Hydrol. Earth Syst. Sci. Discuss., 11, 12223–12256, 2014
www.hydrol-earth-syst-sci-discuss.net/11/12223/2014/
doi:10.5194/hessd-11-12223-2014

Hydrology and Earth System Sciences
Open Access
Discussions

Time-series analysis of the long-term hydrologic impacts of afforestation in the Águeda watershed of North-Central Portugal

D. Hawtree[1], **J. P. Nunes**[2], **J. J. Keizer**[2], **R. Jacinto**[2], **J. Santos**[2], **M. E. Rial-Rivas**[2], **A.-K. Boulet**[2], **F. Tavares-Wahren**[1], **and K.-H. Feger**[1]

[1]Technische Universität Dresden, Institute of Soil Science & Site Ecology, Pienner Str. 19, 01737 Tharandt, Germany
[2]University of Aveiro, CESAM & Department of Environment and Planning, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

Received: 25 August 2014 – Accepted: 7 October 2014 – Published: 4 November 2014

Correspondence to: D. Hawtree (daniel.hawtree@mailbox.tu-dresden.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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 7 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 ~~the~~ large-scale afforestation ~~which had taken place~~. 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 (i.e. promoting 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.

1 Introduction

Water resource management is inherently tied to watershed-scale land use and land cover, and proper management requires understanding how changes in land cover/use will impact hydrological processes (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 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).

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

While the general hydrologic impacts of forests at the watershed scale are fairly well understood, predicting the effects of a forest land cover change for a given watershed requires consideration of both physical site conditions and the specific vegetation types involved. In this respect, Andréassian (2004) identified several prerequisite conditions that need to be met in order to observe hydrologic impacts at the watershed scale.

These include climatic (i.e. periods of hydrologic surplus/deficit), pedological (i.e. soil depth) and eco-physiological (i.e. forest age-dependence) conditions.

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

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

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 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, Iovino et al. (1998) rates of 58 % for a mature *Pinus negra* forest, and Tarazona et al. (1996) rates of 48 % for a mature *Pinus sylvestris* forest.

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

Despite the well-documented potential for hydrologic impacts from afforestation in the Mediterranean region, there has been little investigation into the long-term effects in north-central Portugal. This is in part due to a lack of long-term streamflow records that include the pre-afforestation period. A notable exception to this lack of data is the

Águeda watershed in the Caramulo Mountains, where streamflow data records are available from 1936 until the present.

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

2 Methods

2.1 Watershed description

The Águeda watershed is located in the Caramulo Mountains of north-central Portugal, east of the coastal city of Aveiro (Fig. 1). From the streamflow gauging point Ponte Águeda, the watershed area is approximately 404 km^2. The Águeda River is a left bank tributary to the Vouga River, which terminates at the coastal wetland of the Ria de Aveiro lagoon. This region of Portugal is categorized as a wet Mediterranean climate zone, with pronounced seasonal differences in temperature and precipitation between dry summer and wet winter seasons (Fig. 2). The Serra do Caramulo Mountains, which forms the source area of the Águeda river network, receives a substantial amount of annual rainfall, which can range from 1000 to 2500 $\mathrm{mm\,yr}^{-1}$. The bedrock in the watershed consists primarily of a mix of schist and granite at higher elevations, with sedimentary rock formations present at lower elevations. Topographically, the landscape is dominated by steep hill-slopes with stony and shallow soils, which have a long history of anthropogenic impacts.

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

A key driver was the enactment of legislation in 1938 which encouraged afforestation of areas classified as "uncultivated/wasteland", which often consisted of areas of matos (shrublands), mountain ranges, and sand dunes (Coelho et al., 1995; Estêvão, 1983; Ferreira et al., 2010; Silva et al., 2004; Jones et al., 2011). The primary species planted during this earlier period was *Pinus pinaster*; however beginning in the 1970s,

Eucalyptus globulus became the preferred species due to its faster growth and higher profitability for use in the paper pulp industry. During this period, eucalypt plantations began to replace pine forests as these were harvested, as well as being widely introduced into remaining areas of shrublands and in recently burned areas (Jones et al., 2011).

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

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

The current land cover in Águeda watershed reflects this large-scale transition towards eucalyptus forests. According to the Corine Land Cover classification of 2006, approximately 44 % of the watershed was covered by broad-leaved forest, which primarily consisted of eucalyptus. Other land cover types with significant areal coverage in 2006 include: 22 % mixed forest (mostly mixed stands of eucalypt and pine), 13 %

transitional woodland-shrub (mostly post-fire recovery, or regrowth after clear-cutting), and 7 % coniferous forest, which mainly consisted of *Pinus pinaster* (Fig. 1).

2.2 Hydrometeorological data

Daily precipitation and streamflow records for the Águeda watershed were compiled from hydrological year 1935/1936 (i.e. 1 October 1935 to 30 September 1936) until hydrological year 2009/2010 from the “Sistema Nacional de Informação de Recursos Hídricos” (SNIRH, 2013). Precipitation data were compiled from the rain-gauge “Campia”, which consists of 24 h rainfall totals collected at 09:00 LT each day. Data gaps occurred with the greatest frequency between 1997 and mid-2003, which were filled by linear regression with the nearby rain-gauges “Varzielas” ($r^2 = 0.82$) and “Barragem de Castelo Burgães” ($r^2 = 0.79$).

