Hydrol. Earth Syst. Sci., 19, 3033–3045, 2015
www.hydrol-earth-syst-sci.net/19/3033/2015/
doi:10.5194/hess-19-3033-2015

Hydrology and Earth System Sciences
Open Access

Time series analysis of the long-term hydrologic impacts of afforestation in the Águeda watershed of north-central Portugal

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Received: 25 August 2014 – Published in Hydrol. Earth Syst. Sci. Discuss.: 04 November 2014
Revised: 05 June 2015 – Accepted: 23 June 2015 – Published: 10 July 2015

Abstract. The north-central region of Portugal has undergone significant land cover change since the early 1900s, with large-scale replacement of natural vegetation types with plantation forests. This transition consisted of an initial conversion primarily to *Pinus pinaster*, followed by a secondary transition to *Eucalyptus globulus*. This land cover change is likely to have altered the hydrologic functioning of this region; however, these potential impacts 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 1936–2010. A number of hydrometeorological variables were analyzed using a combined Thiel–Sen/Mann–Kendall trend-testing approach, to assess the magnitude and significance of patterns in the observed data. These trend tests indicated that there have been no significant reductions in streamflow over either the entire test period, or during sub-record periods, despite the large-scale afforestation which has occurred. This lack of change in streamflow is attributed to the specific characteristics of the watershed and land cover change. By contrast, a number of significant trends were found for baseflow index, with positive trends in the early data record (primarily during *Pinus pinaster* afforestation), followed by negative trends later in the data record (primarily during *Eucalyptus globulus* afforestation). These trends are attributed to land use and vegetation impacts on streamflow generating processes, both due to species differences and to alterations in soil properties (i.e., infiltration capacity, soil water repellency). 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 dynamics, and proper management requires understanding how changes in land cover/use will impact hydrological processes (Calder, 2005). A key land cover type are forests, as changes in forest cover have the potential to significantly affect watershed-scale hydrologic processes, particularly by altering interception, evaporation, and streamflow. 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 afforestation typically results in decreased streamflow while deforestation typically leads to increased streamflow (e.g., Bosch and Hewlett, 1982; Brown et al., 2005). However, the hydrologic response to deforestation is in general more consistent than the response to afforestation. This difference may be due to higher variability in land cover following afforestation compared to deforestation, and the effects of different transitional species and/or changes in forest physiology (Andréassian, 2004). 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 reduction 15 to 20 years following planting.

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

While the hydrologic impacts of forests at the watershed scale are generally well understood, predicting the effects of forest land cover change for a specific watershed requires consideration of both the physical site conditions and 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 ecophysiological (i.e., forest age-dependence) conditions.

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

These regional trends are representative of the changes which have taken place in north-central Portugal, where traditional rural agrosilvopastoral activities have been widely replaced by plantations of the tree species *Pinus pinaster* and *Eucalyptus globulus* (Jones et al., 2012; Moreira et al., 2001). Both of these tree species have relatively high consumptive water demand and the potential to substantially reduce local water availability. Bosch and Hewlett (1982) estimated that pine and eucalypt forests cause an average decrease of over 40 mm yr^{-1} in water yield per 10 % change in land cover, while Farley et al. (2005) reported that afforestation with pines and eucalypti lead 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 compared to the original crop lands.

In addition to consumptive water use through transpiration, evaporation from canopy interception is an important component of water use by Mediterranean forests. Interception rates have been found to vary widely in this region, depending on the tree species, canopy density, and climatic conditions. With respect to *Pinus pinaster*, Ferreira (1996) reported interception rates of 15–18 % in the Águeda watershed of north-central Portugal (mean precipitation $\approx$ 1700 mm yr^{-1}), while Valente et al. (1997) found similar rates of 17 % in a drier region of central Portugal (mean precipitation $\approx$ 600 mm yr^{-1}). For *Eucalyptus globulus*, both Ferreira (1996) and Valente et al. (1997) observed lower rates amounting to 10–14 and 11 %, respectively. By contrast, much higher interception rates have been found for other tree species in different parts of the Mediterranean, with values near and even exceeding 50 %. For example, Scarascia-Mugnozza et al. (1988) found canopy interception rates of 68 % for a mature *Quercus cerris* forest in central Italy (mean precipitation 1006 mm yr^{-1}), Iovino et al. (1998) found rates of 58 % for a mature *Pinus negra* forest in southern Italy (mean precipitation 1179 mm yr^{-1}, and Tarazona et al. (1996) observed rates of 48 % for a mature *Pinus sylvestris* forest in northern Spain (long-term mean precipitation of 895 mm yr^{-1}; 1253 mm yr^{-1} during the study period).

