The effect of natural revegetation on streamflow in the Spanish Pyrenees

by

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Abstract

Many of the Mediterranean lowlands depend for their fresh water supply on mountain areas. However, streamflow in mountain areas has been decreasing in the past century. Apart from changes in climate, land use changes have been identified as having as having an impact on the hydrology in mountain areas. One major land use change has been a strong increase in vegetation, which was the result of land abandonment associated with depopulation. The topic of this research is the change of vegetation and its effect on stream flow in the Upper Aragón basin between 1950 and 2050. First, the effect of vegetation on hydrology was modelled using the PyCatch hydrological model in a small catchment within the Upper Aragón basin. Secondly the sensitivity of the modeling outcomes to certain vegetation parameters was assessed. Thirdly, a non-linear vegetation growth equation was fitted through the pixels of twelve Landsat satellite images to determine vegetation growth in the Upper Aragon Basin for the 1950-2050 period. And finally, vegetation growth was coupled to streamflow, in order to determine changes in streamflow in the Upper Aragon Basin for the 1950-2050 period. Hydrological modeling for the Arnás catchment shows that vegetation growth has a large impact on streamflow. Especially initial vegetation growth (from LAI=0 to LAI=1) leads to almost complete drying up of summer streamflow. A complete vegetation recovery (from LAI=0 to LAI=4.5) will lead to a 100 percent decrease yearly streamflow in the Arnás catchment. The non-linear regression suggests a fast increase in vegetation in the UAB between 1960 and 2000. This translates to a stark decrease in streamflow for this period. This might be an overestimation of what is really happening in the UAB.

There are several ways in which our research could be improved in the future. First, the NDVI-LAI saturation problem we encountered in our study, could be a solved by using a different method to find LAI values. For example, the Enhanced Vegetation Index (EVI) could be used. Modeling the vegetation growth could be improved by finding a regression equation that can more accurately describe vegetation growth in this region, and that does not result in missing values in case of constant vegetation or vegetation decrease. In future research also more attention should be given to changes in soil as a result of vegetation change, and its effect on hydrology. Another issue with the hydrological modeling is that, according to our results, almost all streamflow for all scenarios seemed to be the result of sub surface flow. Better ways to model Horton overland flow need to be sought to more realistically describe the hydrological fluxes in the Upper Aragon basin.

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1. Introduction

1.1 Problem definition

Many of the Mediterranean lowlands depend for their fresh water supply on mountain areas. Due to altitudinal gradients in temperature and precipitation, headwaters receive more precipitation and have lower evapotranspiration rates than adjacent lowlands. However, Mediterranean areas are facing increasing hydrological stress (López and Justribó 2010; García-Vera 2013). Water resources in various Spanish river basins have been declining during the 20th century (Poyatos, Llorens, and Gallart 2005; Gallart and Llorens 2004; Beguería et al. 2003). López-Moreno et al. (2011) analyzed the climatic and hydrological trends across 88 sub-basins of the Ebro River basin, in North-Eastern Spain, for the period 1950–2006. This revealed a marked decrease in river discharge in most of the sub basins.

Two possible explanations for this trend are a shift in climate conditions and changes in land cover. In the last five decades, there was a temperature increase between 1 and 2 °C in north eastern Spain (El Kenawy et al., 2012). A rising temperature can, among other things, be linked to an increase of evapotranspiration, which can result in a decrease in runoff (López-Moreno et al., 2011). Also, a decrease in precipitation rates was found (Pérez-Zanón et al., 2017). Apart from changes in climate, land use changes have been identified as having a major environmental impact in the Mediterranean mountains. One of the land use changes that happened was a strong increase in vegetation, which occurred as a consequence of land abandonment associated with depopulation (Collantes and Pinilla 2004; Lasanta-Martínez, Vicente-Serrano, and Cuadrat-Prats 2005; Vicente-Serrano, Lasanta, and Romo 2004; José et al. 2011). Several authors have documented the relation between land abandonment and decreased water availability in the past century (López-Moreno, Beniston, and García-Ruiz 2008; Nunes et al. 2010; Gallart and Llorens 2004). A study conducted by Beguería et al. (2003) in the Central Spanish Pyrenees using climate and discharge data from 1945 to 1995 reported a reduction in discharge of 30 percent as a result of changes in vegetation cover. However, the effect of land use change on hydrology is not always this clear (Morán-Tejeda et al., 2010). The hydrological response depends on several factors, including properties of the catchment, forest age, type of vegetation, spatial scale effects and intensity of precipitation (López-Moreno et al., 2014). These are different for every catchment making runoff difficult to predict under changing land cover scenarios (Andréassian 2004).

There are several ways in which the revegetation that follows land abandonment impacts runoff. The loss of water by interception and transpiration as a result of an increase in vegetation cover is commonly given as the explanation for the low soil water content observed under forest cover and the associated low storm flow discharges (N. Lana-Renault et al. 2011; Bosch and Hewlett 1982). But also soil properties like soil depth and permeability influence the hydrologic response, and these can be gravely impacted by the agricultural practices that took place before abandonment (Gallart et al. 2002; Serrano-Muela et al. 2008; Cosandey et al. 2005; Lasanta, Garcia-Ruiz, and Beguería 2006). Although revegetation will influence land cover and soil properties, it can take several decennia before both vegetation and soil properties of a revegetated area match the ones of a natural forest (Nadal-Romero et al. 2016).

In the future, climate change will probably have a large influence on hydrology in the Pyrenees. The revegetation process will also continue, as many former agricultural fields are not yet covered by forests. Furthermore, an increase in temperature may lead to an increase in the forest cover due to the alpine belt moving to a higher elevation (López-Moreno et al., 2014). There is a need to better understand how these future changes might impact the water availability in the Yesa reservoir, which provides drinking water for the city of Zaragoza and water for irrigation in a large part of the Ebro basin (López-Moreno et al., 2014). Nije Bijvank (2015) studied revegetation patterns and the effect it has on streamflow for a sub basin of the Upper Aragon river, using satellite imagery to model future land cover changes and the PyCatch model to simulate streamflow. More recently, a study by (Bänziger, 2016) suggests that regrowth patterns in the Upper Aragon basin might be better predicted using a non-linear regression model instead of the linear one used by (Nije Bijvank 2015). Furthermore, Lana-Renault et al (2017) recently calibrated the PyCatch model for two catchments with different vegetation covers (abandoned land with shrubs and natural forest), which makes the PyCatch model suited for applying it on other catchments in the region with varying levels of (re)vegetation.

1.2 Objective and research questions

The main objective is to quantify the revegetation in the Upper Aragon Basin and to assess its effect on changes in basin hydrology and water supply, by using a spatially distributed hydrological model and a series of satellite images. The research questions are:

1. How are streamflow, interception, evapotranspiration and soil moisture in the Arnás catchment (a sub-basin of the UAB) influenced by vegetation growth?
2. What is the uncertainty in these calculations and what is the sensitivity of the model outcomes to certain soil and vegetation parameters (hydraulic conductivity of the topsoil, albedo and soil thickness)?
3. What is the change in vegetation cover in the Upper Aragon Basin for the period 1950-2050?
4. What is the effect of the change in vegetation cover on streamflow in the Upper Aragon Basin?

2 Theoretical background

2.1 Land abandonment in the Spanish Pyrenees

Traditionally mountain communities in the Pyrenees were mostly self-sufficient. The farmers produced cereal and held livestock, which for the largest part consisted of sheep. For their flocks they made use of the system of transhumance, which meant they let the flocks graze in the lower lying Ebro Valley in winter, and in summer they moved the flock back to the mountain areas (José M. García-Ruiz & Lasanta-Martínez, 1993). For cereal and other produce they used the best fields located close to the settlements in valley bottoms or on stone walled, bench terraced slopes, where they applied fertilizer and constructed irrigation (J.M. García-Ruiz et al., 1996). Since the middle ages there was a constant population growth which reached its peak around 1840-1860 (Lasanta, Garcia-Ruiz, and Beguería 2006). Because the best places for agriculture were already cultivated, the increase in population forced the farmers to occupy marginal lands, located far from settlements. At the end of the 19th century cultivated fields occupied all possible locations, even in very difficult topographic conditions, on steep slopes and on stony soils (Lasanta, Garcia-Ruiz, and Beguería 2006).

Lasanta-Martinez (1988) studied land abandonment in the high Aragonese Pyrenees using aerial photographs taken between 1957 and 1981. In the study area 16 percent was in use as farmland before 1957. Only looking at the area below 1600 meters this was 28 percent. 54 percent of the farmland had a slope over 20 percent, which means it was not really suitable for agriculture due to the high erosion that occurs (Lasanta-Martinez, 1988). Many mountain hillsides were cultivated with a shifting agriculture system. This means that bushes were cleared and burnt, and the resulting ashes were used as fertilizer. When after 2 to 3 years the fertility was depleted, the field was abandoned and after 25-30 years ploughed again. This system was implemented by many pre-industrial European societies, and results in strong erosion rates and soil fertility losses, even long after the fields are abandoned (Lasanta et al., 2017). Shifting agriculture occupied about 22.8% of the total cultivated area at the beginning of the 20th century, though in some valleys it represented a much larger area (Lasanta-Martinez, 1988).

The abandonment process started during the early decades of the 20th century and intensified in the 1950s and 1960s. One of the big land use changes in Europe since the 19th century is the abandonment of farm land. This happened especially in mountainous and semiarid environments. In the high Aragonese Pyrenees, 63 percent of the agricultural land was already abandoned in 1957. In 1981 this further increased to 70 percent (Lasanta-Martinez, 1988). Much of this abandonment was related to depopulation of rural areas that started at the beginning of the 20th century (José M. García-Ruiz, 2010). When the mountain economy became part of a national and international economy self-sufficiency was no longer necessary, and many of the traditional practices were deserted (Lasanta-Martinez, 1988). The diversity of land uses lost importance in favor of more competitive products on the market (Lasanta et al., 2017). Certain environmental conditions like small field size, steep slopes, and difficulties in mechanization and accessibility made farming no longer lucrative (J.M. García-Ruiz & Lana-Renault, 2011). Depopulation also led to a shortage of manpower and resulted in a decrease in livestock pressure and seasonal movement of flocks (J.M. García-Ruiz and Lana-Renault 2011). According to research by Lasanta-Martinez (1988) using aerial photos, the fields on the steepest slopes and highest grounds and with north and south aspect were deserted earliest. These fields often had poor soils and low fertility and were often very rocky. The ones closest to villages and those that had access to machines (asphalt road) were farmed for the longest period. In parallel with the process of abandonment, many hillsides were reforested for economic purposes such as wood production. Reforestation was also done for environmental purposes such as land reclamation and restoration (J.M. García-Ruiz and Lana-Renault 2011). The abandonment of farmland is still going on. Between 1990 and 2004 the number of farms was reduced by 30%. In 40 % of the cases this was the result of retirement of the owner, and in almost 60 percent of the cases farming was replaced by another economic activity, mostly tourism (Lasanta et al., 2017).

2.2 Vegetation growth following land abandonment

After a field is abandoned by farmers, natural revegetation starts. Vegetation regrowth after land abandonment is called secondary succession. In general, abandoned fields of the central Pyrenees pass through a series of succession stages. During the first year of abandonment the fields are invaded by herbaceous plants. Woody scrubs start growing after 10 to 15 years. It takes between 10 to 35 years for the scrubs to cover the whole area. Young trees are introduced more than 60 years after abandonment. In this last stage the field begins to look like a natural hillslope (Molinillo et al., 1997). It will take more than 100 years before the former agricultural field will have the characteristics of a real forest (Lasanta-Martínez, Vicente-Serrano, and Cuadrat-Prats 2005).

At what rate secondary succession takes place depends on several factors. One of these is land use before abandonment (Molinillo et al., 1997; Sluiter & De Jong, 2007). Several authors have highlighted the effect of slash and burn agriculture on the ensuing secondary succession (Garcia-Ruiz et al., 1995; Pardini et al., 2017). Experimental simulation of slash-and-burn practices in NW Spain showed extremely high soil erosion rates (about 40 times more than the control, shrub covered plot) and increases in nutrient loss of about 20- to 50-fold that of the control plot (Soto et al., 1995). Another study found a total soil loss that was about 14 times higher on plots under shifting agriculture than on plots under dense shrub cover, and almost 3 times higher than on permanent cereal fields. Several years after abandonment the soil erosion rates were still two times that of the cereal field. These observations imply that, after abandonment, a field is still affected for many years by the effects of slash-and-burn practices (Lasanta, Garcia-Ruiz, and Beguería 2006). This is confirmed by Seeger and Reis who found poorly developed and shallow soils in several catchments in the Pyrenees as a result of past agricultural practices (Seeger & Ries, 2008). Loss of soil and nutrients negatively impacts the rate of secondary succession after abandonment (Lasanta et al., 2000). In the Arnás catchment for example large differences in soil properties exists, as a result of erosion. This is at least partly the cause for the differences in stage of secondary succession in different parts of the catchment (Navas et al. 2008).