Streamflow data consisted of daily average discharge measurements from the gauging station “Ponte Águeda”. This station was operational from June 1935 until the end of September 1990, and was then reactivated in October 1999. Streamflow for the interim period (1990/1991 until 1998/1999) was estimated by linear regression with the upstream gauges “Ribeiro” ($r^2 = 0.76$) and “Ponte Redonda” ($r^2 = 0.75$). However, the streamflow estimates from the hydrologic years of 1999/2000 through 2002/2003 were eliminated from the dataset, due to concerns about the data quality and, in particular the absence of an adequate stage-discharge curve during this period.

In addition, a number of smaller streamflow gaps occurred throughout the streamflow dataset. When they occurred in periods with little or no precipitation, they were filled by fitting a logarithmic decay curve to the streamflow recession. Where this method was not possible, and the result was that more than 5 % of daily values were missing, then the entire hydrological year was removed from analysis, which was the case for the years 1954/1955 and 1975/1976. Finally, data for the driest months of the year (i.e. June to September) during the period before 1963 and after 2004 had very high uncertainty, due to unreported and variably occurring impoundments of streamflow during

these months. Therefore, these four months were removed from the streamflow analysis for all years, to keep the inter-annual comparisons consistent.

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

2.3 Thiel–Sen/Mann–Kendall trend testing approach

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

After the “Trend Free Pre-whitening procedure”, a Mann–Kendall test was applied to assess the statistical significance of any non-zero slope identified by the Thiel–Sen test. The Mann–Kendall test is a widely used, rank-based significance test, where the null hypothesis is that there is no trend in the observed series (Helsel and Hirsch, 1992). Statistical significance was determined using an α value of 0.05.

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

Over the time periods shown in Fig. 4, the trend testing was conducted for aggregated “annual” and “seasonal” values of precipitation (mm yr^{-1}), streamflow quantity (mm yr^{-1}), streamflow yield (streamflow/precipitation), baseflow quantity (mm yr^{-1}), and baseflow index (baseflow/streamflow). 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. As stated previously however, 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.

3 Results

3.1 Summary of the seasonal breakdown

To characterize the hydrometeorological conditions of the three seasons, the median temperature, precipitation, streamflow quantity, streamflow yield, and baseflow index values over the study period are presented in Table 2. They clearly reveal the strong seasonality in precipitation patterns, with distinctly lower amounts ~~occurring~~ during the dry season. During the wet and transitional periods, streamflow quantities are similar. However, both streamflow yield and baseflow index are higher during the transitional period, which reflects the sustained streamflow carried over from the wet season precipitation and the lower proportion of streamflow coming directly from precipitation events.

3.2 Analysis of the elimination of the dry season streamflow

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

3.3 Assessment of the baseflow calculations

To provide a check on the baseflow values estimated with the Eckhardt digital filter (Eckhardt, 2008), the obtained results were compared against baseflow values calculated using conductivity data from 2001 to 2009 with the “Conductivity Mass-Balance Method” (Stewart et al., 2007). At a monthly time-scale, the two baseflow data-sets were strongly correlated (Pearson’s correlation coefficient of 0.96), which indicates that the Eckhardt method agreed well with the more empirical Conductivity Mass-Balance Method. This in itself does not confirm the accuracy of the baseflow values utilized, but it does indicate their consistency over the study period, and thus their suitability for time series 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, which provides visualization for a selection of the time-series with the most noteworthy findings. The full results for all periods and variables analyzed are available in the Supplement. 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.

For the precipitation data, two significant trends were identified at the annual timescale. The first concerned the 50 year period from 1961 to 2010, with a trend of $-13.8\,\mathrm{mm\,yr^{-1}}$. The second concerned the 35 year period from 1976 to 2010 and corresponded to a decrease of $-16.6\,\mathrm{mm\,yr^{-1}}$. 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 $4.8\,\mathrm{mm\,yr^{-1}}$ over the entire 75 year data record from 1936 to 2010, $7.9\,\mathrm{mm\,yr^{-1}}$ trend over the 50 years from 1961 to 2010, $11.3\,\mathrm{mm\,yr^{-1}}$ trend over the 35 years from 1976 to 2010, and $14.3\,\mathrm{mm\,yr^{-1}}$ trend over the 25 year period from 1976 to 2000. These trends indicate that there was an overall trend towards a decline in precipitation from February to May during the study period, and that this tendency was strongest during the period's final part.