A further hydrologic factor relevant to afforestation in north-central Portugal is the potential for impacts on soil water repellency (SWR). 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; Ferreira et al., 2000; 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 (Benito and Santiago, 2003; Doerr and Thomas, 2000; Keizer et al., 2005b; Shakesby et al., 2000). While in many regions SWR is associated primarily with post-fire soil conditions, Doerr et al. (1996) demonstrated that SWR is a widespread characteristic of both burned and unburned soils in the Águeda watershed 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 and eucalypt plantations. Their findings suggested that the breakdown of SWR following dry summer conditions occurs through different mechanisms in the pine and eucalypt stands. In the pine stands, SWR breakdown occurred from the top-down (i.e., vertically downwards), while in the eucalypt stands, breakdown occurred from the bottom-up (i.e., vertically upwards). Unpublished results indicated that this contrast reflected varying infiltration patterns, with infiltration occurring relatively slowly (i.e., matrix flow) in pine stands, as opposed to much faster (i.e., macropore flow) in eucalypt stands. This contrast in infiltration patterns appeared to be a product of SWR-induced alterations in flow pathways.

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 allow for historical analyses. 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 mesoscale watershed (404 km^2), where afforestation has occurred progressively over an extended period of time. Furthermore, the present study case lacks a nearby watershed to serve as a paired site, which has a similarly long data record, similar physical–environmental characteristics, or a land use history without similar land cover changes (to serve as a control site).

To assess the hydrologic impacts of afforestation in the Águeda watershed, this study therefore adopts a data-driven and exploratory approach, which conducts multiple trend analyses on the 75-years of hydrometeorological data available from 1936 to 2010. This assessment is conducted over the entire data record as well as over multiple (overlapping) sub-periods for both annual and seasonal trends. The significant trends detected through this analysis are then considered with respect to the regional afforestation trends, and discussed in the context of previous field studies conducted in this watershed. 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 can be detected, and to relate these changes to the afforestation 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 of 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, receive a substantial amount of annual rainfall, which can range from 1000 to 2500 mm yr^{-1}. Topographically the landscape is dominated by steep hill slopes with stony and shallow soils (< 0.5 m), which have a long history of anthropogenic impacts. These shallow soils were characterized by Ferreira et al. (2000) as stony, sandy loam, weakly structured Umbric Leptosols.

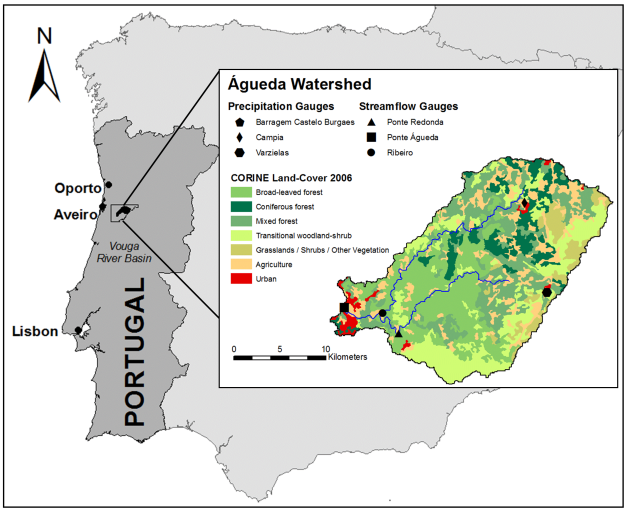

Figure 1. Location and land cover of the Águeda watershed.

North-central Portugal has undergone substantial land cover/use changes over the past centuries, which have fundamentally altered the vegetative landscape of this region. 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 (e.g., *matos* (wooded) shrublands and mixed forests). This trend was primarily driven by the adoption of fertilizers and mechanization, as well as the abolition of feudal land systems (Estêvão, 1983; Jones et al., 2011; Silva et al., 2004). 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; Jones et al., 2011; Silva et al., 2004). The primary species planted during this earlier period was *Pinus pinaster*, and beginning in

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

Land cover period	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 1986 wildfire), replacement of *Pinus pinaster*.
E2	1990–2010	Relatively stable forested area, with continued replacement of *Pinus pinaster* with *Eucalyptus globulus*.

