover.

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

22

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12



1 Table 1. Summary of afforestation trends in Águeda watershed from 1935 to 2010.

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

2

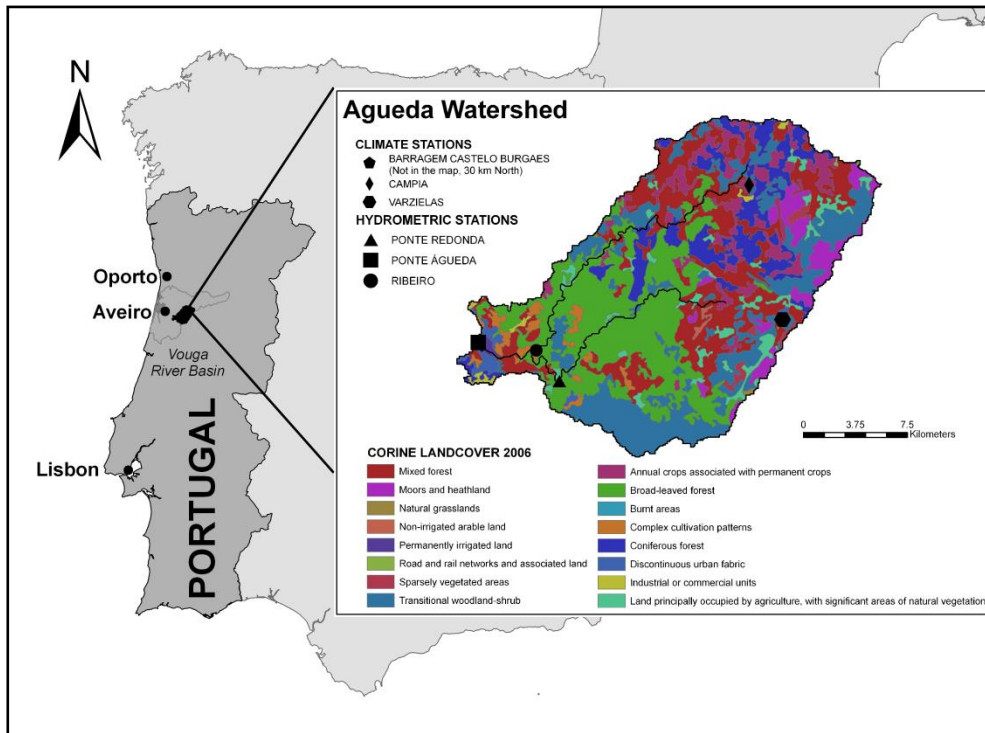
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4 Table 2. Season and annual median values of T = temperature (°C); P = precipitation (mm/yr);  
 5 Q = streamflow; Q<sub>yield</sub> = streamflow yield (streamflow/precipitation); BFI = baseflow index  
 6 (baseflow/streamflow) in Águeda watershed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

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

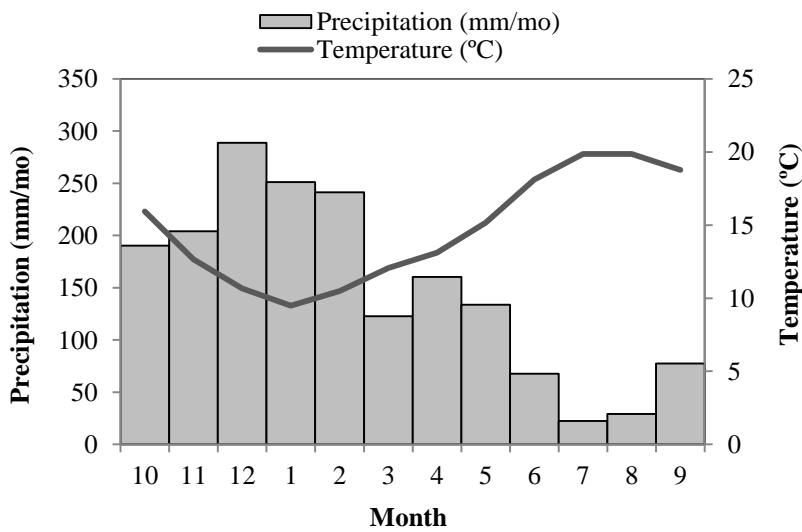
7 \* The months of June to September are not included for Q (mm), Q<sub>yield</sub> (%), BF (mm), and BFI (%).