For the streamflow quantity data, a single significant trend of $-0.9\,\mathrm{mm\,yr^{-1}}$ was found during the 50 year period from 1961 to 2010, which also corresponds with a period of a significant decrease in precipitation ($-4.9\,\mathrm{mm\,yr^{-1}}$). With respect to streamflow yield data, a single positive trend was found for the annual data as well as for both the wet and transitional season. All three trends occurred during the 25 year period from 1946 to 1970, and corresponded to similar rates of increase (annual: $+0.78\,\%\,\mathrm{yr^{-1}}$; wet season: $+0.77\,\%\,\mathrm{yr^{-1}}$; transitional season: $+0.74\,\%\,\mathrm{yr^{-1}}$). These results indicated that the trend in streamflow yield during this period was fairly consistent across the year, although no assessment can be made about the dry season.

For the baseflow quantity data, significant negative trends were found for the annual data and the transitional season during the 50 year period from 1961 to 2010; with values of -6.1 and $-3.3\,\mathrm{mm\,yr^{-1}}$ respectively (this also corresponds with a negative precipitation trend period). By contrast, the baseflow index data (BFI) showed the greatest number of significant trends of the variables considered, with a total of ten over the different periods of analysis. Over the 35 year period from 1936 to 1970, the annual data revealed an increase of $+0.16\,\%\,\mathrm{yr^{-1}}$, whereas the wet season data showed an increase of $+0.28\,\%\,\mathrm{yr^{-1}}$. During the following 35 year test period from 1956 to 1990, by contrast, there was a significant negative trend in the annual BFI data of $-0.22\,\%$, and in the west season BFI data of $-0.19\,\%\,\mathrm{yr^{-1}}$. Similar significant trends were found for the 25 year test periods, with increases of $0.31\,\%\,\mathrm{yr^{-1}}$ for the annual data from 1946 to 1970 and 0.25 % for the wet season data from 1936 to 1960. Significant trends were detected for the period of 1966 to 1990, corresponding to decreases of 0.46, 0.33, and 0.35 % in the annual, wet and transitional season data, respectively.

4 Discussion

4.1 Precipitation trends

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

A further consideration is that these reductions in precipitation during the transitional season could have impacted soil moisture levels in the dry season, during which there is little additional precipitation input. 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). This is discussed further in the section on potential impacts on the~~n~~ baseflow index.

4.2 Streamflow trends

The streamflow data revealed only one significant negative trend for quantity ~~(mm yr^{-1})~~ and none for yield over the periods tested, despite the large-scale afforestation that occurred in the test watershed. In addition, the single negative trend with respect to quantity corresponds with a significant negative trend in precipitation, and can therefore be attributed to a response to the reduction in precipitation input rather than to land cover change. Overall therefore, the results of this study do not support the general finding that afforestation tends to reduce streamflow (e.g. Bosch and Hewlett, 1982; Brown et al., 2005; Farley et al., 2005). However, this does not imply that this finding contradicts the complete findings of these studies, which also include examples where afforestation had either a positive or negligible impact on streamflow. Rather, this study supports the assertion of Andréassian (2004) that there are prerequisite soil, climatic, and physiological conditions that must be present in order to observe hydrologic impacts at the watershed scale.

With respect to soil conditions, it is likely that the characteristics of the soils of the Águeda watershed are a key factor in the lack of a reduction in streamflow. Under

conditions of well-developed soils, the deeper rooting depths of trees will give greater access to soil moisture, allowing for more transpiration, resulting in higher water consumption. However, the soils of the Águeda watershed tend to be fairly shallow, being frequently less than a meter in depth, and are often as shallow as 20–30 cm (Santos et al., 2013). These depths are well below the maximum rooting depth of shrub species, as well as of pine and eucalypt, and therefore are likely to be a constraint to deep rooting for both species (Canadell et al., 1996). In addition, the schist and granite bedrock in this watershed is relatively impermeable and not easily penetrated by tree roots, which restricts the access of tree species to groundwater reserves as well. Therefore, the capability of tree species to access deeper soil moisture than other vegetation types is likely much less relevant in this watershed than it would be in a site with deeper soils. In this case, the most important soil related factor in water consumption appears to be the low moisture storage capacity of the soils, and therefore the potential impact of higher water consumptive capacity of tree species is severely offset.

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

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

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

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

4.3 Baseflow trends

For baseflow quantity (mm yr^{-1}), the only negative trends were found during the 50 year period from 1961 to 2010. However, as with the streamflow data this period corresponds with a negative precipitation trend period, and can therefore be attributed to the same cause. For baseflow index (BFI), no significant trend was found over the entire data record (1936–2010), but interestingly, numerous significant trends existed within the shorter ~~test~~ periods. The general pattern in BFI was a positive trend during the P1 and P2 periods, followed by a negative trend from the middle of the P2 period through the E1 period. The P1/P2 periods correspond with a period of pine afforestation, which also showed the only significant positive trend in streamflow yield. This may indicate modifications in hydrologic flow pathways and/or soil moisture levels (i.e. higher soil moisture levels allowing for more baseflow) during this period. With respect to changes in flow pathways, an increase in baseflow index could indicate that there is less overland flow and fast subsurface flow (i.e. via macropores), and more water entering the soil matrix via infiltration. Given that previous studies have shown that hydrophobic soil conditions can be promoted by pine species (Keizer et al., 2005b; Santos et al., 2013), pine afforestation would not necessarily be expected to increase BFI. However, the initial conversion to pine forests could have a positive impact on infiltration rates, especially due to ground preparation and planting operations breaking up the repellent topsoil layer and creating sinks for overland flow. With time, and in particular with soil and vegetation recovery, the repellent top soil layer would then become re-established, accounting for the reversal of the BFI trend in the later part of the P2 period. Also, the typical hydrologic impact of pine afforestation of reducing soil moisture due to higher consumptive water usage (e.g. Bosch and Hewlett, 1982) would not lead to a positive trend in BFI. However, as discussed previously, due to the shallow soils of the Águeda watershed, and expectedly similar water consumptive demands of matos shrubland and pine forest, this response is unlikely to occur in this study site. Again, the positive trend in baseflow in this period could also reflect that the immature pine forests actually have less water consumption than the previous land cover, leading to higher levels of soil moisture.