Other things that might influence the rate of secondary succession are certain topographic factors like slope, aspect and altitude (Lasanta-Martínez, Vicente-Serrano, and Cuadrat-Prats 2005; Taillefumier and Piégay 2003). Because these influence climatic conditions, like shading and temperature, which affect vegetation growth. Climate change is also impacting revegetation, because it results in changes in precipitation and temperature (J.M. García-Ruiz & Lana-Renault, 2011). According to Vicente-Serrano, Lasanta, and Romo (2004) there is a significant and positive trend in vegetation growth in the central Spanish Pyrenees that can be linked to the increase of annual mean temperature. And finally, the rate of secondary succession is influenced by the distance from bordering vegetation (J.M. García-Ruiz & Lana-Renault, 2011). The nearer an area is situated to old trees, the higher the reforestation rate (Tasser et al., 2007).

Besides natural revegetation there is also afforestation. Due to the slow process of secondary succession, and with productive (to achieve self-sufficiency in the supply of pulp and paper) and environmental objectives (to control hydrological and geomorphic processes in order to reduce flood frequency and magnitude and soil erosion), extensive afforestation programs were conducted by national forest services all over the Mediterranean region. In the case of the Pyrenees, large areas were afforested with Pinus Nigra and Pinus Sylvestris (Ortigosa et al., 1990).

Both the natural vegetation growth and afforestation resulted in an increase in biomass in the Spanish Pyrenees in the past decennia. Vicente-Serrano, Lasanta, and Romo (2004) studied vegetation growth in the period 1982-2000 and concluded that abandoned fields presented the greatest biomass increase, followed by shrub covered areas and forest. Rafael Poyatos et al., (2009) who studied revegetation after land abandonment in the pre-Pyrenees, determined that about 64% of the area was covered by forest by 1996, whereas in 1957 forests accounted for only 40% of the land cover. This expansion of woodland was the result of spontaneous afforestation of abandoned fields with pine trees in terraced areas and areas of sparse scrub vegetation, in combination with an increase in the density of forest canopies.

2.3 Influence of vegetation growth on hydrology

The amount of streamflow that is generated in response to a rainfall event in a catchment depends on soil-, vegetation- and other catchment characteristics. Streamflow can consist of both subsurface flow and surface runoff. Streamflow that is generated in forested catchments in the Upper Aragon Basin is probably for a large part the result of subsurface flow. According to observations made by (Serrano-Muela et al. 2008) in a forested catchment, significant streamflow generation was only active when the water table was close to the surface. This is generally the case between autumn and spring, while in summer the water table and consequently streamflow are low. In many catchments in the Upper Aragon Basin the water table follows a seasonal pattern involving a drying-down period of the water table from the end of spring (as a result of increased evapotranspiration), a wetting-up period starting with the first autumn rainfalls, and a wet period during winter and spring. The length of these periods varies among years, depending on variations in rainfall and evapotranspiration (N. Lana-Renault et al., 2014).

There are several ways in which vegetation growth changes the hydrological situation of a catchment. These include changes both in vegetation and in soil properties. The first factor of importance is the increase of the number of leaves above the terrain. This determines the extent of the transpiring surface and the degree to which rain and snow are intercepted and retained to consequently evaporate (Dingman, 2015). When a field of cereal crops or meadows is replaced by forest, the decrease in runoff that follows is for a large part because of this rise in rainfall interception and transpiration (Bosch & Hewlett, 1982; J.M. García-Ruiz & Lana-Renault, 2011). Secondly, revegetation influences the hydrologic situation by changes in plant type and height, which impact the roughness of the transpiring surface, and thus the role of air turbulence in the exchange of water vapor and heat between land and atmosphere. A third aspect that changes is the water conductance of leaves, which is species dependent, and exerts a strong control on the rate of transpiration (Navas et al. 2008). Finally, soils under dense vegetation have a higher moisture content than soils without cover. Uncovered soils experience higher incoming solar radiation, surface temperatures and evaporation rates (Navas et al. 2008).

Vegetation growth also impacts the hydrological characteristics of the soil. The increase in the extent of the root systems has a major effect on surface porosity and thus the infiltration capacity and hydraulic conductivity of the soil (Li & Shao, 2006; Nadal-Romero et al., 2016). The depth of the root systems also impacts the size of the soil storage reservoir from which water is available for transpiration (Li & Shao, 2006; Nadal-Romero et al., 2016). In a semi-arid area on the loess plateau in China, soil physical properties (infiltration, hydraulic conductivity) improved every year with a succession of natural vegetation from pioneer grassland to climax forest on degraded farmland. This was especially significant when woody shrubs started growing 14 years after abandonment (Li & Shao, 2006). Over time, vegetation growth also leads to an increase in soil thickness as a result of the accumulation of organic matter. Thicker soils lead to a decrease in streamflow (N. Lana-Renault et al. 2011).

Although revegetation can impact both land cover and soil properties, it will take several decennia before both vegetation and soil properties of a reforested area match the ones of a natural forest (Nadal-Romero et al. 2016). How long it takes for these changes to set in has a lot to do with former land use. As stated earlier slash and burn practices lead to poor and shallow soils, were after years there is still more erosion and runoff than in a comparable hillside (N. Lana-Renault et al., 2014). Directly after abandonment often a soil crust is formed as a result of rain splash, which leads to increased runoff, erosion and consequently thin soils. Soil characteristics are also changed through the construction of small terraces and drainage canals that were built for agricultural purposes (N. Lana-Renault et al., 2014). On a site in the Spanish Pyrenees that was afforested 50 years before, many of the old features (stoniness and thin soils) that characterize degraded soils following cultivation, were still present (Nadal-Romero et al. 2016)

García-Ruiz et al. (2008) analyzed the hydrological behavior of three catchments with varying types of vegetation cover (forest, former agricultural land with shrubs and grazing meadows, and badlands). In the forest catchment there was no hydrological response in summer, despite the occurrence of severe rainstorms. The largest amount of discharge was found in the badlands, and a moderate discharge was recorded in the abandoned catchment. Nadal-Romero et al. (2016) compared a catchment which was afforested 50 years earlier with a catchment with a natural forest. In the afforested area greater flows and peak discharges were recorded than in the natural forest. Afforestation did reduce the number of floods, peak discharges and stormflows compared to non-vegetated areas and abandoned lands. Lana-Renault et al. (2011) also compared the hydrological response in two catchments: One covered with natural forest and the other a former agricultural area. According to them it was especially the soil characteristics, like thickness and infiltration, that cause the differences in streamflow between the two catchments. Cosandey et al. (2005) also suggests that the different hydrological behavior among catchments is primarily the result of differences in permeability and soil depth. According to Andréassian (2004) with respect to floods, the effect of forest cover is only found for less intense rainfall events (floods with a return period of less than 5 years).

3. Data and methods

3.1 Description of study area and climate

Vegetation growth will be calculated for the complete Upper Aragon Basin (UAB) (figure 1), while hydrological fluxes will be modelled for a small catchment located in eastern part of this basin, the Arnás catchment (figure 2 and 3). The hydrological results for the Arnás will later be extrapolated to the whole UAB.

3.1.1 The Upper Aragon Basin

The Upper Aragón river basin is a part of the Ebro river basin in the Spanish Pyrenees. It is situated against the border with France and has a surface area of 2100 km^2. The elevation ranges between 2860 in the North (marked by the highest mountain, the Collarada peak) and 500 a.s.l to the south west, where the Yesa reservoir is located (J.M. García-Ruiz et al., 2010). The river Aragón originates in Astún in the north east, and flows in southern direction till Jaca, eventually ending in the Yesa reservoir. Northern tributaries are: Lubierre, Estarrún, Aragón Subordán, Veral and Esca (Beguería, 2006; J.M. García-Ruiz et al., 2010).

The climate is Mountainous Mediterranean with an oceanic influence in the west. The average annual precipitation ranges from 1600 mm in the north, to 800 mm in the inner depression in the south (López-Moreno et al., 2004). Due to oceanic influence precipitation also has a positive gradient towards the west of the basin. Precipitation follows a seasonal pattern, with most precipitation in autumn and spring and a dry period in summer (figure 4). This is common in the Mediterranean region (Latron et al., 2009). The mean annual temperature ranges from 10 °C near Canfranc in the north eastern part of the area to 13 °C near Yesa reservoir in the south west of the Upper Aragón basin. Temperature is highest in August and reaches its low point in January (figure 4). The mean annual temperature is lowest in the north due to the higher elevation, and shows an increase towards the west (Nije Bijvank 2015).

3.1.2 The Arnás catchment

Part of the Upper Aragon Basin is a small catchment called the Arnás (figure 2 and 3). It has a surface area of 2.84 km^2 and ranges in elevation between 910 and 1340 m a.s.l. In the past it has been heavily cultivated with cereal crops until the 1950s when it was abandoned and left to be recolonized by native vegetation. At present most of the area is covered in shrubs while a small part is covered by forest. A large proportion of this catchment has compact and shallow soils due to past human activities. Under forest cover, soils have more organic matter and greater permeability (N. Lana-Renault et al. 2011) . The Arnás has the same seasonally in precipitation and temperature that is typical for the UAB, as described above. The mean annual temperature is 10°C, and the mean annual precipitation (1999-2008) is 926±182 mm, most of which occurs in autumn and spring. The mean annual reference evapotranspiration, is 1088±31 mm (Noemi Lana-Renault et al., n.d.).

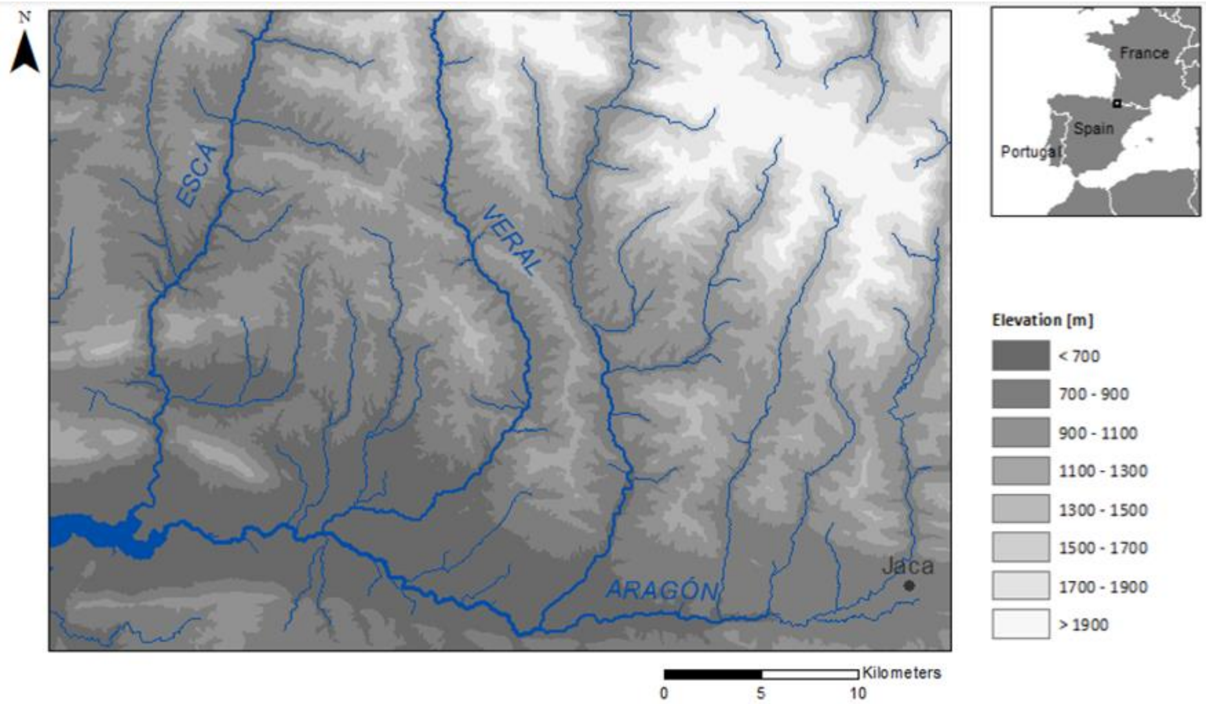

Figure 1 Elevation map of the main part of the Upper Aragon Basin (Nije Bijvank, 2011)

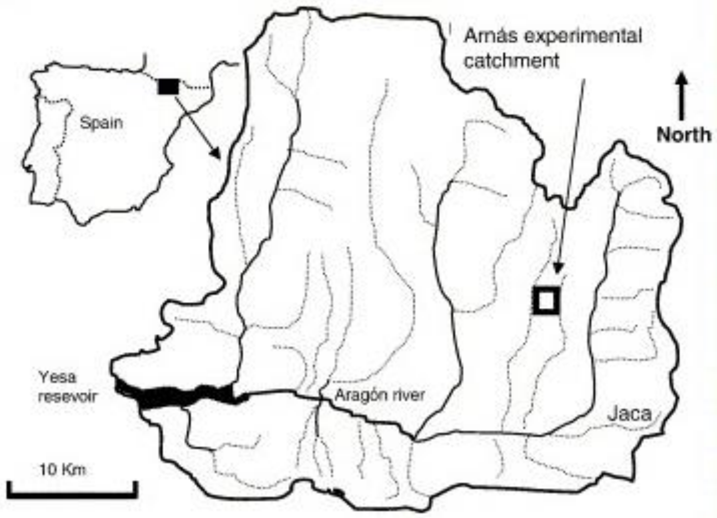

Figure 2 The Upper Aragon Basin and the Arnás catchment (Lana-Renault & Regüés, 2007)