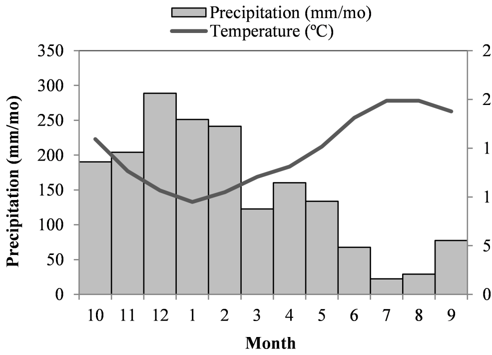

Figure 2. Average monthly precipitation and temperature in the Águeda watershed from 1971 to 2000.

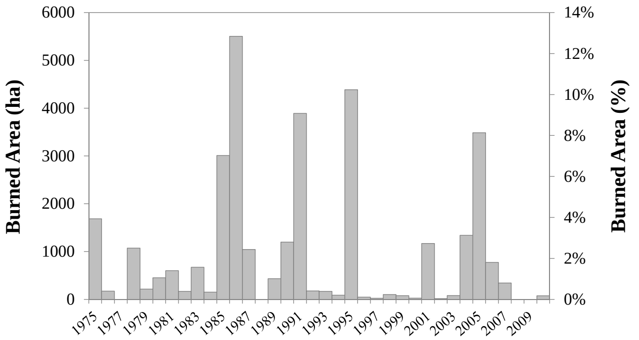

Figure 3. Burned area in the Águeda watershed from 1975 to 2010; total watershed area is 404 km^2.

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).

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

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

The current land cover in the Águeda watershed reflects this large-scale transition towards eucalyptus forests. According to the Corine Land Cover classification of 2006, approximately 46 % of the watershed was covered by broadleaf forest, which is predominantly eucalyptus (Corine Land Cover, 2010). Other land cover types with significant areal coverage in 2006 include 22 % mixed forest (mostly mixed stands of eucalypt and pine), 14 % agriculture, 10 % pine forest, 6 % mato shrubland, 2 % urban, and 1% grasslands (Fig. 1).

2.2 Hydrometeorological data

Hydrometeorological records for the Águeda watershed were compiled from hydrological year 1935–1936 (i.e., 01 October 1935 to 30 September 1936) until hydrological year 2009–2010, for the variables: precipitation, temperature, potential evapotranspiration, streamflow quantity, streamflow yield, baseflow quantity, and baseflow index. Table 2 provides an overview of the hydrometeorological variables used in this study.

Precipitation data were obtained from the rain gauge “Campia”, of the “Sistema Nacional de Informação de Re-

Table 2. Summary of hydrometeorological variables.

Hydrometeorological variables			
Variable	Description	Data source	Unit
P	Precipitation	SNIRH gauge data	mm
T	Temperature	IPMA gauge data	°C
PET	Potential evapotranspiration	Thornthwaite equation	mm
Q	Streamflow quantity	SNIRH gauge data	mm
Q_{yld}	Streamflow yield	$\sum Q_{\mathrm{mm}}/\sum P$	%
BF	Baseflow quantity	Recursive digital filter	mm
BFI	Baseflow index	$\sum \mathrm{BF}_{\mathrm{mm}}/\sum Q_{\mathrm{mm}}$	%

cursos Hídricos" (SNIRH, 2013), which consists of 24 h rainfall totals collected at 09:00 LT each day. The SNIRH provides a reliability ranking for the data in the range of 5–15, for which Campia is ranked as 14 (highly reliable). 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" ($r^2 = 0.79$).

Temperature data were compiled using data from the gauge Campia of the Instituto Portugues do Mar e Atmosfera (IPMA, 2014). When data for "Campia" were not available, the time series gaps were filled using linear regression with the temperature gauge Coimbra ($r^2 = 0.93$) which is part of the Global Historical Climate Network available at the National Climatic Data Center (NCDC).

Potential evapotranspiration (PET) was estimated using the Thornthwaite (1948) equation, using the temperature data from the gauge Campia. The Thornthwaite equation was selected for PET, as opposed to more sophisticated equations (e.g., Hargreaves, Penman–Monteith), as there was insufficient data available over the entire time series to support calculations from these equations. Another option considered for long-term PET values is the gridded Penman–Monteith-based data set available from the Climatic Research Unit (CRU) at the University of East Anglia (Harris et al., 2014). To assess the suitability of this data set to the study's watershed, the monthly PET values of the CRU data and the locally derived Thornwaite values were compared against locally derived Penman–Monteith values, over the period of January 2002 to September 2010. This assessment indicated that the locally derived Thornwaite values are better correlated than the gridded CRU data set with local Penman–Monteith values. This may be due to the mountainous terrain of the study watershed, and the relatively large grid size of the CRU data set (0.5°) being unable to capture smaller scale impacts on PET. Based on this assessment, the locally derived Thornwaite PET values were identified as the most reliable and representative data source available for assessing long-term trends.