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

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

4.4 Pine vs. eucalypt afforestation

From the standpoint of promoting well-regulated streamflow (i.e. higher baseflow) the impacts of the afforestation with pine were generally positive, while those of re-/afforestation with eucalypts were generally negative. This agrees with the popular perception that eucalyptus species diminish the availability of water for human usage.

However, it is important to stress that the pine and eucalypt planting in the study catchment took place on dissimilar types of land cover. Pines were primarily replacing naturally occurring shrublands, while eucalypts were primarily substituting planted pines. Therefore, a direct comparison between the impacts of widespread planting with pine or with eucalypt cannot be drawn from this study. Nonetheless, the general pattern in the detected trends suggested that the conversion from matos shrubland to pine forests had significant impacts on hydrologic processes, at least initially, while the conversion from pines to eucalypts did not.

5 Conclusions

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

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

The Supplement related to this article is available online at doi:10.5194/hessd-11-12223-2014-supplement.

Acknowledgements. The authors would like to express their gratitude to Celeste Coelho at the University of Aveiro, Centre for Environmental and Marine Studies (CESAM) for providing her expertise knowledge on the background and land use history of the study region. Thanks are also given to Ameur Manceur at the Helmholtz-Centre for Environmental Research, Computational Landscape Ecology and Community Ecology, for providing assistance on the statistical methods used. Funding for this research was provided by the "Erasmus Mundus – Forest and Nature for Society (FONASO) Joint Doctoral Program"; the European Regional Development Fund (through COMPETE), the European Social Fund and the Portuguese Republic (through FCT), both by individual fellowships (references: SFRH/BPD/87571/2012; SFRH/BPD/64425/2009; SFRH/BD/61451/2009) and research projects (references: FCOMP-01-0124-FEDER-009308; FCOMP-01-0124-FEDER-008534; PTDC/CTE-ATM/111508/2009); and the German Academic Exchange Service (DAAD) for sponsoring a bilateral collaboration action between Universidade de Aveiro and TU Dresden.

References

Andréassian, V.: Waters and forests: from historical controversy to scientific debate, J. Hydrol., 291, 1–27, doi:10.1016/j.jhydrol.2003.12.015, 2004.

Asner, G. P., Scurlock, J. M. O., and Hicke, A. J.: Global synthesis of leaf area index observations: implications for ecological and remote sensing studies, Global Ecol. Biogeogr., 12, 191–205, doi:10.1046/j.1466-822X.2003.00026.x, 2003.

Benito, E. and Santiago, J. L.: Deforestation of water repellent soils in Galicia (NW Spain): effects on surface runoff and erosion under simulated rainfall, Earth Surf. Proc. Land., 28, 145–155, doi:10.1002/esp.431, 2003.

Bosch, J. M. and Hewlett, J. D.: A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, J. Hydrol., 55, 3–23, doi:10.1016/0022-1694(82)90117-2, 1982.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, J. Hydrol., 310, 28–61, doi:10.1016/j.jhydrol.2004.12.010, 2005.

Bruijnzeel, L. A.: Hydrological functions of tropical forests: not seeing the soil for the trees?, Agr. Ecosyst. Environ., 104, 185–228, doi:10.1016/j.agee.2004.01.015, 2004.

Calder, I. R.: Water use by forests, limits and controls, Tree Physiol., 18, 625–631, doi:10.1093/treephys/18.8-9.625, 1998.

Calder, I. R.: Blue Revolution: Integrated Land and Water Resource Management, Earthscan, London, 2005.

Canadell, J., Jackson, R. B., Ehleringer, J. B., Mooney, H. A., Sala, O. E., and Schulze, E.-D.: Maximum rooting depth of vegetation types at the global scale, Oecologia, 108, 583–595, doi:10.1007/BF00329030, 1996.

Coelho, C. O. A., Ferreira, A. J. D., Prats, S. A., Tomé, M., Soares, P., Cortiçada, A., Tomé, J. A., Salas, G. R., Páscoa, F., and Amaral, A.: Assessment of climatic change impact on water resources and CO_2 fixation in fast growing stand in Portugal, Final Report Silvaqua Project POCTI/MGS/49210/2002, 2008.