8



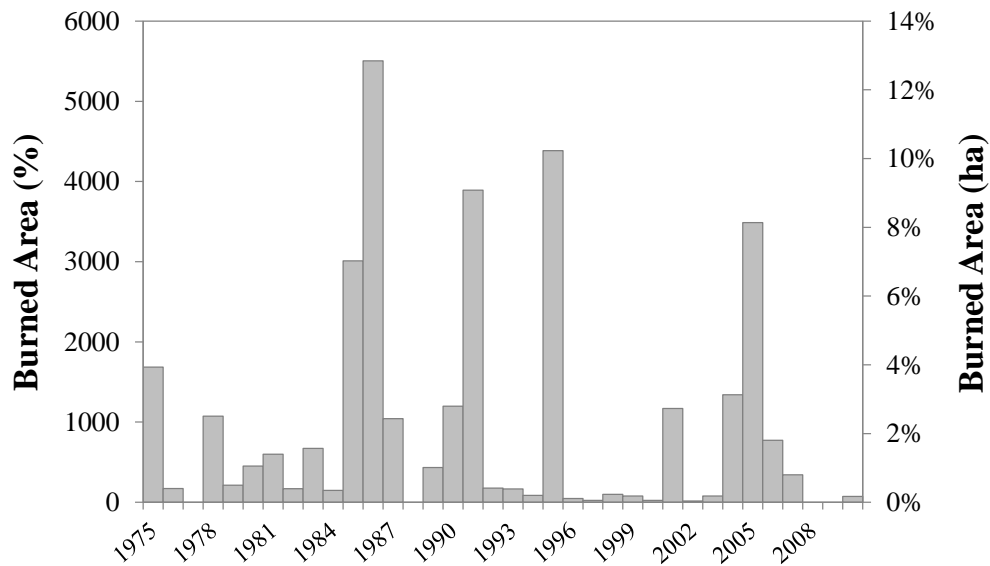
1  
2 Figure 1. Map of the Águeda watershed.

3



4  
5 Figure 2. Average monthly precipitation and temperature in the Águeda watershed from 1971  
6 – 2000.

7



1  
 2 Figure 3. Burned area in the Águeda watershed from 1975 to 2010. Total watershed area is  
 3 404 km<sup>2</sup>.

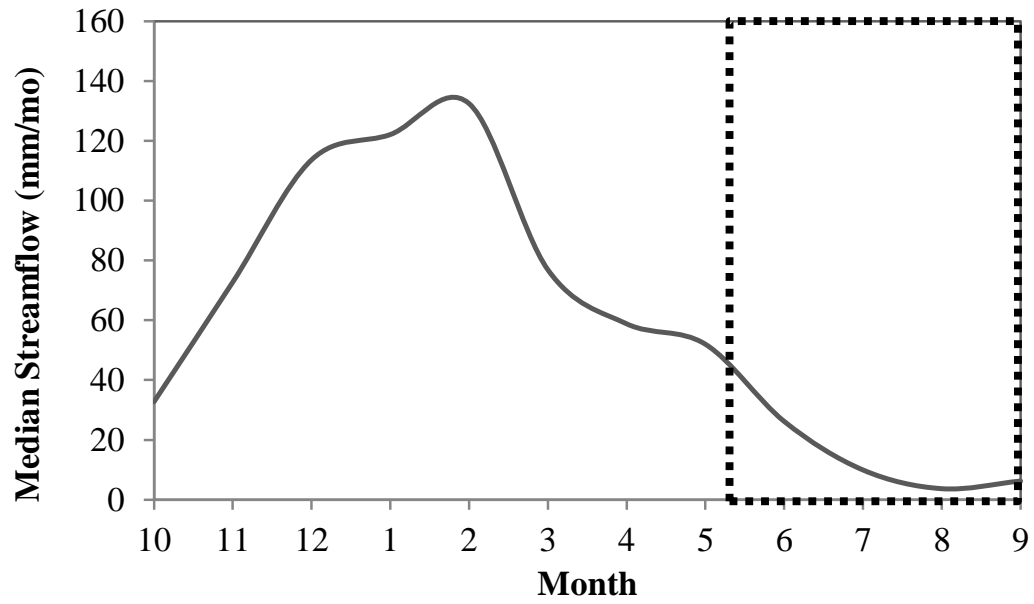
4

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						1976 to 2010									
	1936 to 1960														
				1946 to 1970											
			1956 to 1980						1966 to 1990						
										1976 to 2000					
												1986 to 2010			