Streamflow data consist of daily average-discharge measurements from the gauging station "Ponte Águeda" of the SNIRH (2013). This station was operational from June 1935 to the end of September 1990, and was then reactivated in October 1999. Streamflow for the interim period (1990–1991 to 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 to 2002–2003 were eliminated from the data set due to low data quality, owing to the absence of an adequate stage-discharge curve during this period.

In addition, a number of smaller streamflow gaps occurred throughout the daily streamflow data set. When they occurred during periods with little or no precipitation, the gaps were filled by fitting a logarithmic decay curve (traditional linear reservoir with a semi-log fitting) to the streamflow recession. If gaps occurred during a precipitation event, then this approach was not applied and the gaps were left unfilled. If the number of gaps was greater than 5 % of the total record, then the entire period was removed from analysis, which was the case for the hydrologic years 1954–1955 and 1975–1976. Finally, data for the driest months of the year (i.e., June to September) during the period from before 1963 and after 2004 have very high uncertainty, due to unreported and variably occurring impoundments of streamflow during these months. Therefore, this 4 month period had to be removed from the streamflow analysis for the entire data record, to keep the inter-annual comparisons consistent. After the streamflow gaps were filled, the ratio of precipitation which becomes streamflow was calculated, to allow potential changes in the streamflow–precipitation relationship to be assessed. This ratio is defined as the "streamflow yield", which is the total streamflow divided by total precipitation, with the period of summation determined by the period being considered (i.e., the annual or the seasonal ratio).

The final data set utilized in this study is a baseflow time series calculated with the Eckhardt digital filter (Eckhardt, 2005) using the daily streamflow data set. 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. The relative proportion of baseflow from each day of streamflow was estimated, which was 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 hydrometeorological time series, a multi-step trend-testing approach was applied, following the general approach presented in Yue et al. (2002). This approach first determines the magnitude (i.e., slope) of any potential trend in

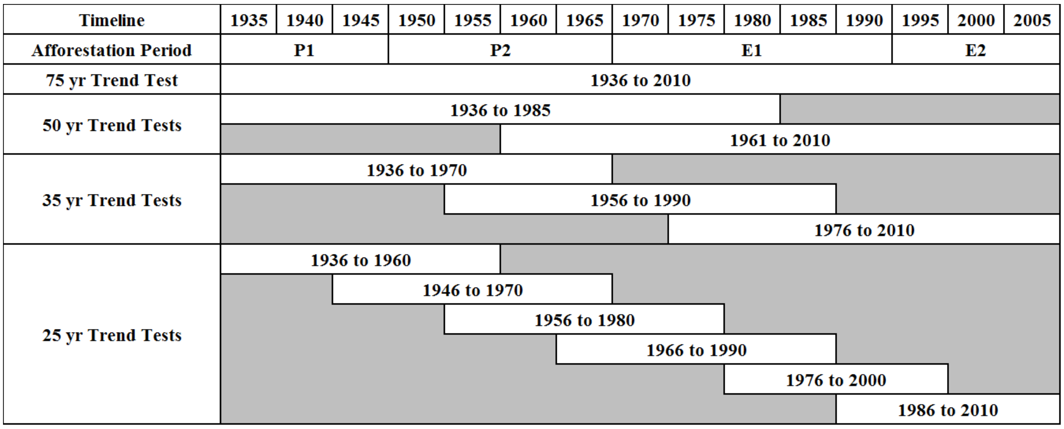

Figure 4. Timeline of the trend-testing periods and their correspondence with the different afforestation periods.

the data using the non-parametric Thiel–Sen slope estimator (Sen, 1968). This value is determined by calculating 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 the sample points, which provides a measure of uncertainty of the median Thiel–Sen value. If a potential trend is detected by the Thiel–Sen test (i.e., a non-zero slope), then the data are processed using the "trend-free pre-whitening" procedure of Yue et al. (2002). This step reduces the overestimation of significance which can occur in time series data that exhibits positive serial correlation, as is typically the case for streamflow time series data.