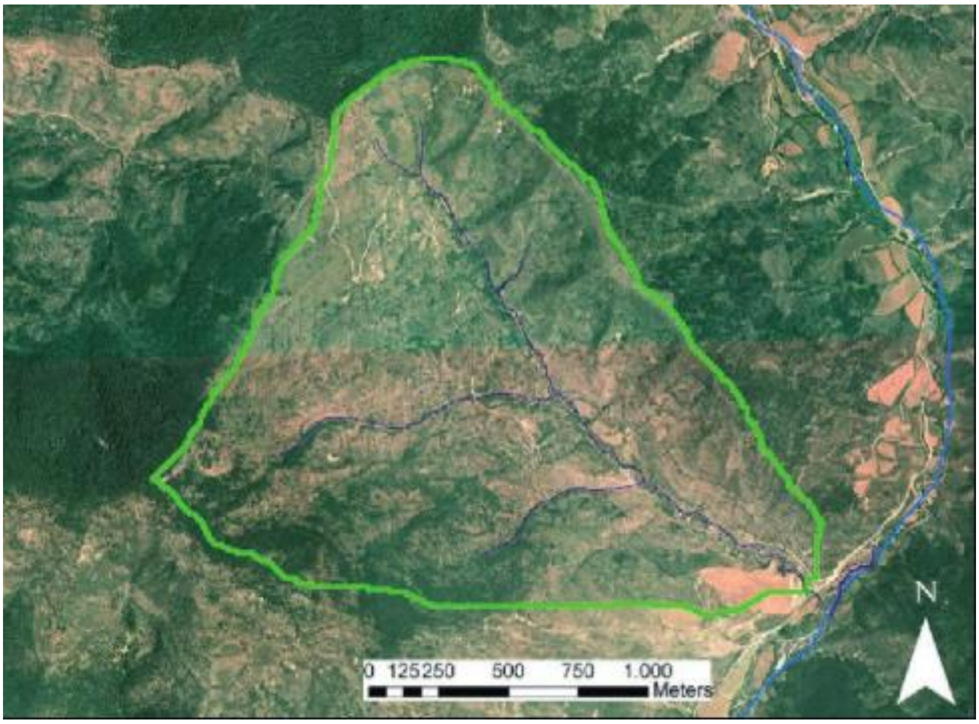

Figure 3 Satellite image of the Arnás catchment (Seeger et al., 2005).

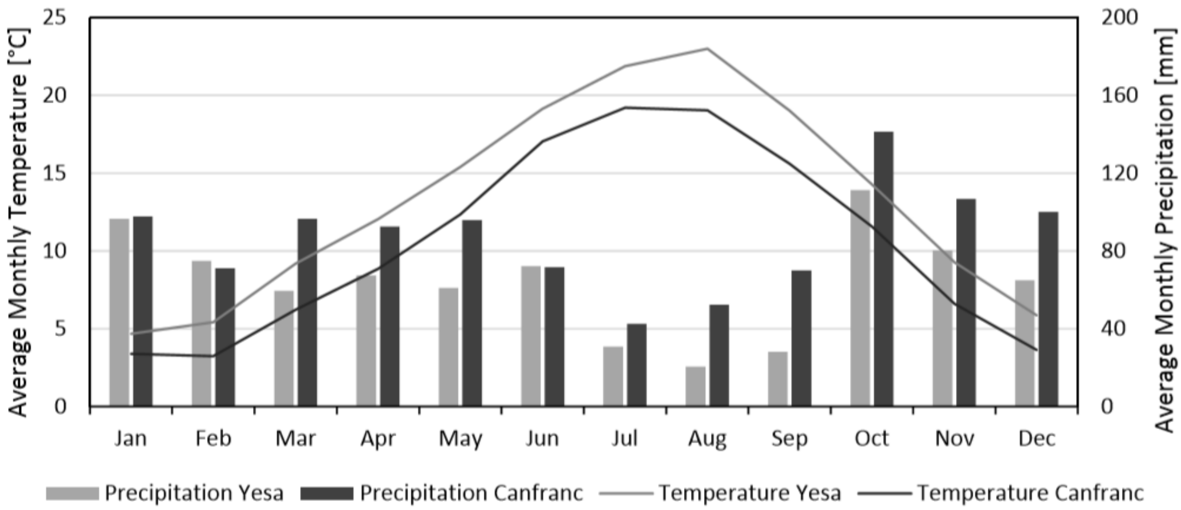

Figure 4 Mean monthly precipitation and temperature at Yesa reservoir and Canfranc, June 2008-2013 (Nije Bijvank 2015)

3.2 Overview of the research steps

Figure 5 shows the steps we take to find changes in hydrological fluxes in the Upper Aragon Basin during the 1950-2050 period. The first part of our research consists of running the hydrological PyCatch model for the Arnás catchment for several LAI values ranging from 0 to 4.4, so we can draw a relationship between LAI and hydrological fluxes (streamflow, evapotranspiration, soil moisture). Because there is such a large level of uncertainty in choosing the right soil and vegetation parameter values, 8 additional scenarios will be run with alternative inputs for certain soil and vegetation parameters.

The second part of our research consists determining changes in vegetation during the 1950-2050 period in the UAB. In order to estimate change in leaf area index (LAI) in the Upper Aragon Basin, 12 NDVI maps created by (Nije Bijvank 2015) are used. The 12 maps are based on 12 Landsat satellite images collected between 1984 and 2013. The NDVI maps are transformed into LAI maps, using two NDVI-LAI transformation methods, a linear and non-linear one. For each of the pixels on the LAI maps a non-linear vegetation growth formula is fitted. This results in maps of the parameters of this non-linear growth model, *c*, *x0*, *k*, for each of the NDVI-LAI relations. These maps are then used as input in the same vegetation growth formula, to calculate LAI values for the 1950-2050 period. Of the resulting LAI maps, we will take the average value over all pixels of each map, and the standard deviation. Now we can draw the relation between year (1950-2050) and average LAI for the Upper Aragon Basin.

The third part of the research brings the earlier two parts together and focusses on finding the relationship between year (1950-2050) and hydrological fluxes for the Upper Aragon Basin. Methods are explained in more detail below.

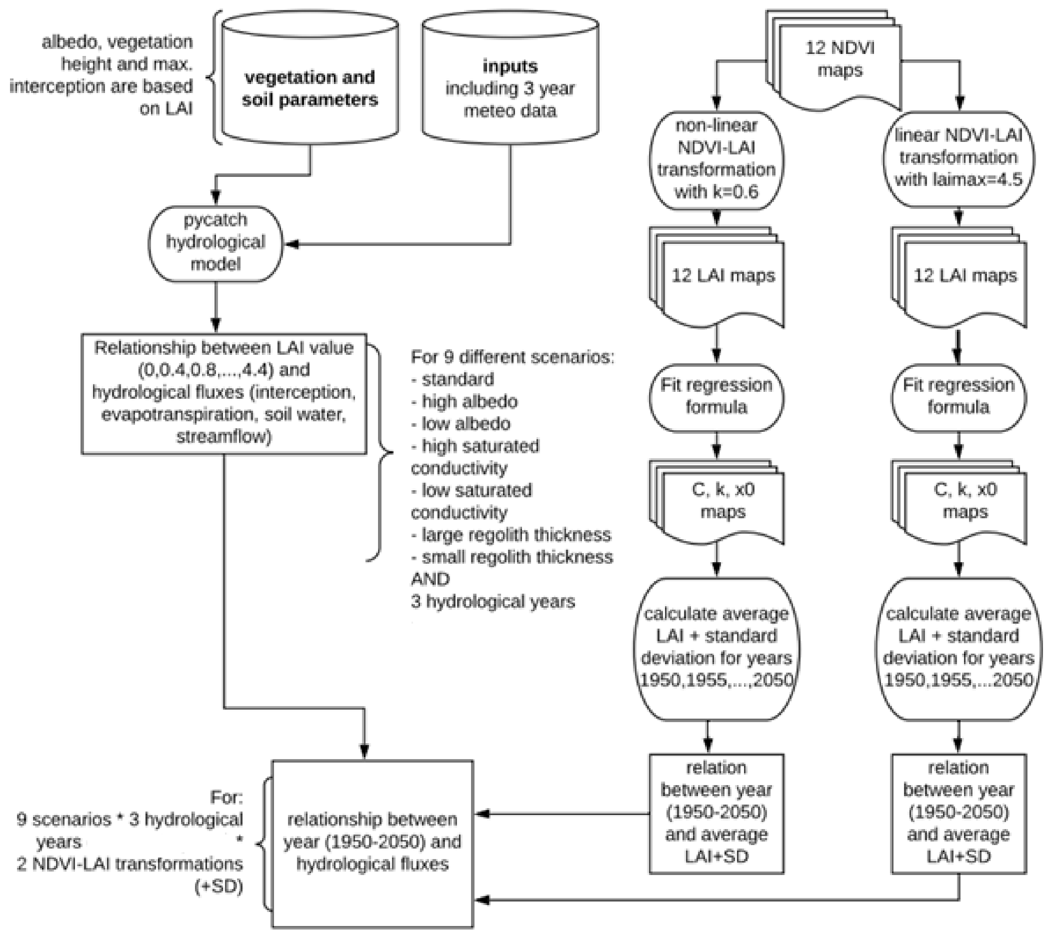

Figure 5 Schematic representation of the research steps.

3.3 Modeling changes in hydrological fluxes due to vegetation change

The goal is to find the relation between vegetation growth and streamflow in the Arnás catchment. Results will later be extrapolated to the complete Upper Aragon Basin. Vegetation growth will be simulated using different LAI values as input in the hydrological model, and analyzing how this impacts streamflow (yearly, monthly, hourly). Vegetation growth does not only mean an increase in LAI, other parameters will change too. We simulated this by coupling LAI to albedo, max. interception and vegetation height. The rest of the model parameters will be kept constant. Because there is such a large uncertainty in our choice of parameter values, we will also run additional scenarios with 25 percent higher and lower values for albedo, regolith thickness and saturated conductivity of the topsoil.

3.3.1 Description of the hydrological model

PyCatch is a distributed dynamic hydrological model built with the PCRaster scripting language (N. Lana-Renault et al. 2011; Karssenberg and Lana-Renault 2013). It is used for modelling water fluxes at the catchment scale. PyCatch simulates interception, evapotranspiration, surface storage, infiltration, subsurface and overland flow with equations that use spatially and temporally distributed input data. A schematic overview of the model is shown in figure 6. The hydrological processes are represented as water fluxes that move between a series of interconnected stores. The cells of the grid map are 10 m by 10 m and are updated every hour.

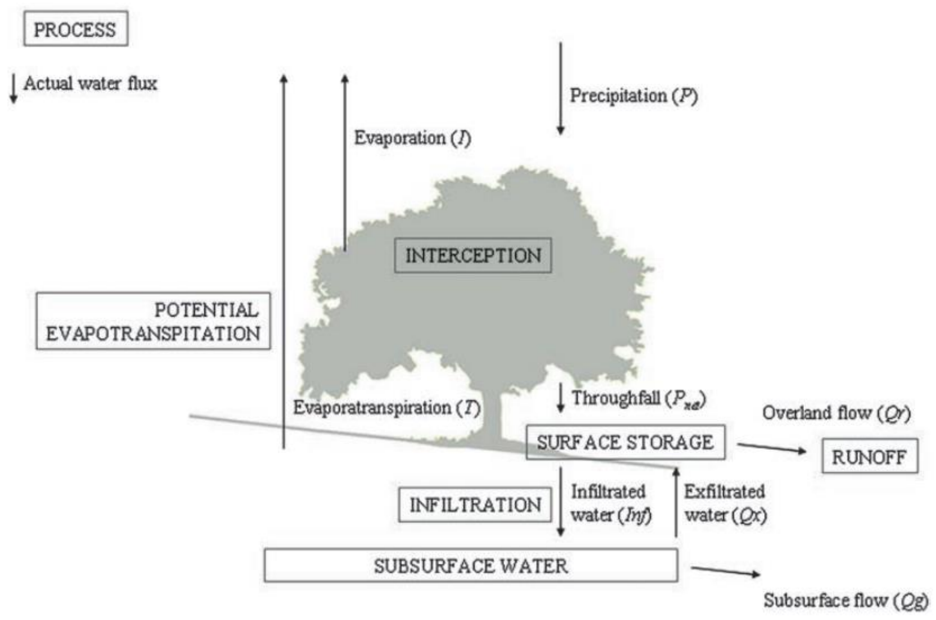

Figure 6 Schematic overview of the hydrological model PyCatch (Lana-Renault et al. 2013)