5

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

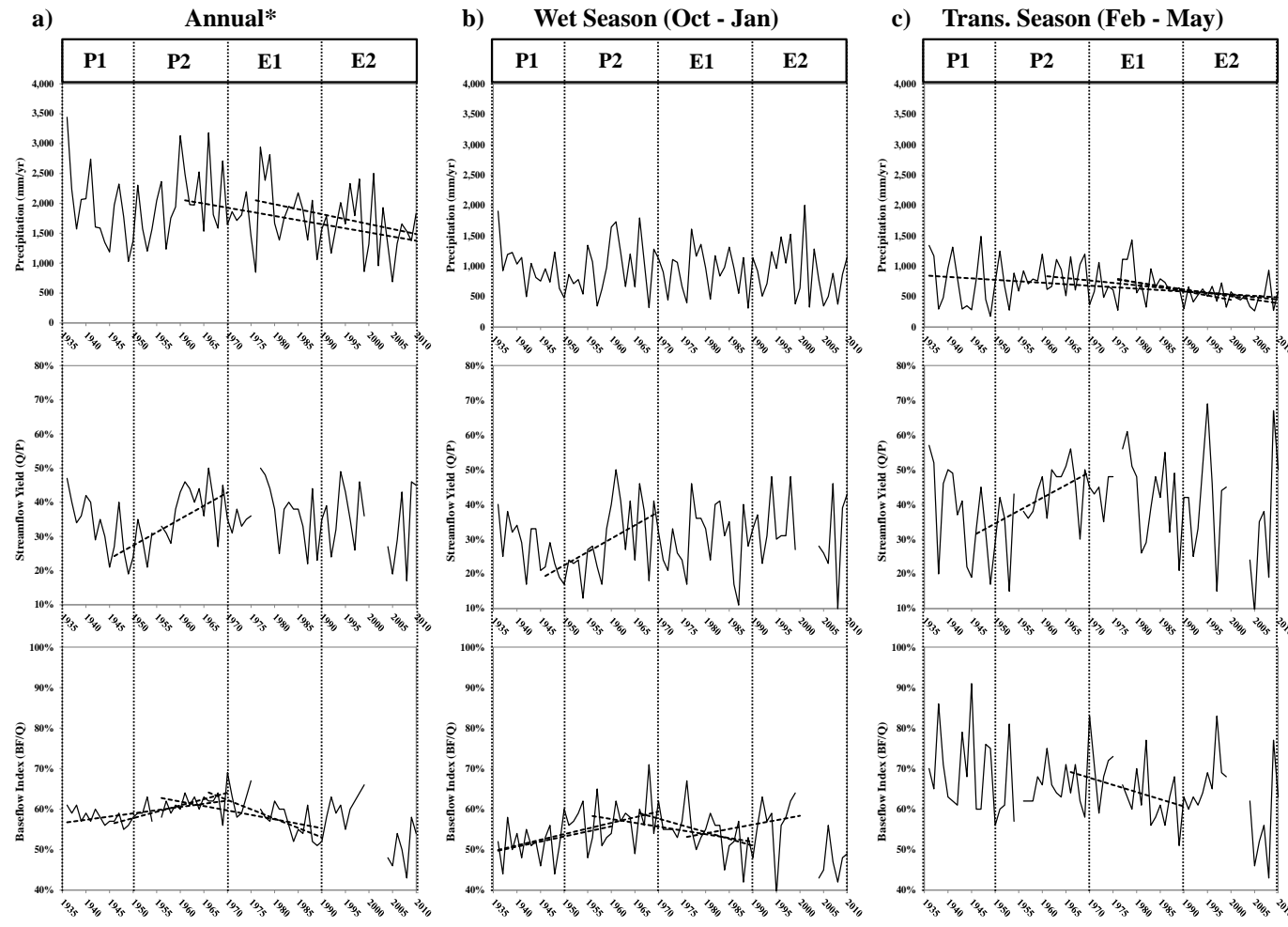
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1

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

5



1  
 2 Figure 6. Summary of the trend testing results, with the afforestation periods (P1, P2, E1, E2: cf. Table 1) overlain for comparison. Significant  
 3 trends are indicated with dashes lines.