After the trend-free pre-whitening, 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 data (Helsel, 1993). For this study, statistical significance was determined using an α value of 0.05.

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

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

Over the time periods shown in Fig. 4, the trend testing was conducted over both annual and seasonal time periods. The seasonal breakdown corresponds to the prevailing precipitation patterns of the study site, which consists of a "wet season" from October to January when the largest amount of precipitation occurs, a "transitional season" from February to May when precipitation rates are reduced, and a "dry season" from June to September when precipitation is lowest. Due to gaps in the streamflow record (discussed in Sect. 2.2), the hydrologic years 1999–2000 through 2002–2003 were unavailable for the trend testing for both the annual and seasonal time periods, and the hydrologic years 1954–1955 and 1975–1976 were unavailable for the annual and transitional season. In addition, the trend tests were not conducted during the dry period for streamflow (and therefore also baseflow), due to the uncertain data quality during these months.

3 Results

3.1 Summary of the seasonal breakdown

To characterize the hydrometeorological conditions of the three seasons used in this study, the median values of the hydrometeorological variables during the study period are

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

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

* The months of June to September are not included for Q (mm), Q_{yld} (%), BF (mm), and BFI (%). NA = not available.

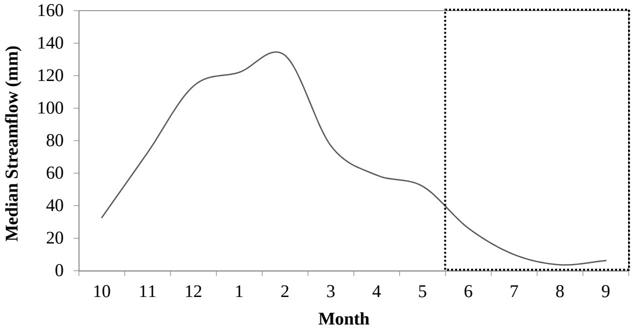

Figure 5. Monthly mean streamflow during the years without seasonal impoundments; the boxed off period (June–September) indicates the period removed from the streamflow and baseflow analysis.

presented in Table 3. This summary shows the strong climatic pattern in the watershed, with distinctly contrasting precipitation, temperature, and potential evapotranspiration values between seasons. With respect to streamflow, the values are similar during the wet and transitional seasons; however, both streamflow yield and baseflow index are higher during the transitional season, 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

The baseflow index used in this study is estimated by the Eckhardt digital filter, which contains two parameters: $\mathrm{BFI}_{\mathrm{max}}$ (maximum value of the baseflow index) and a (a filter parameter). These parameters were set at $\mathrm{BFI}_{\mathrm{max}} = 0.80$, and $a = 0.98$, based on an examination of different recommended values provided by Eckhardt (2005). To provide a check on the baseflow values estimated using this method, the results were then compared against baseflow values calculated using conductivity data from 2001 to 2009 with the conductivity mass balance method (Stewart et al., 2007).

At the monthly timescale, the two compared baseflow data sets have a Pearson's correlation coefficient of 0.96 for all months (Fig. 6a), and 0.83 for months with less than 100 mm of baseflow (Fig. 6b), 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 the time series trend analysis.

3.4 Thiel–Sen/Mann–Kendall trend-testing results

The results for the Thiel–Sen/Mann–Kendall trend tests for the variables with the most noteworthy results (i.e., precipitation, temperature, potential evapotranspiration, streamflow yield, and baseflow index) are presented by Fig. 7. The full test results for all hydrometeorological variables and test periods are provided in the supplementary material.

For the precipitation data, three significant trends were identified during the transitional season. All trends corresponded to decreases in precipitation: a $-7.9\,\mathrm{mm\,yr^{-1}}$ trend over the 50 years from 1961 to 2010, a $-11.3\,\mathrm{mm\,yr^{-1}}$ trend over the 35 years from 1976 to 2010, and a $-14.3\,\mathrm{mm\,yr^{-1}}$ trend over the 25-year period from 1976 to 2000. These trends indicate that there was a pattern of decreasing precipitation totals during the transitional season (February to May) starting during the P2 land cover period, and this pattern continued through the E1 and E2 land cover periods (cf. Table 1).