Precipitation is intercepted or reaches the soil. What part of the precipitation is intercepted depends on the canopy gap fraction, which is a function of the leaf area index and the light extinction coefficient. The precipitation that is not intercepted reaches the ground as throughfall. The intercepted water evaporating from the canopy, and water that evaporates from the sub subsurface through plants, is computed using the Penman-Monteith equation (Allen et al., 1998) for potential evaporation of open water:

$$E_p = \frac{1}{\lambda}\frac{\Delta \mathrm{R_n} + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \left(\frac{r_s}{r_a}\right)} \qquad 3.1$$

Where λ [J kg-1] is the latent heat of vaporization, Δ [Pa K^{-1}] is the slope of the saturation pressure temperature relationship, R_n [W m^{-2}] is the net radiation, ρ_a [kg m^{-3}] is the mean air density at constant pressure, c_p [J kg^{-1} $^{\circ -1}$] is the specific heat of the air, e_s [Pa] is the saturated vapor pressure, e_a [Pa] is the actual v actual vapor pressure, r_a [h m^{-1}] is the aerodynamic resistance, r_s [h m^{-1}] is the surface (or canopy) resistance [h m^{-1}] and γ [Pa $°C^{-1}$] is the psychometric constant.
Water stored at the surface can become surface runoff or infiltrate into the soil. The infiltration of water is calculated using the Green-Ampt model for potential infiltration (Heber Green & Ampt, 1911):

$$f_p(t) = K_s(1 + \left(\frac{\Psi(\phi - \theta_i)}{F}\right)) \qquad 3.2$$

Where K_s [m h^{-1}] is the saturated conductivity of the upper part of the soil, ψ [m] is the suction head, ϕ [-] is the porosity of the soil, θi [-] is the initial moisture content of the soil and F [m] is the cumulative infiltration.
Subsurface flow from one cell to its downstream neighbor (Qg, [m h^{-1}]) is modelled using Darcy's Law:

$$Q_g(t) = K_s\ L\ G\ i \qquad 3.3$$

Where L [m] is the cell length, s [-] is the slope to the downstream cell and G [m] is soil water storage. The drainage direction for each cell is calculated by assigning to each grid cell the direction to the steepest downhill cell over the digital elevation. Upward seepage happens when the storage capacity of the soil is exceeded. Water on the surface might result in overland flow which follows a network of connecting cells in downhill direction where each cell has a single flow direction to the steepest downstream neighbor.

3.3.2 Data acquisition and preparation

Model inputs

The inputs needed in the PyCatch model are depicted in table 1.

Description	Unit
Meterological inputs	
Incoming shortwave radiation	W m^{-2}
Air temperature	°C
Air relative humidity	–
Wind velocity	m h^{-1}
Vegetation parameters	
Leaf Area Index (LAI)	–
Interception storage per LAI	m
Albedo	–
Vegetation height	m
Vegetation stomatal conductance	m h^{-1}
Soil parameters	
Regolith thickness	m
Soil water content at which root water uptake by the plant declines	–
Soil water content at saturation	–
Soil water content at wilting point	–
Soil water content at field capacity	–
Saturated conductivity	m h^{-1}
Saturated conductivity of the upper soil	m h^{-1}
Wetting front capillary pressure head	m
Others	
Digital elevation model	m
Maximum surface storage	m
Latitude, longitude	°

Table 1. Main inputs and parameters for PyCatch (Lana-Renault et al. 2013)

Meteorological Inputs

Meteorological data were measured at a meteorological station in the Arnás catchment. These consist of air temperature [°], precipitation [mm hour-1], wind [m s-1], relative humidity [-] and shortwave radiation [W m-2] data. Data of three consecutive hydrological years (2003-2006) were used.

Vegetation and soil parameters

Albedo

There are several methods to estimate representative albedo values. One option is to derive albedo from weighted bands of the Landsat images. Another option is to model it, for example by using the

Triffid vegetation model (Cox, n.d.). The Triffid model was applied by Bernhard (2013) to model the secondary succession in the Upper Aragon Basin. However, because during succession the type of vegetation changes, and with-it maximum canopy albedo, this model is not suitable for modeling secondary succession because it produces abrupt changes in albedo.

Because of the lack of an appropriate model linking albedo to LAI, albedo values in our study are based on values found in literature. Breuer et al., (2003) collected albedo measurements from the literature per vegetation type. For crops, pasture and deciduous forest they found a mean minimum value of 0.20 and a maximum value of 0.27. Coniferous forests have a substantially lower minimum of 0.11 and a mean maximum of 0.14. Assuming there is a relationship between vegetation type and LAI, and one between vegetation type and albedo, one could draw up a relationship between LAI and albedo. This means an LAI of 0 results in an albedo of 0.18 (bare ground), an LAI of 3 in an albedo of 0.235 (shrubs) and an LAI of 4 or higher is assigned an albedo of 0.17 (mix of pine and oak) (all based on Breuer et al., (2003)). This results in the LAI-albedo relationship shown in figure 7.

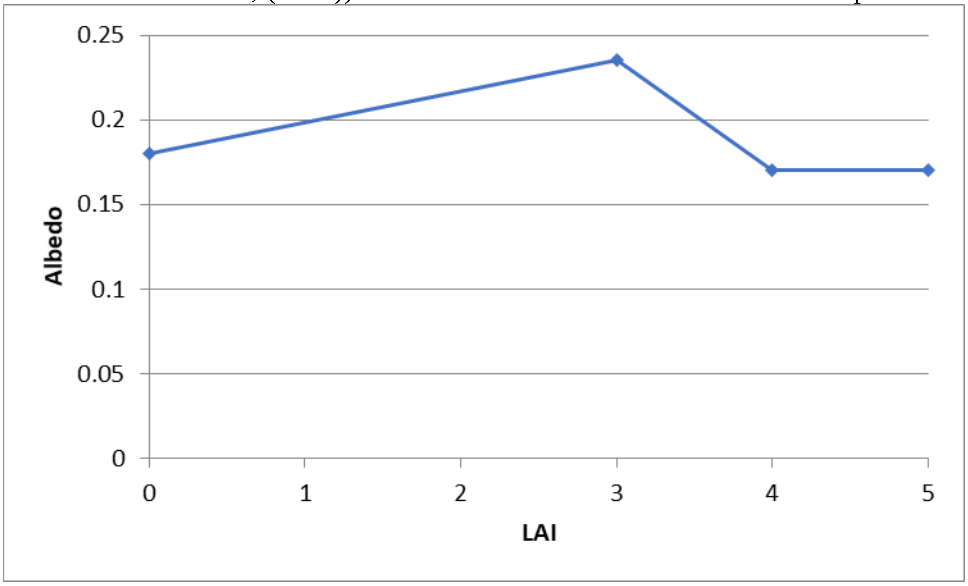

Figure 7 Relation between LAI and albedo. Based on (Breuer et al., 2003)*) as described above.*

Maximum interception storage

Maximum interception storage is the maximum amount of water left on the canopy at the end of a precipitation event, when drip has stopped and there is zero evaporation. It is determined by the sum of leaf and woody area and their characteristics like surface structure and roughness. Interception capacity plays an important role in the water balance because it controls what part of the precipitation may be evaporating from the plant into the atmosphere (Breuer et al., 2003). The leaf area index (LAI) is a good predictor for interception capacity. Several authors have published both LAI and interception storage values, and have derived statistical relationships between LAI and interception storage (See authors cited in: de Jong & Jetten, (2007) and Vegas Galdos et al. (2012)). Vegas Galdos et al. (2012) collected LAI and interception capacity values from different studies in order to find a general relationship between interception capacity and LAI. They tried to find a relationship between LAI and interception capacity for six different groups of corresponding to the main vegetation in the study area: grass and crops, shrubs, conifers, deciduous, evergreen and eucalyptus. For the general relationship they proposed the following equation:

$$S_{max} = f \log(1 + LAI)$$

With S_{max} as the maximum interception storage (mm). The value of *f*, different for each vegetation type, was determined using an algorithm called GRG2. This resulted in an *f* value of 1.0 for grasses, 2.6 for shrubs and 2.0 for a conifer forest, which produces a relation between LAI and interception storage for each vegetation type (figure 8).

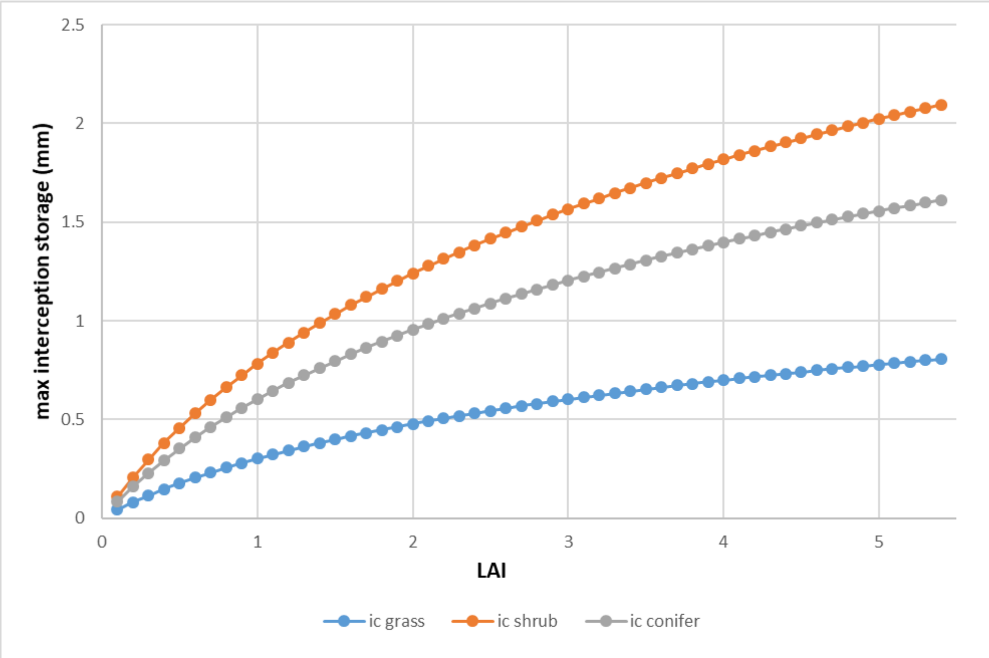

Figure 8 Relationship between LAI and max interception storage

Because in our study area secondary succession takes place, different vegetation types and multiple vegetation layers need to be considered which complicates this relationship. Because it is not possible to find a relation that covers all vegetation types at the same time, it was decided to use the formula of Vegas Galdos et al. (2012) and assign to *f* a value of 1.867, which is the average of the *f* values for grasses (1.0), shrubs (2.6) and conifer forest (2.0).

Stomatal conductance

There is no clear relation between maximum stomatal conductance and LAI or plant age, although in general woody plants have a lower stomatal conductance (2.5–4.0 mm s^{-1}) compared to herbal plants species (6 mm s^{-1}) (Breuer et al., 2003). But the range of published values for stomatal conductance in herbal plants is large, which shows in the relatively high standard deviation of 6 mm s^{-1} for herbs, forbs and grasses. Because the relation between LAI and maximum stomatal conductance is very uncertain, we decided to keep the value for max stomatal conductance constant at 4.5 mm/s.

Vegetation Height

The possible relationship between vegetation height and LAI was examined by Yuan, Wang, Yin, & Zhan (2013). Using a large dataset of H and LAI, several functions were fitted through the data. A linear, power, logarithmic and exponential function all fitted the data to some degree. The power function had the best fit with an R^2 of 0.46. It was followed by the linear fitting.

There are only few data available about the relation between vegetation height and LAI in the Upper Aragon basin. Lana-Renault measured a vegetation height of 20 meters for the maximum LAI (which we chose as 4.5), and a vegetation height of 1.4 for the area with shrubs, which would have an LAI somewhere between 2 and 4. Poyatos, Llorens, and Gallart (2005) measured an LAI of 2.4 for a vegetation height of 11 meters, without understory. According to Breuer et al. (2003), you can add up to 2 points for understory. So, this means a vegetation height of 11 meters would have an LAI somewhere between 2.4 and 4.4.

Based on this information combined with the power function found by (Yuan et al., 2013) we assumed the relationship between LAI and H as shown in Figure 9 (For equations see table 2).