Coelho, C. O. A., Shakesby, R. A., and Walsh, R. P. D.: Effects of Forest Fires and Post-fire Land Management Practice on Soil Erosion and Stream Dynamics, Águeda Basin, Portugal, Soil and groundwater research report V, European Commision, Luxembourg, 1995.

David, T. S., Ferreira, M. I., David, J. S., and Pereira, J. S.: Transpiration from a mature Eucalyptus globulus plantation in Portugal during a spring-summer period of progressively higher water deficit, Oecologia, 110, 153–159, doi:10.1007/PL00008812, 1997.

Doerr, S. H. and Thomas, A. D.: The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal, J. Hydrol., 231–232, 134–147, doi:10.1016/S0022-1694(00)00190-6, 2000.

Doerr, S. H., Shakesby, R. A., and Walsh, R. P. D.: Soil hydrophobicity variations with depth and particle size fraction in burned and unburned Eucalyptus globulus and Pinus pinaster forest terrain in the Águeda Basin, Portugal, Catena, 27, 25–47, doi:10.1016/0341-8162(96)00007-0, 1996.

Doerr, S. H., Shakesby, R. A., and Walsh, R. P. D.: Soil water repellency: its causes, characteristics and hydro-geomorphological significance, Earth-Sci. Rev., 51, 33–65, doi:10.1016/S0012-8252(00)00011-8, 2000.

Domingo, F., Puigdefabregas, J., Moro, M. J., and Bellot, J.: Role of vegetation cover in the biogeochemical balances of a small afforested catchment in southeastern Spain, J. Hydrol., 159, 275–289, doi:10.1016/0022-1694(94)90261-5, 1994.

Eckhardt, K.: A comparison of baseflow indices, which were calculated with seven different baseflow separation methods, J. Hydrol., 352, 168–173, doi:10.1016/j.jhydrol.2008.01.005, 2008.

Estêvão, J. A.: A florestação dos baldios, Análise Soc., 19, 77–79, 1983.

Farley, K. A., Jobbágy, E. G., and Jackson, R. B.: Effects of afforestation on water yield: a global synthesis with implications for policy, Global Change Biol., 11, 1565–1576, doi:10.1111/j.1365-2486.2005.01011.x, 2005.

Ferreira, A. J. D., Coelho, C. O. A., Walsh, R. P. D., Shakesby, R. A., Ceballos, A., and Doerr, S. H.: Hydrological implications of soil water-repellency in Eucalyptus globulus forests, north-central Portugal, J. Hydrol., 231–232, 165–177, doi:10.1016/S0022-1694(00)00192-X, 2000.

Ferreira, A. J. D., Coelho, C. O. A., Boulet, A. K., Leighton-Boyce, G., Keizer, J. J., and Ritsema, C. J.: Influence of burning intensity on water repellency and hydrological processes at forest and shrub sites in Portugal, Soil Res., 43, 327–336, 2005.

Ferreira, C. G.: Erosão hídrica em solos florestais: estudo em povoamentos de Pinus Pinaster e Eucalyptus Globulus em macieira de Alcôba-Águeda, Revista da Faculdade de Letras – Geografia I Série, vol XII/XIII, 145–244, 1997.

Ferreira, R. V., Cerqueira, M. A., de Melo, M. T. C., de Figueiredo, D. R., and Keizer, J. J.: Spatial patterns of surface water quality in the Cértima River basin, central Portugal, J. Environ. Monitor., 12, 189–199, doi:10.1039/b914409a, 2010.

Garcia-Estringana, P., Alonso-Blázquez, N., and Alegre, J.: Water storage capacity, stemflow and water funneling in Mediterranean shrubs, J. Hydrol., 389, 363–372, doi:10.1016/j.jhydrol.2010.06.017, 2010.

Geri, F., Amici, V., and Rocchini, D.: Human activity impact on the heterogeneity of a Mediterranean landscape, Appl. Geogr., 30, 370–379, doi:10.1016/j.apgeog.2009.10.006, 2010.

Giorgi, F. and Lionello, P.: Climate change projections for the Mediterranean region, Global Planet. Change, 63, 90–104, doi:10.1016/j.gloplacha.2007.09.005, 2008.

Helsel, D. R. and Hirsch, R. M. (Eds.): 12 Trend Analysis, in Studies in Environmental Science, vol. Volume 49, pp. 323-355, Elsevier, available from: http://www.sciencedirect.com/science/article/pii/S0166111608711117 (last access: 27 October 2014), 1992.

Instituto da Conservaçao da Natureza e das Florestas: Mapas de áreas ardidas entre 1990–1996, 1997–2004, 2010, 2011, 2012 e 2013, available at: http://www.icnf.pt/portal/florestas/dfci/inc/mapas, last access: 1 July 2014.

Iovino, F., Cinnirella, S., Veltri, A., and Callegari, G.: Processus hydriques dans des écosystèmes forestiers, Ecologie, 29, 369–375, 1998.