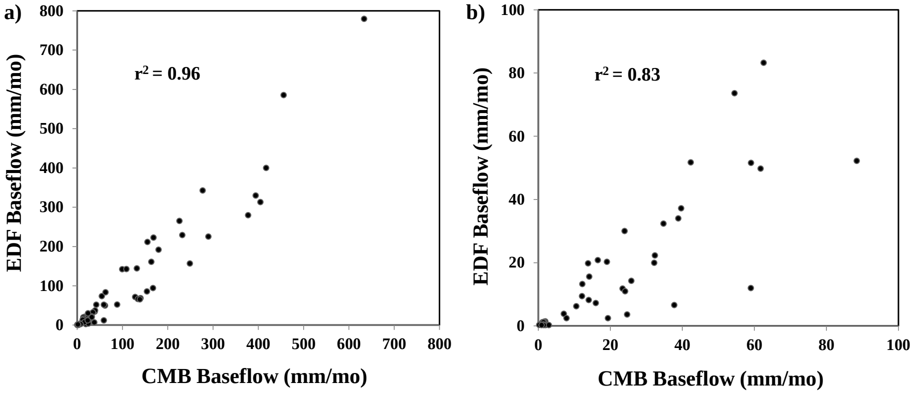

Figure 6. Monthly plots of baseflow from the conductivity mass balance (CMB) and Eckhardt digital filter calculations; **(a)** includes all months ($r^2 = 0.96$) and **(b)** includes months with less than 100 mm of baseflow ($r^2 = 0.83$).