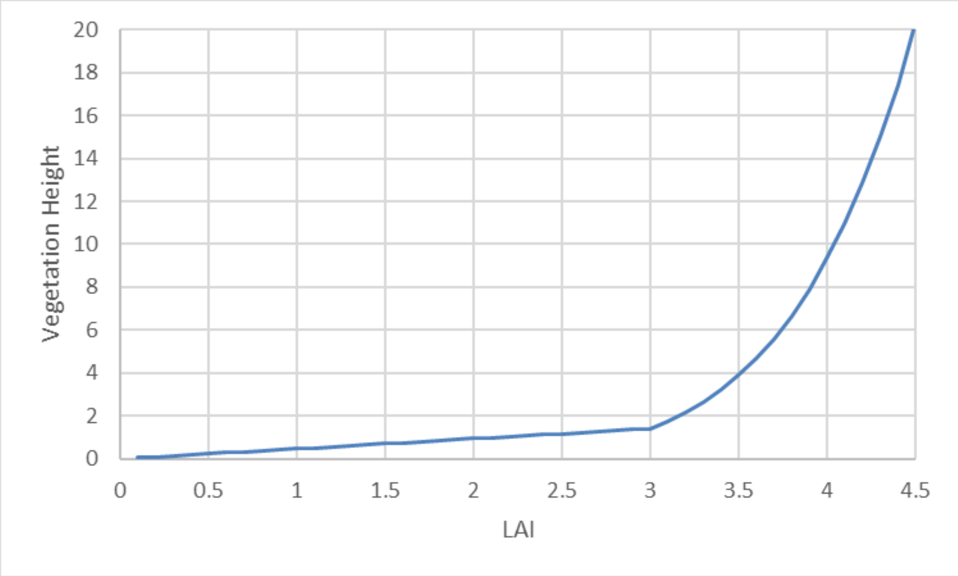

Figure 9 Relationship between vegetation height and LAI

Which is partially linear (because otherwise the vegetation height is too low for low LAI values) and partially a power function.

Soil parameters

For the soil parameters we use the values derived from Noemi Lana-Renault et al. (n.d.). They determined values for the soil parameters for two different catchments, one is the Arnás catchment covered with mostly shrubs and the other a forested catchment. Their soil parameter values are partly based on literature (Navas et al., 2005) and partly the result of calibration. For each soil parameter, we will take the average value of the two catchments.

3.3.3 Scenarios

The PyCatch hydrological model will be run for 9 scenarios. The standard scenario will have the input parameters as described in the text above. Details can be found in the table 2. Because there is much uncertainty in our choice of vegetation and soil parameter values, we also run the model with a 25 percent higher and lower value for a selection of parameters. These parameters are albedo, soil thickness and saturated conductivity of the topsoil. In this way we can analyze the sensitivity of the model to these parameters and the uncertainty of our modeling outcomes. We will also run a low streamflow scenario and a high streamflow scenario where albedo, saturated conductivity and regolith thickness are 25 percent higher/lower to get the lowest and highest average streamflow.

Vegetation parameters	Units	
albedo	-	Depends on LAI (see figure 7). lai 0-3: 0.0183*LAI+ 0.18 lai 3-4: -0.065*LAI + 0.43 lai 4<..: 0.17
Max. stomatal conductance	mm/s	4.5
Max. canopy interception storage capacity	m	Depends on LAI (see figure 8) $S_{max} = f \log(1 + LAI)$ With f=1.866667
Leaf Area Index	-	Ranges from 0 to 4.4 with steps of 0.2
Vegetation Height	m	Depends on LAI (see figure 9).

		LAI 0-3: 0.47*LAI LAI >3: =0.00105*LAI^6.5585
Soil Parameters		
Saturated conductivity of the topsoil	m/h	0.03
Saturated conductivity	m/d	27.59
Soil thickness	m	2.71
Volumetric moisture content at field capacity	-	0.34
Volumetric moisture at which root water uptake by the plant decline	-	0.295
Volumetric moisture at wilting point	-	0.115
Volumetric pore space of the regolith	-	0.55

Table 2 Input parameter values for PyCatch model.

3.4 Vegetation change in the Upper Aragon basin

3.4.1 NDVI-LAI transformation

Starting point are the 12 NDVI maps created by Nije Bijvank (2015). These were based on 12 Landsat satellite images collected between 1984 and 2013. There are several ways in which NDVI values can be transformed into LAI values. A simple way is to assume a linear relation (Yin & Lee Williams, 1997):

$$LAI_i = LAI_{max} \frac{NDVI_i - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \qquad 3.4$$

Where LAI_{max} is the leaf area index of a forest in the climax stage of succession, $NDVI_{min}$ is the NDVI of a bare field and $NDVI_{max}$ is the NDVI of a forest in the climax stage. Although this model is capable of predicting LAI values based on NDVI between the LAI of 0 and 3, at higher LAI values the NDVI curve tends to become saturated (Bierkens et al., 2008). One solution to this problem is Beers Law (Gigante et al., 2009):

$$LAI = -\frac{1}{k} \ln \frac{NDVI_{max} - NDVI}{NDVI_{max} - NDVI_{min}} \qquad 3.5$$

where $NDVI_{max}$ is the asymptotic value of NDVI for higher LAI values, $NDVI_{min}$ is the NDVI value corresponding to bare soil and *k* is the light extinction coefficient.

In our research we will use both the linear and non-linear method in transforming NDVI into LAI. When applying the linear LAI-NDVI transformation, values for $NDVI_{min}$, $NDVI_{max}$ and LAI_{max} are needed. The values for $NDVI_{min}$ and $NDVI_{max}$ were earlier calculated by Nije Bijvank (2015). For the $NDVI_{min}$ 10 bare fields were selected on the 1984 and the 2013 image and from this the average $NDVI_{min}$ value was calculated. The $NDVI_{max}$ was obtained by taking the 99 percentile value of the 2013 image.

The LAI_{max} refers to the maximum LAI at the climax stage of succession in the Upper Aragon Basin. Originally many hillsides were covered by an oak dominated forest (Quercus gr. Faginea), but due to human disturbance and reforestation measures these are in most places replaced by pines (Pinus Sylvestris), which also started to grow on abandoned fields (Navas et al. 2008). Here we will assume that the climax vegetation in this area consists of a mixed pine and oak forest. LAI values for pine are lower than for oak. Several LAI values for pine forest have been measured in the field. Breuer et al.,

(2003) gathered a series of representative parameter values from several studies and found for Pinus Sylvestris values between 1.1 and 7.2. Other measurements of LAI in pine stands found in the literature range between 1.7 and 3.6 (Bequet et al., 2012; Hernández-Clemente et al., 2011; Jonckheere et al., 2005; Riaño et al., 2004). LAI values ranging from 4.4 to 6.6 were measured in a series of pine stands in the central mountain range in Spain (Montes et al., 2007). The above LAI values are almost all calculated using DBH allometry. Allometry is a method that relates forest inventory parameters (in this case: diameter at breast height (DBH)) to aboveground biomass components (e.g., leaves, branches, stems) (Jonckheere et al., 2005). Although this is an accurate method, allometric equations are site-specific and vary with stand age and density, and climatic conditions (Jonckheere et al., 2005). This means it is uncertain how the values derived from measurements in one forest stand apply to those in another stand at a different location (Jonckheere et al., 2005). So, it would be preferable to get an LAI value measured in the same region. The only LAI measured in the region is from R. Poyatos, Llorens, and Gallart (2005) who determined the maximum LAI to be 2.4 in a Pyrenean forest stand with the oldest trees around 60 years old, 11 meters in height overgrowing an abandoned terraced slope at an elevation of ca. 1260 m. It is uncertain if this value could be considered representative for the maximum climax vegetation in the Upper Aragan Basin. In the study area of Poyates there was not much understory present. While at least in one other study area in the Upper Aragon Basin, the San Salvador catchment, pine trees were found of 20 meters in height with a dense understory (Noemi Lana-Renault et al., n.d.) which would most probably correspond to a higher LAI. According to Breuer, Eckhardt, and Frede (2003) on average a surcharge for understory vegetation and litter of approximately 2.0 should be added to the total LAI of deciduous and coniferous forests stands. Oak trees generally have an LAI of around 5 (Breuer et al., 2003). The above information taken into account, an LAI_{max} value between 4 and 5 would probably be a realistic estimation for the LAI in the climax state of succession in the Upper Aragon Basin.

When using Beer's law to estimate LAI, apart from $NDVI_{min}$, $NDVI_{max,}$ a value for *k* needs to be determined. The value of *k* can be found by a calibration procedure formulated by Gigante et al. (2009). For this a sufficiently large dataset of NDVI maps is needed, after which a *k* value for each vegetation type can be found. Using this method, Milella et al. (2012) found *k* values ranging from 0.16 to 0.41 depending on remote sensing source and vegetation type in a semi-arid Mediterranean environment. Having only 12 NDVI maps available finding a *k* value by calibration is not possible. Another option is to derive the *k* value from literature. Several reference values are available for the Mediterranean ranging from 0.153, 0.212 and 0.213 for mixed (or non-specified) natural vegetation, to 0.363 for coniferous forests (Anselmi et al., 2004; Lacaze & Hill, 1996). The extinction coefficient depends both on the sensor type and the vegetation characteristics as density, leaf angle distributions, soil optical properties and leaf physiological properties (Gigante et al., 2009). Which means using a *k* value derived from literature results in a high level of uncertainty. Figure 10 shows the effect of different k estimates on the NDVI-LAI relation. Although a value of 0.2 seems realistic when looking at the literature, it does in our case lead to unrealistically high LAI values. Considering the maximum LAI value found in literature for the climax vegetation, it is not probable that LAI will exceed a value of around 5. For this reason, we chose a *k* value of 0.6. Both the linear method with LAI_{max} of 4.5 and the non-linear method with a k value of 0.6 will be implemented (figure 11).

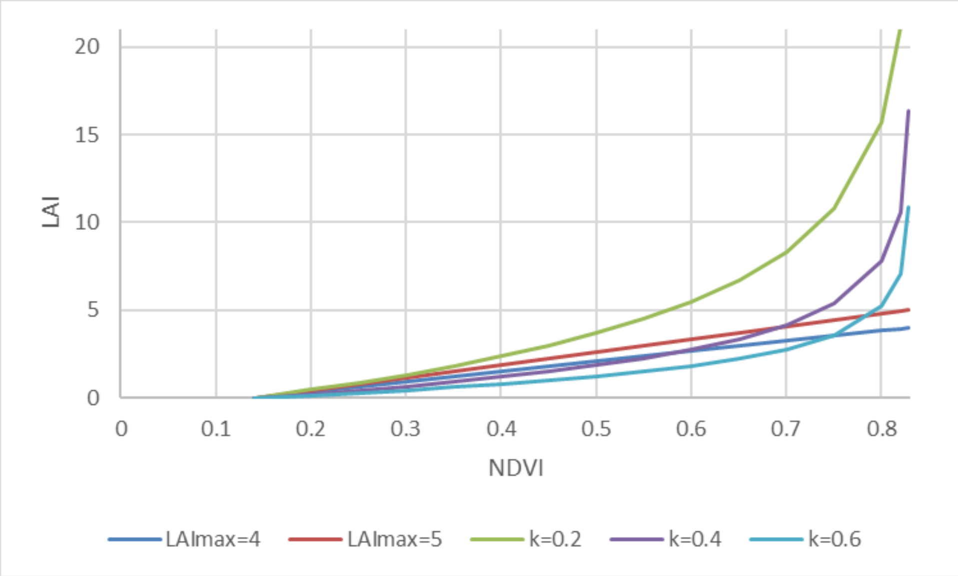

figure 10 Different LAI-NDVI transformation methods. The linear method with LAImax=4 and LAImax=5, and the non-linear method with k=0.2, k=0.4 and k=0.6.

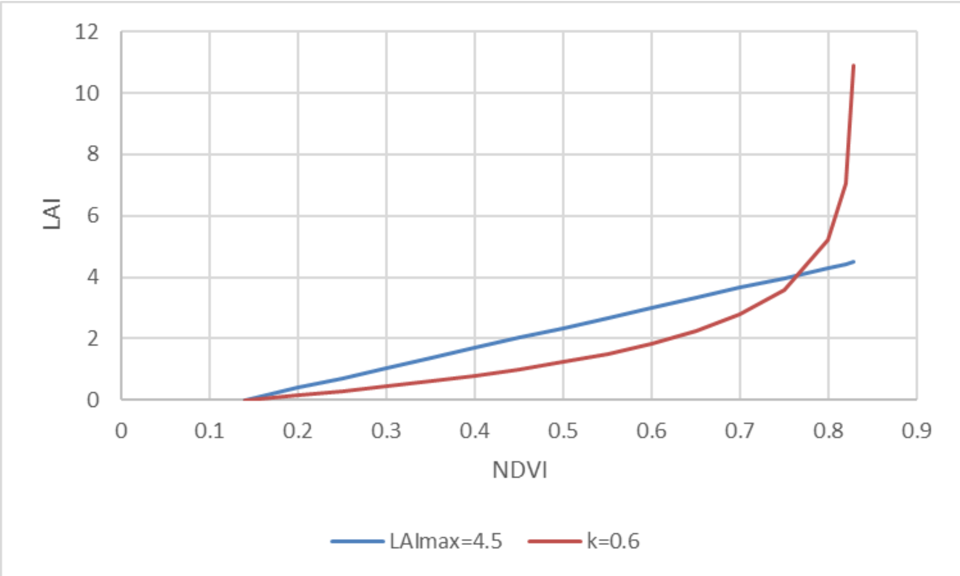

Figure 11 The blue line depicts the linear NDVI-LAI transformation with an LAImax of 4.5. The red line depicts the non-linear NDVI-LAI transformation with a k value of 0.6.