Jacinto, R., Cruz, M. J., and Santos, F. D.: Development of water use scenarios as a tool for adaptation to climate change, Drink. Water Eng. Sci., 6, 61–68, doi:10.5194/dwes-6-61-2013, 2013.

Jones, N., de Graaff, J., Rodrigo, I., and Duarte, F.: Historical review of land use changes in Portugal (before and after EU integration in 1986) and their implications for land degradation and conservation, with a focus on Centro and Alentejo regions, Appl. Geogr., 31, 1036–1048, doi:10.1016/j.apgeog.2011.01.024, 2011.

Keizer, J. J., Coelho, C. O. A., Matias, M. J. S., Domingues, C. S. P., and Ferreira, A. J. D.: Soil water repellency under dry and wet antecedent weather conditions for selected land-cover types in the coastal zone of central Portugal, Soil Res., 43, 297–308, 2005a.

Keizer, J. J., Ferreira, A. J. D., Coelho, C. O. A., Doerr, S. H., Malvar, M. C., Domingues, C. S. P., Perez, I. M. B., Ruiz, C., and Ferrari, K.: The role of tree stem proximity in the spatial variability of soil water repellency in a eucalypt plantation in coastal Portugal, Soil Res., 43, 251–259, 2005b.

Lim, K. J., Engel, B. A., Tang, Z., Choi, J., Kim, K.-S., Muthukrishnan, S., and Tripathy, D.: Automated Web Gis Based Hydrograph Analysis Tool, What1, J. Am. Water Resour. Assoc., 41, 1407–1416, doi:10.1111/j.1752-1688.2005.tb03808.x, 2005.

Llorens, P. and Domingo, F.: Rainfall partitioning by vegetation under Mediterranean conditions, a review of studies in Europe, J. Hydrol., 335, 37–54, doi:10.1016/j.jhydrol.2006.10.032, 2007.

Moreira, F., Rego, F. C., and Ferreira, P. G.: Temporal (1958–1995) pattern of change in a cultural landscape of northwestern Portugal: implications for fire occurrence, Landsc. Ecol. Eng., 16, 557–567, 2001.

Nunes, J. P., Seixas, J., and Pacheco, N. R.: Vulnerability of water resources, vegetation productivity and soil erosion to climate change in Mediterranean watersheds, Hydrol. Process., 22, 3115–3134, doi:10.1002/hyp.6897, 2008.

Rego, F. C.: Florestas Públicas, Ministério da Agricultura, Desenvolvimento Rural e Pescas, Lisbon, Portugal, 2001.

Rodríguez-Suárez, J. A., Soto, B., Perez, R., and Diaz-Fierros, F.: Influence of Eucalyptus globulus plantation growth on water table levels and low flows in a small catchment, J. Hydrol., 396, 321–326, doi:10.1016/j.jhydrol.2010.11.027, 2011.

Santos, J. M., Verheijen, F. G. A., Tavares Wahren, F., Wahren, A., Feger, K.-H., Bernard-Jannin, L., Rial-Rivas, M. E., Keizer, J. J., and Nunes, J. P.: Soil water repellency dynamics in pine and eucalypt plantations in Portugal – a high-resolution time series, Land Degrad. Dev., doi:10.1002/ldr.2251, in press, 2013.

Scarascia-Mugnozza, G., Valentini, R., and Spinelli, R. E. G.: Osservazioni sul ciclo dell'acqua in un bosco ceduo di Quercus cerris L., Ann. Dell'Accademia Ital. Sci. For., 37, 3–21, 1988.

Scott, D. F. and Lesch, W.: Streamflow responses to afforestation with Eucalyptus grandis and Pinus patula and to felling in the Mokobulaan experimental catchments, South Africa, J. Hydrol., 199, 360–377, doi:10.1016/S0022-1694(96)03336-7, 1997.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's Tau, J. Am. Stat. Assoc., 63, 1379–1389, doi:10.1080/01621459.1968.10480934, 1968.

Serra, P., Pons, X., and Saurí, D.: Land-cover and land-use change in a Mediterranean landscape: a spatial analysis of driving forces integrating biophysical and human factors, Appl. Geogr., 28, 189–209, doi:10.1016/j.apgeog.2008.02.001, 2008.

Shakesby, R. A., Doerr, S. H., and Walsh, R. P. D.: The erosional impact of soil hydrophobicity: current problems and future research directions, J. Hydrol., 231–232, 178–191, doi:10.1016/S0022-1694(00)00193-1, 2000.

Silva, G., Antunes, A., Escada, A. and Marques, J.: Relações Agricultura/Floresta Ambiente, Gabinete de Planeamento e Política Agro-Alimentar (GPPAA), Ministério da Agricultura, do Desenvolvimento Rural e das Pescas, Lisbon, Portugal, 2004.

SNIRH: Sistema Nacional de Informação de Recursos Hídricos, Agência Portuguesa do Ambiente, Lisbon, available at: http://snirh.pt, last access: 9 October 2013.