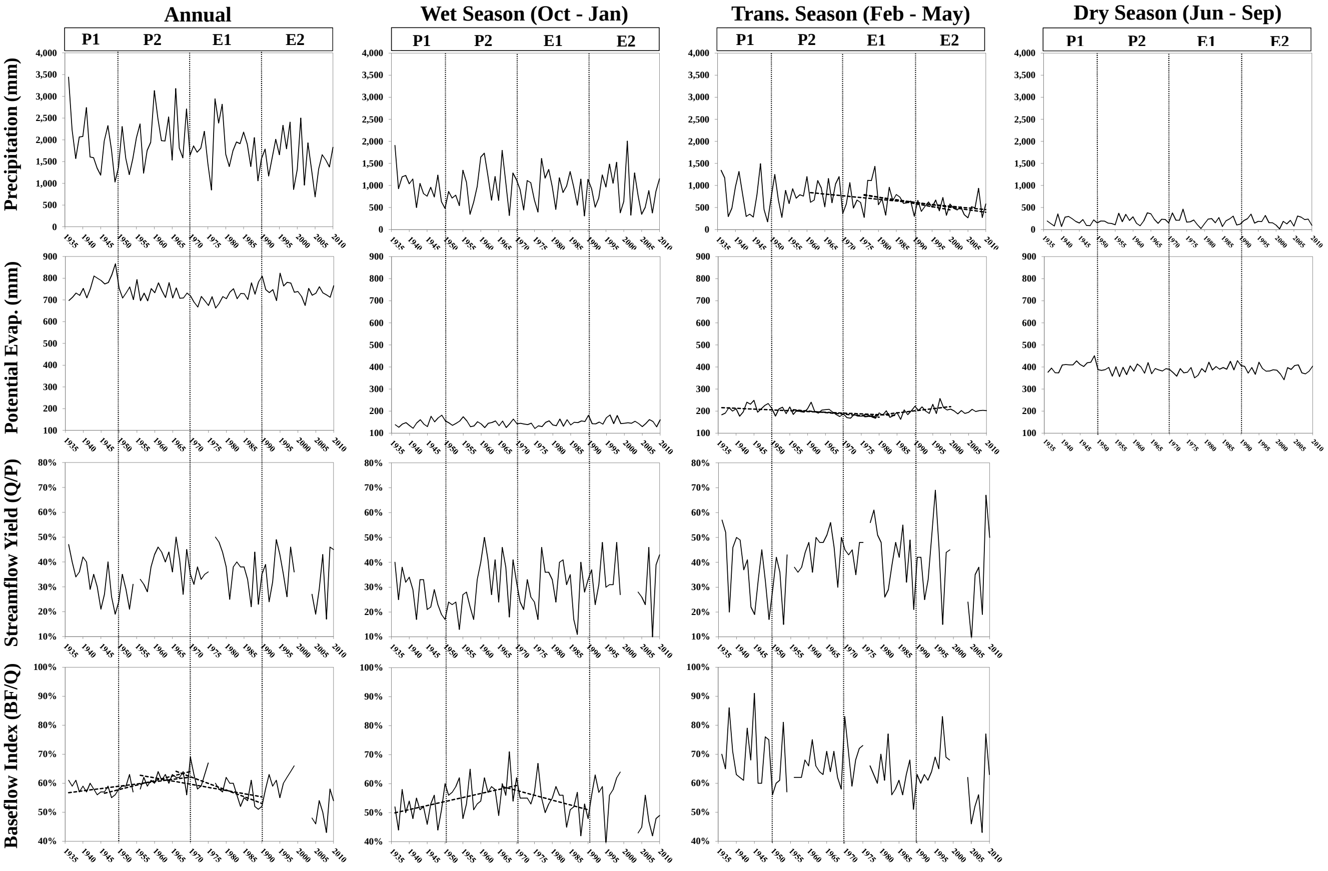

Figure 7. Summary of the trend-testing results, with the afforestation periods (P1, P2, E1, E2; cf. Table 1) overlain for comparison. Significant trends are indicated with dashes lines.

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

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

4 Discussion

4.1 Streamflow trends

The streamflow trend tests revealed that there were no significant trends for either quantity or yield over any of the periods tested (Fig. 7). These results therefore contrast with the overall pattern found in meta-analysis studies dealing with the hydrologic impacts of afforestation/deforestation, which indicate that afforestation tends to reduce streamflow (e.g., Bosch and Hewlett, 1982; Brown et al., 2005; Farley et al., 2005). However, there are a number of individual cases within these meta-analyses studies which show contrasting trends to the overall pattern. These cases are difficult to directly compare to the current study, however, as most were conducted at the plot to micro-catchment scale, which underwent relatively rapid land cover change. By contrast, this study was conducted on a 404 km^2 watershed, which underwent relatively gradual land cover change over a 75 year period. In this case, any potential changes in hydrologic processes are likely to be far more diffuse and difficult to detect, when compared to the paired catchment studies.

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

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

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

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

Given the lack of significant climate trends at the annual timescale, and the contrasting findings during the transitional season, offsetting climatic trends do not appear to be an adequate explanation for the overall lack of observed streamflow changes in the Águeda watershed. However, given that the observed climate trends occurred during the transitional season, there may have been streamflow impacts during the (following) dry season. This can only be speculated on however, since no assessment can be made on streamflow during the dry season, due to the limitations in the streamflow data (i.e., the summer streamflow impoundments). Therefore, no comparison could be made with the findings of Rodríguez-Suárez et al. (2011), who found dry season reductions in the water table and streamflow discharge following afforestation with eucalyptus, or to Brown et al. (2005) whose work found that afforestation led to much larger proportional reductions in summer flows compared to winter flows.

An alternate explanation for the lack of streamflow change could relate to the specific characteristics of the watershed, which may make it less responsive to changes in forest land cover than is typical. With respect to watershed characteristics, Andréassian (2004) identifies several prerequisite conditions necessary to observe hydrologic impacts, including soil, climatic, and eco-physiological factors.

With respect to soil conditions, the characteristics of the soils of the Águeda watershed may be 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 typically less than 1 m deep and often as shallow as 20–30 cm (Santos et al., 2013). These depths are less than the maximum rooting depth of pine and eucalypt trees, 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 the fast-growing pine and eucalypt trees to access deeper sources of soil moisture than the original shrub and slow-growing tree species is likely much less relevant in this watershed than it would be in a location with deeper soils. In the case of the Águeda watershed, the most important soil related factor in water consumption appears to be the low moisture storage capacity of the soils, severely offsetting the potential impact of widespread planting of trees with higher water consumptive capacity.

A second factor which could contribute to the lack of reductions in streamflow is the Mediterranean climate 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 (Brown et al., 2005). 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 Águeda catchment may have an amplifying effect on the impacts of the shallow soils, by further reducing the higher evapotranspiration potential of fast-growing trees species.

With respect to eco-physiological conditions, the specific land cover changes in the Águeda watershed may 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 Águeda watershed, however, the interception rates appear to be comparatively low for pine and eucalypt species (Coelho et al., 2008; Ferreira, 1996; Valente et al., 1997), while 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 that was the most common vegetation type in the 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. Average tree density from unpublished plot assessments put the density of unevenly spaced eucalyptus stands (< 15 years old) at 1600 trees ha^{-1}, of evenly spaces eucalyptus stands on terraces (< 5 years old) at 1,500 trees/ha, of eucalyptus on flat terrain (< 5 years old) at 2600 trees ha^{-1}, and of unevenly spaced pines (< 30 years old) at 500 trees ha^{-1}. 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 the prerequisite conditions identified by Andréassian (2004) for observing afforestation-driven streamflow changes at the watershed scale. Given this lack of prerequisites conditions, and the absence of offsetting climate trends as an alternative explanation, the streamflow findings of this study appear to be primarily a function of watershed characteristics, with soil properties as the most important factor.