3.4.2 Calculating LAI values for the period 1950-2050

To create LAI values for the complete study period (1950-2050) we will apply the non-linear regression method used by Bänziger (2016). Bänziger fitted a logarithmic function through the 12 LAI maps calculated by Nije Bijvank (2015). We will use the same method but this time with new LAI maps that were created as described in chapter 3.4.1. For each cell:

$$LAI = c(1 - e^{-k(x-x0)}) \qquad 3.6$$

where LAI is the leaf area index [m^2 m^{-2}], *x* is the date [year], *c* is the maximum LAI value [m^2 m^{-2}], *k* is the growing rate [-] and *x0* is the date when farmland was abandoned [year].
This will result in a set of maps for each of the two NDVI-LAI relations with for each pixel a *c*, *k* and

x value. These values can than used as input in the same equation to calculate LAI maps for the years 1950,1955, 1960, etc. up to 2050, for each of the two NDVI-LAI relations. To find average vegetation growth in the UAB (for each of the two NDVI-LAI relations), we then take the average of the pixels in these maps for each of the years (1950, 1955,.. 2050). We will also calculate the standard deviation for each of these LAI maps.

3.5 Calculating streamflow as a result of average vegetation growth in the Upper Aragon Basin

The average LAI values of the LAI maps (1950-2050) for the Upper Aragon basin are coupled to the average streamflow for that LAI value that is calculated with the PyCatch model for the Arnás catchment. This way we get a rough estimate of the hydrological fluxes through time.

4. Results

4.1 Streamflow, evapotranspiration and soil moisture as a function of vegetation growth in the Arnás catchment

The water that precipitates in the Arnás catchment can leave the catchment in three ways: it can be intercepted by leaves and then evaporate from there, it can infiltrate in the ground and then be taken up by plants and transpire, or it can become streamflow. The water that leaves the catchment as transpiration (m/h) during the three years (2003-2006) is depicted in figure 14. When the Arnás catchment has an LAI of 0 there is no transpiration. When the LAI is higher than 0 there is a clear seasonal pattern: transpiration is highest in summer and lowest in winter. With an increase in LAI there is an increase in transpiration. This increase is the largest for the low LAI (0, 0.2, 1) values. In contrast, the difference in transpiration between the scenarios with an LAI of 1, 2 and 3 is relatively small. The difference in transpiration between the LAI of 3 and LAI of 4 catchment is again larger, but only for the first year (2003-2004). The evaporation from the interception store is depicted in figure 15. The amount of interception evaporation is small compared to that of transpiration. Also, there is no seasonal pattern.

Evapotranspiration has a large influence on the amount of soil moisture. Figure 16 depicts the fluctuations in soil moisture fraction for six different LAI values. The straight line depicts the soil moisture fraction at field capacity. When LAI is 0 the soil moisture fraction is always above field capacity because no water is lost by evapotranspiration. This means that a rainfall event will always lead to streamflow because the soil is always saturated. For all LAI's above 0, soil moisture is highest in winter and lowest in summer following the transpiration pattern. Higher LAIs lead to a lower soil moisture fraction. An increase in LAI means field capacity is reached later in autumn (and sometimes it is not reached at all). What is also visible is that the lack of rainfall during the dry year (2004-2005) (figure 12) results in lower soil moisture values in the following year, in this way impacting the amount and timing of streamflow in the next year. The higher the soil moisture fraction is, the more probable it is that a rainfall event will result in streamflow. Figure 17 depicts water above field capacity (m). The pattern of the water above field capacity corresponds roughly to the hourly streamflow (m/h) (see figures 18,19,20). When the LAI is 0, water is always above field capacity. For this reason, there is not a clear link between water above field capacity and streamflow, in the case of LAI=0.

Figure 21 shows the average monthly rainfall and streamflow during the three-year period (2003-2006) for seven different LAI values. For an LAI of 0, the streamflow seems to be closely related to the amount of rainfall each month. For higher LAI values, even as low as 0.2 the relation between rainfall and streamflow becomes considerably less clear. This is especially the case in the summer months (June-September), where there is a large decrease in streamflow between the LAI=0 and LAI=0.2 scenarios. This is the result of increased evapotranspiration in the summer months which depletes soil moisture (figure 14 and 16), due to the increase in vegetation. For all LAIs, except for the LAI of 0, streamflow shows approximately the same seasonal pattern: flow is highest in Oct-Nov-Dec, then there is a dip around February, followed by an increase in spring (around April), and then in summer the streamflow becomes almost zero. The dip in streamflow around February seems to be caused by a decrease in rainfall in this time of year which happens in all three years. The lack of streamflow in summer is the result of increased transpiration combined with reduced rainfall. The amount of streamflow decreases with the increase of LAI. As stated earlier this decrease is largest in summer and happens almost immediately after vegetation growth starts. When LAI keeps increasing the decrease in streamflow happens first at the start of the wet season (Oct-Dec). Higher LAI means that streamflow starts later in autumn/winter. When LAI keeps going up also in spring streamflow will start going down.

Although all three years show roughly the same pattern, there are also large differences. The first year clearly has the highest amount of streamflow as a result of a large amount of rainfall mostly concentrated in autumn. Streamflow in the second year is low, as the result of there being little rainfall. Although the amount of rainfall in the third year is comparable to that of the first year, streamflow is a lot lower. This can be explained by looking at the timing of the rainfall, and the amount of soil moisture at the start of the year. Because of the limited amount of precipitation in the second hydrological year, soil moisture at the start of the third year is low. This means it takes longer before the subsurface is saturated and streamflow starts. Also, because in the third year a smaller amount of the rainfall is concentrated at the start of the hydrological year, less water is available in winter to form streamflow. In the first year more water is concentrated at the start of the year which adds to the fast wetting up of the soil and more streamflow in winter.

Figure 22 shows the yearly runoff coefficient for the Arnás catchment as a function of LAI. The three lines depict the three hydrological years (2003-2006). All three years show roughly the same pattern: there is a stark decrease in the runoff coefficient for the very low LAIs, then after the LAI of 1 the relation between the runoff coefficient and LAI becomes roughly linear. And after the LAI of around 3, again there is a starker decrease. After the LAI of four there is almost no runoff. Apart from the similarities there are also differences between the three years. The 2003-2004 year has quite a bit higher runoff coefficient than the other two years. The runoff coefficient of the 2004-2005 and 2005-2006 years are quite similar. The fact that the runoff coefficient of the 2003-2004 and 2005-2006 years are so different while the amount of rainfall is the same, is the result of rainfall pattern and amount and soil moisture as explained earlier.

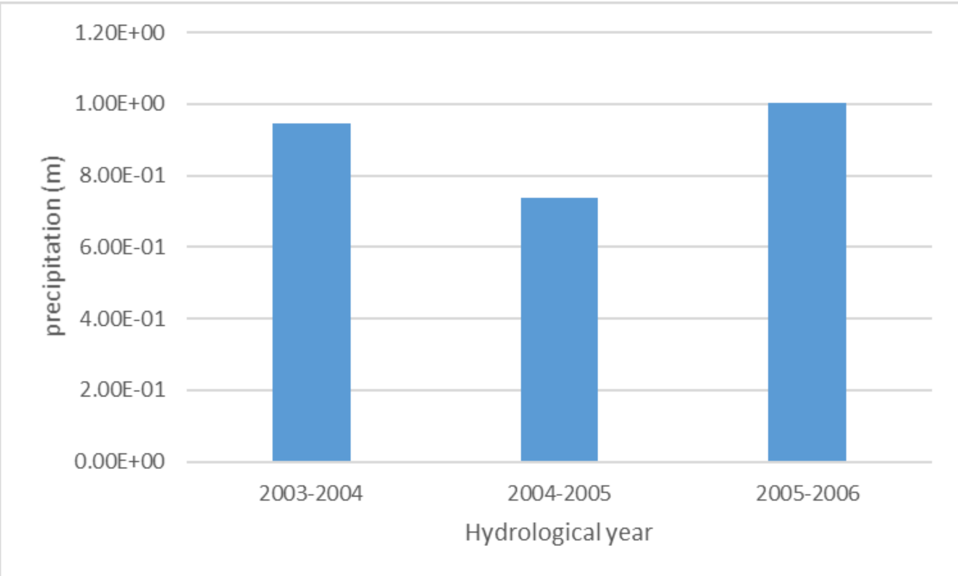

Figure 12 Measured total yearly rainfall for each hydrological year in the Arnás catchment in meters

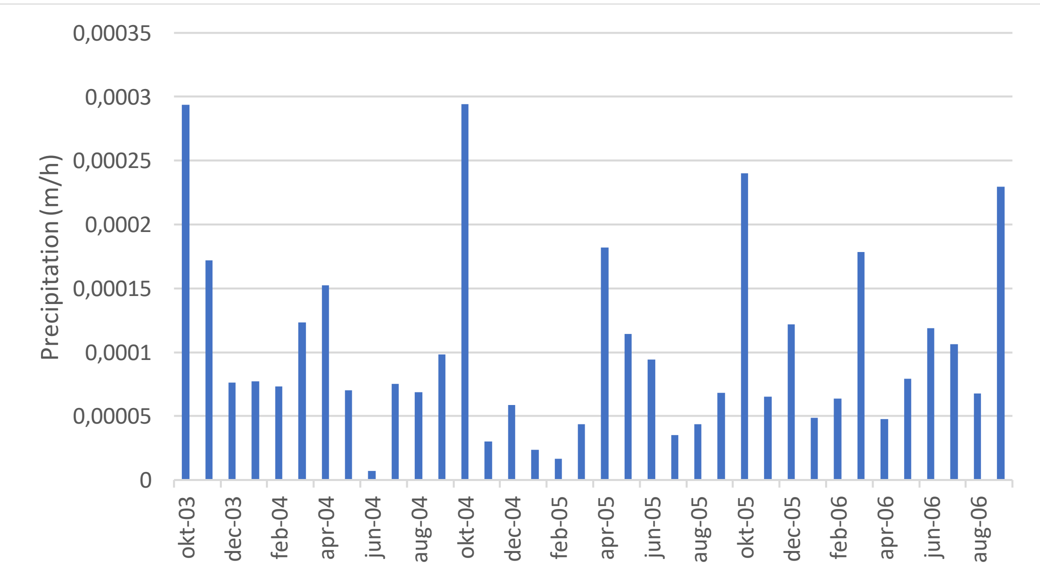

Figure 13 Measured monthly average precipitation (m/h)

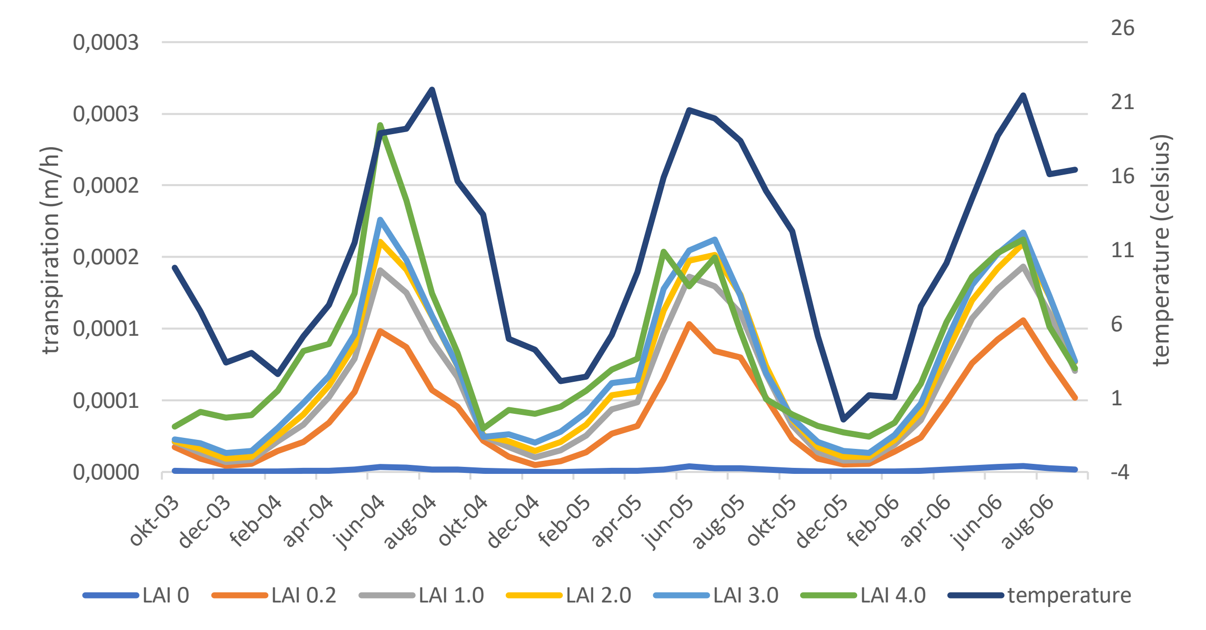

Figure 14 Measured temperature and modelled average transpiration in the Arnás catchment for six different LAI values in the Arnás catchment for three hydrological years (2003-2006).