Stewart, M., Cimino, J., and Ross, M.: Calibration of base flow separation methods with streamflow conductivity, Ground Water, 45, 17–27, doi:10.1111/j.1745-6584.2006.00263.x, 2007.

Tarazona, T., Santa Regina, I., and Calvo, R.: Interception, throughfall and stemflow in two forest of the "Sierra de la Demanda" in the province of Burgos, Spain, Pirin, Espana available at: http://agris.fao.org/agris-search/search.do?f=1998%2FES%2FES98017.xml%3BES1998000049 (last access: 4 May 2014), 1996.

Valente, F., David, J. S., and Gash, J. H. C.: Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models, J. Hydrol., 190, 141–162, doi:10.1016/S0022-1694(96)03066-1, 1997.

Wahren, A., Schwärzel, K., and Feger, K.-H.: Potentials and limitations of natural flood retention by forested land in headwater catchments: evidence from experimental and model studies, J. Flood Risk Manage., 5, 321–335, doi:10.1111/j.1753-318X.2012.01152.x, 2012.

Yue, S., Pilon, P., Phinney, B., and Cavadias, G.: The influence of autocorrelation on the ability to detect trend in hydrological series, Hydrol. Process., 16, 1807–1829, doi:10.1002/hyp.1095, 2002.

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

Period code	Time period	Dominant afforestation trend
P1	1935–1950	Large scale replacement of shrubland with *Pinus pinaster.*
P2	1950–1970	Continuing afforestation with *Pinus pinaster,* but at a slower rate.
E1	1970–1990	Rapid reforestation with *Eucalyptus globulus* (particularly post ’86 wildfire), replacement of *Pinus pinaster.*
E2	1990–2010	Relatively stable forested area, with continued replacement of *Pinus pinaster* with *Eucalyptus globulus.*

Table 2. Season and annual median values of T = teperature (°C); P = precipitation ($\mathrm{mm\,yr^{-1}}$); Q = streamflow; Q_{yield} = streamflow yield (streamflow/precipitation); BFI = baseflow index (baseflow/streamflow) in Águeda watershed from 1936–2010.

		Median values: 1936–2010				
Season	Months	T (°C)	P ($\mathrm{mm\,yr^{-1}}$)	Q ($\mathrm{mm\,yr^{-1}}$)	Q_{yield} (%)	BFI (%)
Wet	Oct–Jan	11.7	965	301	30 %	55 %
Transitional	Feb–May	12.6	626	281	43 %	63 %
Dry	Jun–Sep	19.3	193	NA	NA	NA
Annual	All*	14.7	1787	565	36 %	59 %

* The months of June to September are not included for Q ($\mathrm{mm\,yr^{-1}}$), Q_{yield} (%), and BFI (%).

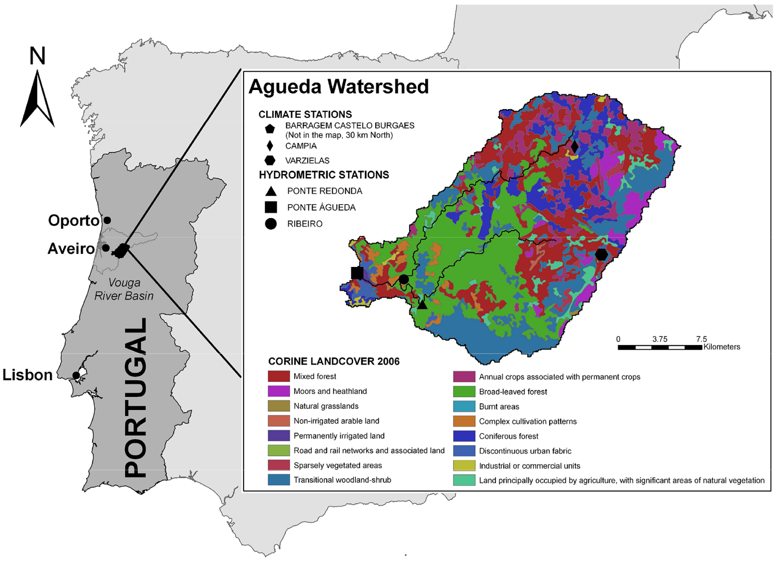


Figure 1. Map of the Águeda watershed.

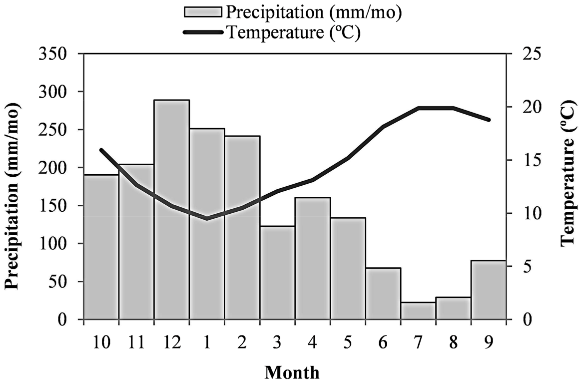


Figure 2. Average monthly precipitation and temperature in the Águeda watershed from 1971–2000.