4.2 Baseflow trends

No significant trends were found for baseflow quantity (BF) over any of the periods or seasons tested. However, a number of trends were found for BFI, for both the annual data and the wet season data, which includes both positive and negative trends over different parts of the data record.

Positive trends in BFI were found from 1936 to 1970 for the annual data and the wet season, and from 1946 to 1970 for the annual data (Fig. 7). These trends correspond with the pine afforestation land cover periods P1 and P2 (cf. Table 1). These trends could be an indication that the pine afforestation promoted slower flow pathways, by increasing the amount of water entering the soil matrix via infiltration, and reducing surface flow and fast sub-surface flow (i.e., via macropores). However, given that previous studies in Águeda watershed have found SWR conditions at pine stands (during dry periods), pine afforestation would not normally be expected to increase matrix infiltration in this location (Keizer et al., 2005a, b; Santos et al., 2013). However, the land cover state during the initial conversion to pine forests were significantly different from the state during these studies, which may have led to a more positive impact on infiltration rates. This is due to the ground preparation and planting operations used, which would have the effect of breaking up the repellent topsoil layer and creating sinks for overland flow, both of which would promote infiltration. This effect would be reduced over time, and eventually SWR would recover in established stands.

Negative BFI trends were found from 1956 to 1990 for the annual data, and from 1966 to 1990 for the wet season (Fig. 7). This corresponds with the early part of the P2 land cover period, and the entirety of the first eucalyptus afforestation period (E1; cf. Table 1). Therefore, the negative BFI trends occur during the period when *Pinus pinaster* plantations reached greater maturity and (after logging) were being rapidly replaced with *Eucalyptus globulus*. The reductions in baseflow during this period may therefore be related to high rates of SWR in the established pine stands and the newly established eucalypt stands. An increase in SWR could lead to an increase in quick flow, particularly via fast sub-surface flow from macropore infiltration, and lead to more rapid conversion of precipitation into streamflow.

The temporal correspondence between the significant trends in BFI and land cover changes which could affect hydrologic flow pathways indicate there may be a relationship between afforestation and changes in baseflow index in the Águeda watershed. These findings are further supported by field studies conducted in the watershed, which show the strong impact of SWR in pine and (particularly) eucalyptus stands on hydrologic flow pathways (Santos et al., 2013). However, given that there is no field data available to verify the site conditions during the time of the observed trends, the attribution of the changes in BFI to land cover change is necessarily speculative. To test this hypothesis, further field studies would be needed to examine baseflow dynamics under land cover conditions which replicate the historic conditions.

5 Conclusions

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

With respect to baseflow trends, the initial conversion from more natural land cover types (i.e., *matos* shrublands, mixed forests) to pine plantations appears to have had a significant – initial – positive impact on baseflow index, while the substitution of pine plantations by eucalypt plantations had a negative impact on baseflow index. The positive trends are attributed to the impact of the site preparation methods applied during the initial pine planting on soil infiltration capacity, while the negative baseflow trends are attributed to the onset of soil water repellency (SWR) under the mature pine and eucalypt stands. Therefore, from the standpoint of promoting well-regulated streamflow (i.e., higher baseflow), the impacts of the afforestation with pine appear generally positive, while those of re-/afforestation with eucalypti were generally negative.

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, which was followed by the replacement of the planted pines by eucalypti. Therefore, a direct comparison between the impacts of widespread planting with pine or with eucalypt cannot be drawn from this study. In addition, these baseflow findings are based on a statistical/historical analysis, with no field data available for validation. To further test this hypothesis, field studies would be needed to examine baseflow dynamics under different land cover conditions replicating the historic conditions.

The Supplement related to this article is available online at doi:10.5194/hess-19-3033-2015-supplement.

Acknowledgements. The authors would like to express their gratitude to Professor Celeste Coelho at the University of Aveiro, Centre for Environmental and Marine Studies (CESAM) for providing her expertise on the background and land use history of the study region. Thanks are also given to Ameur Manceur and Robert Schlicht, for providing assistance on the statistical methods. 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.

Edited by: C. Harman

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