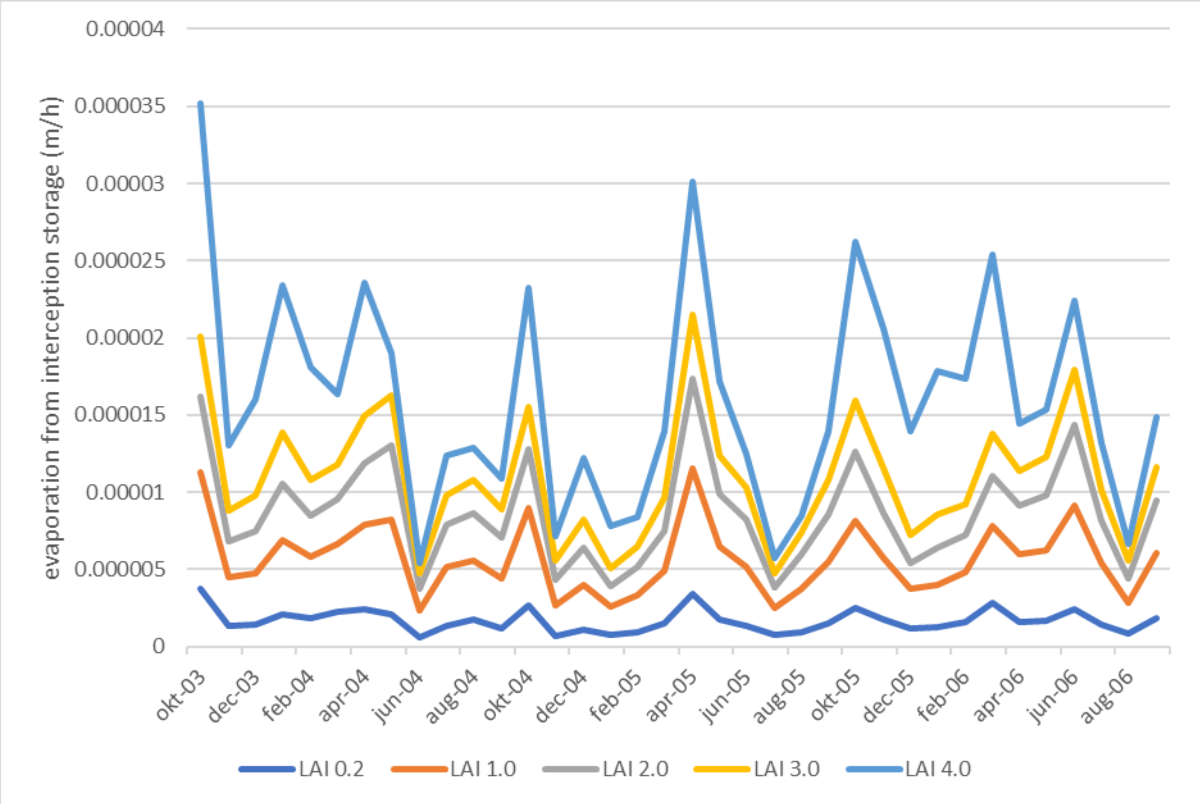

Figure 15 Average evaporation (m/h) from the interception store in the Arnás catchment (2003-2006), for five different LAI values.

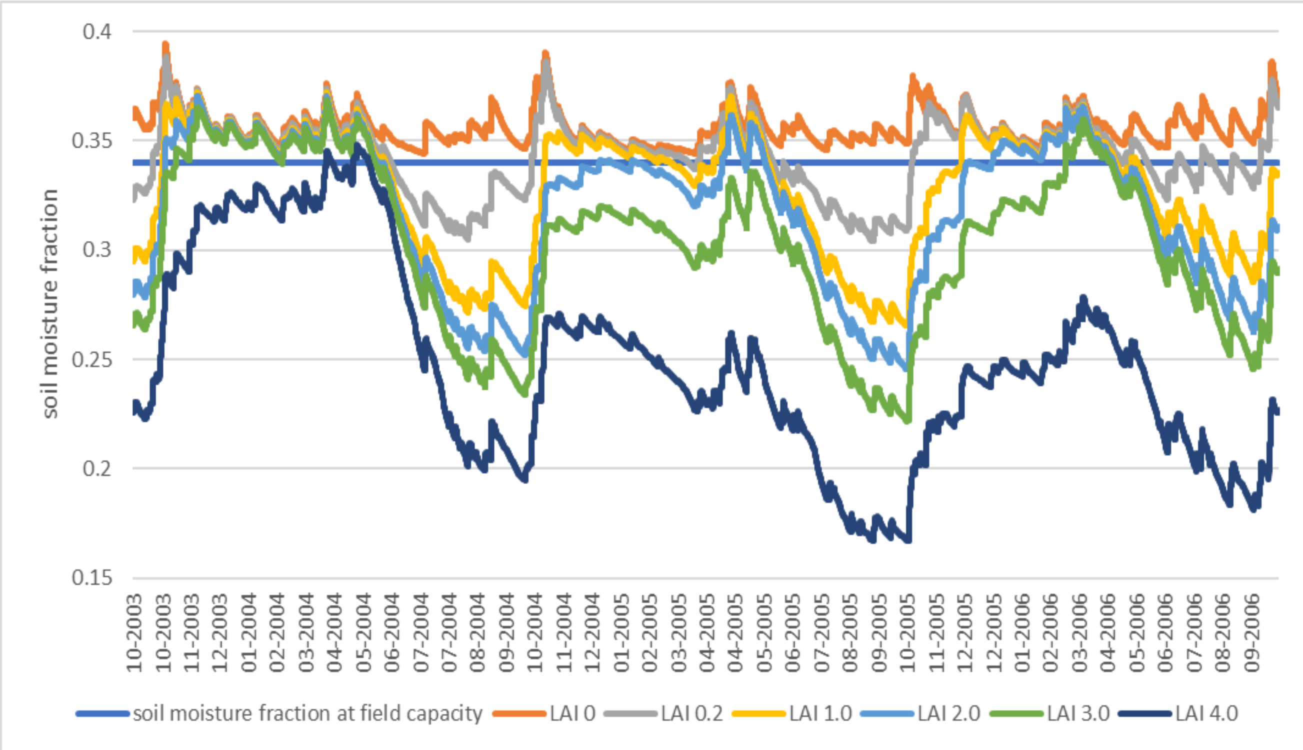

Figure 16 Average soil moisture fraction (2003-2006) in the Arnás catchment for six different LAI values.

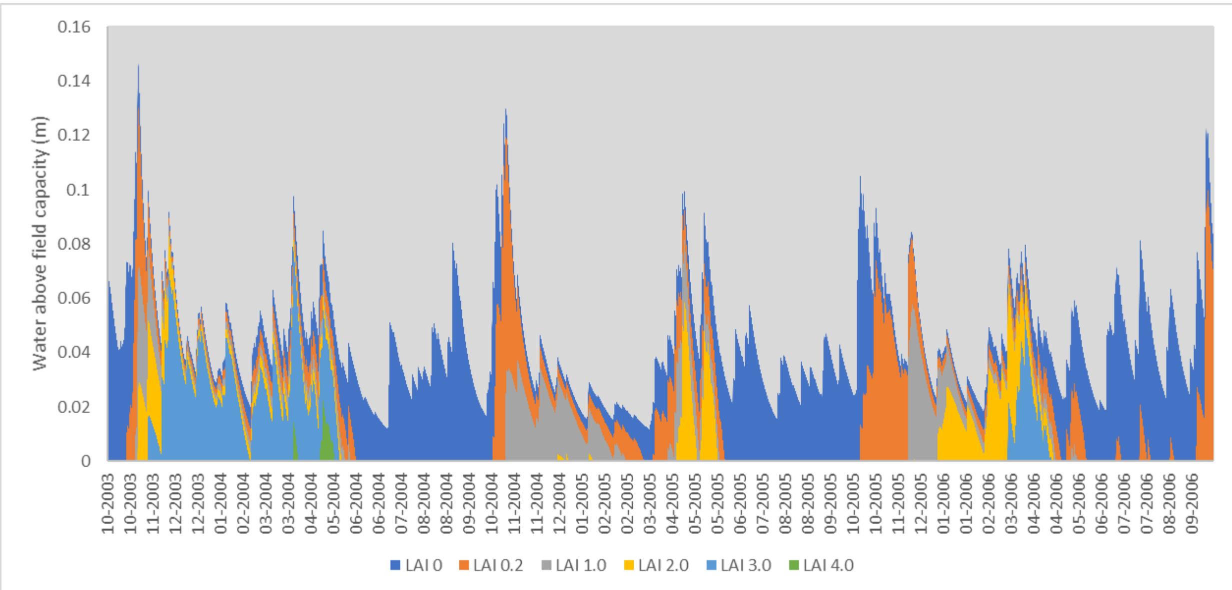

Figure 17 Water above field capacity (m) in the Arnás catchment during three hydrological years (2003-2006) for six different LAI values.

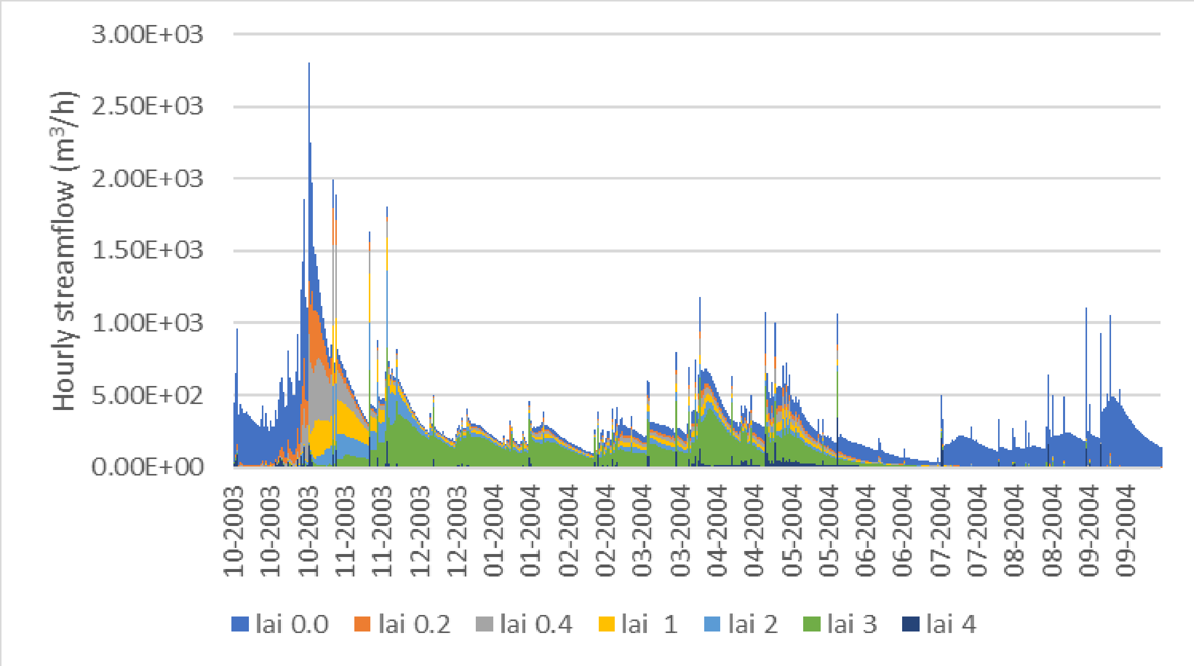

Figure 18 Hourly streamflow (m^3/hour) in the Arnás catchment for seven different LAI values during one hydrological year (2003-2004)

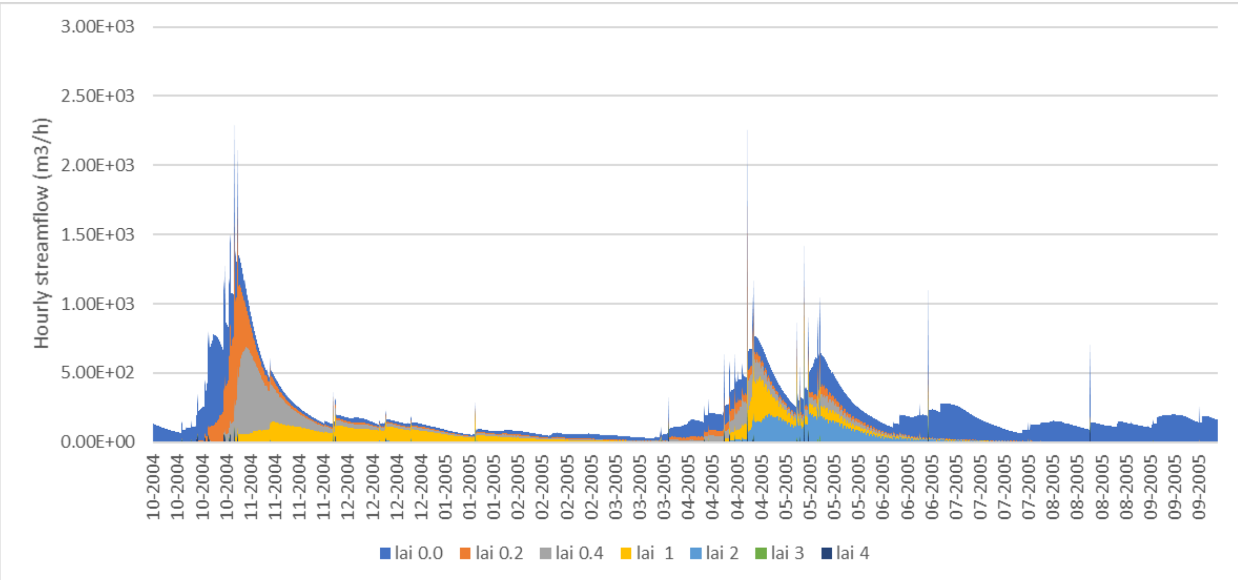

Figure 19 Hourly streamflow (m3/hour) in the Arnás catchment for seven different LAI values for one hydrological year (2004-2005)