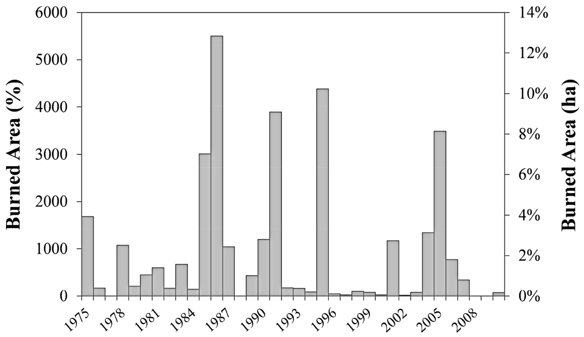
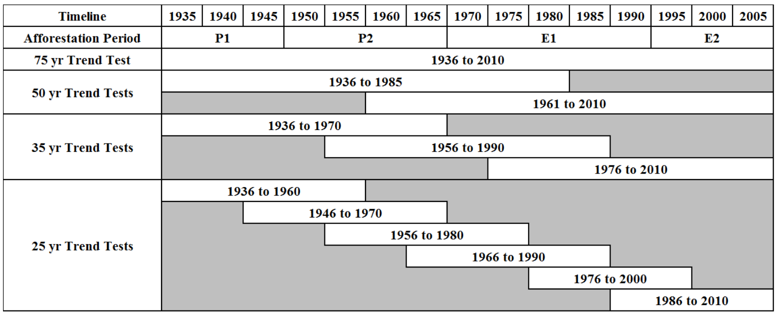


Figure 3. Burned ~~are~~ in the Águeda watershed from 1975 to 2010; total watershed area is 404 km^2.



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										
									1976 to 2010						
25 yr Trend Tests	1936 to 1960														
			1946 to 1970												
					1956 to 1980										
							1966 to 1990								
										1976 to 2000					
												1986 to 2010			

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

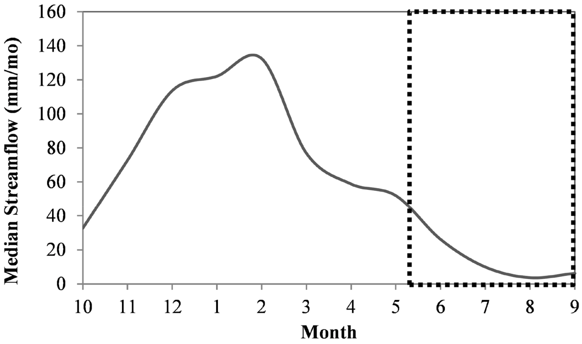


Figure 5. Monthly means of streamflow during the years without seasonal impoundment. The boxed off period (June–September) represents the period removed from the streamflow and baseflow analysis.

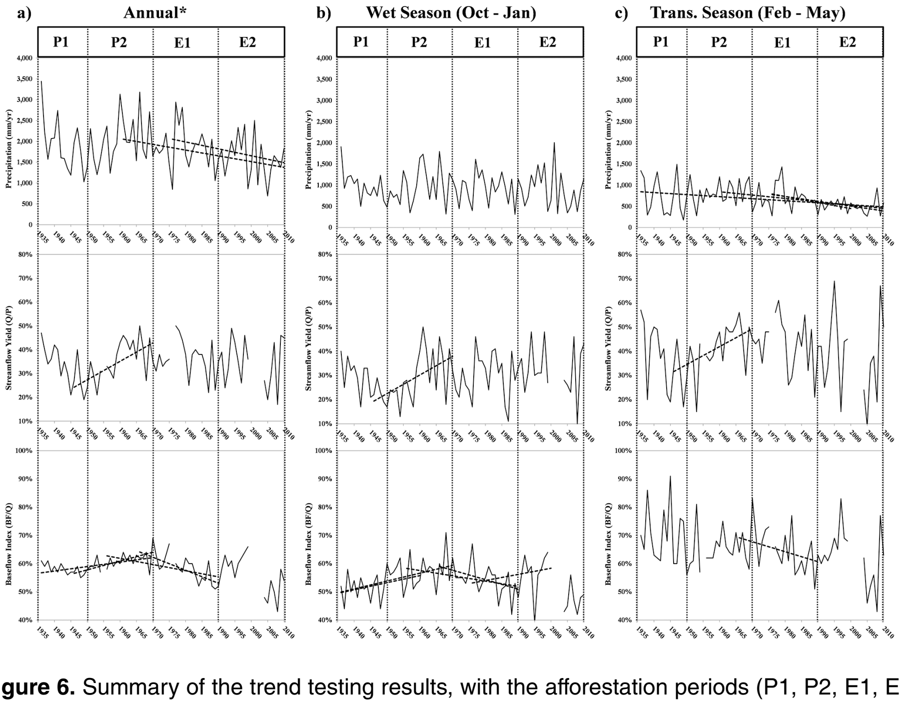


Figure 6. Summary of the trend testing results, with the afforestation periods (P1, P2, E1, E2: cf. Table 1) overlain for comparison. Significant trends are indicated with dashes lines.