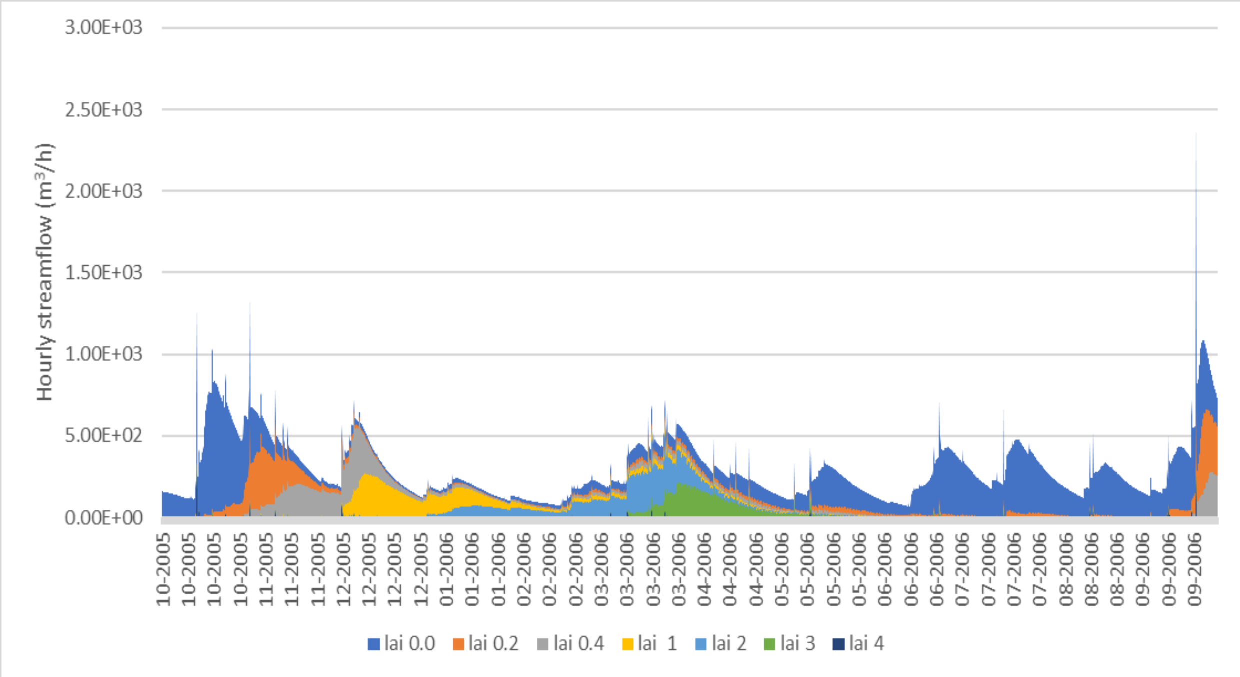

Figure 20 Hourly streamflow (m3/hour) in the Arnás catchment for seven LAI values for one hydrological year (2005-2006).

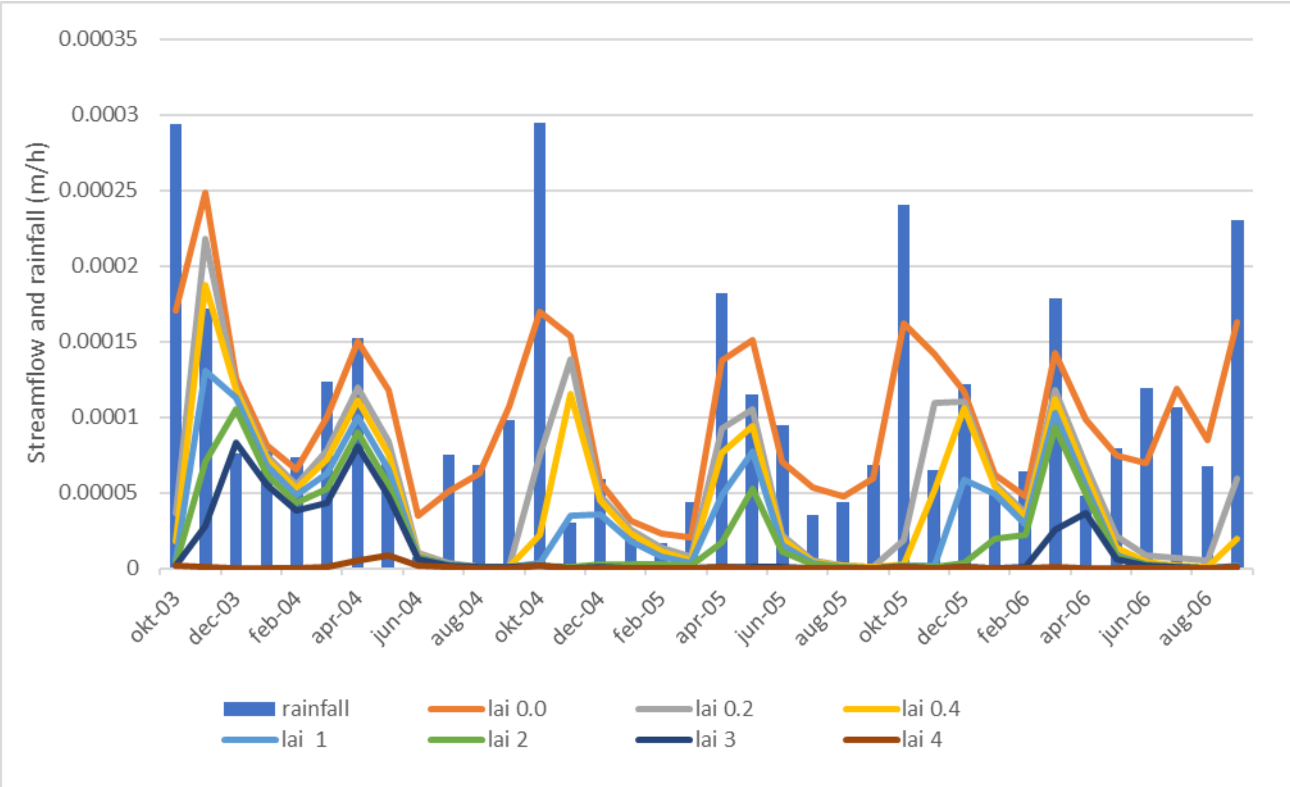

Figure 21 Monthly streamflow and rainfall (m) in the Arnás for seven different LAI values

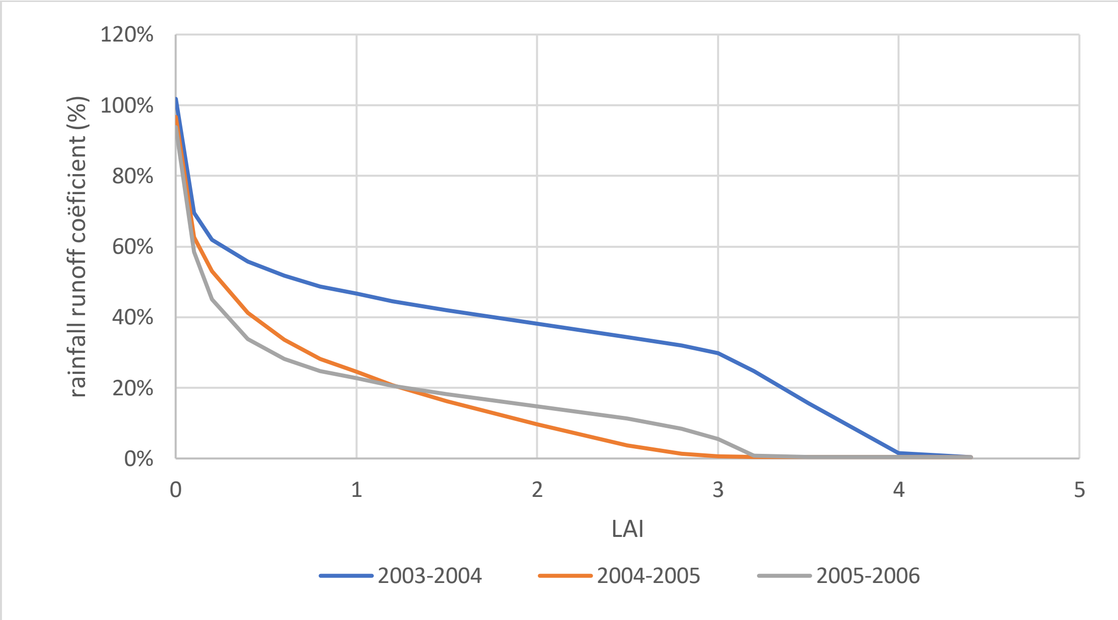

Figure 22 The relation between yearly runoff coefficient and LAI in the Arnás for three hydrological years (2003-2006).

4.2 Influence of vegetation and soil parameter values on streamflow, evapotranspiration and soil moisture in the Arnás catchment

In order to determine the sensitivity of our outcomes to vegetation and soil parameters and to assess the uncertainty in our model outcomes, eight additional scenarios were run (see paragraph 3.3.3). Figure 23 depicts transpiration during three hydrological years, for 9 scenarios with an LAI of 2. The change in the rate of transpiration is caused primarily by the change in albedo, with higher albedo values resulting in low levels of transpiration and low albedo values resulting in high levels of transpiration. Soil thickness does not influence the amount of transpiration (or evaporation, see figure 24). A lower or higher hydraulic conductivity of the topsoil also has no effect on transpiration.

Figure 25 shows soil moisture fraction for the 9 scenarios for three hydrological years. Largest impact of the change in parameter values is in summer, where difference in soil moisture fraction can be up to 0.04 point. This affects streamflow in autumn. For scenarios with a high albedo and a shallow soil field capacity is reached earlier in autumn, while for the scenarios with a low albedo and thick soil it is reached later in the wet season (autumn/winter/spring). When field capacity is reached the difference between the scenarios disappears, streamflow response to rainfall becomes the same, but this starts growing again in summer as a result of evapotranspiration.

Figures 26, 27, 28 depict hourly streamflow for each hydrological year. In the first year (2003-2004), streamflow is heavily impacted by changes in vegetation and soil parameter value, but only in November and December. In winter and spring streamflow is roughly the same for all scenarios. In the other two years, the impact is still largest in early autumn but this time also streamflow in the other months is affected. In general, the effect of soil and vegetation parameter values on streamflow becomes smaller when approaching spring. What is interesting to see is that in the first year the impact of albedo is larger than that of soil thickness, while for the other two years it is the other way around.

Figure 29 shows the effect of the different parameter values on the monthly streamflow. Again, it becomes clear that the impact of the different parameter values is most prominent in the early part of the wet season (Oct-Nov-Dec). The impact becomes a lot smaller from February onwards.

The yearly runoff coefficient for the different scenarios in the 2003-2004 year is depicted in figure 30. The graphs of the different scenarios all have roughly the same shape. Furthermore, the 25 percent increase in soil thickness has roughly the same effect on the yearly streamflow as a 25 percent lower albedo, and vice versa. Both result in a 3 percent (absolute) difference in runoff coefficient with the standard scenario for roughly all LAI values. Which means that for higher LAI values the difference is relatively larger than for smaller LAI values. The impact of the 25 percent higher or lower hydraulic conductivity values is very small, and results in almost the same values as that of the standard scenario.

Figure 30 shows the effect of the low streamflow scenario (thick soil, low albedo, low infiltration) and high streamflow scenario (thin soil, high albedo and high infiltration) on the yearly runoff coefficient. The graph has the same shape as that of the standard scenario: there is a stark decrease in streamflow for the lowest LAI values, followed by a more gradual decrease, and this becomes again stronger from LAI=3 onwards. The difference in runoff coefficient between the low scenario/high scenario and the standard scenario seems to be roughly the same for all LAI values, except for the very low and high values. The absolute differences in runoff coefficient for all three years can be found in appendix A in more detail. The difference with the standard scenarios varies between 4 and 8 percent. The difference becomes larger when LAI increases but this diminishes quickly when LAI approaches zero There are also differences between the three hydrological years. The effect of the low/high streamflow scenarios seems to be the largest in the 2003-2004 hydrological year.

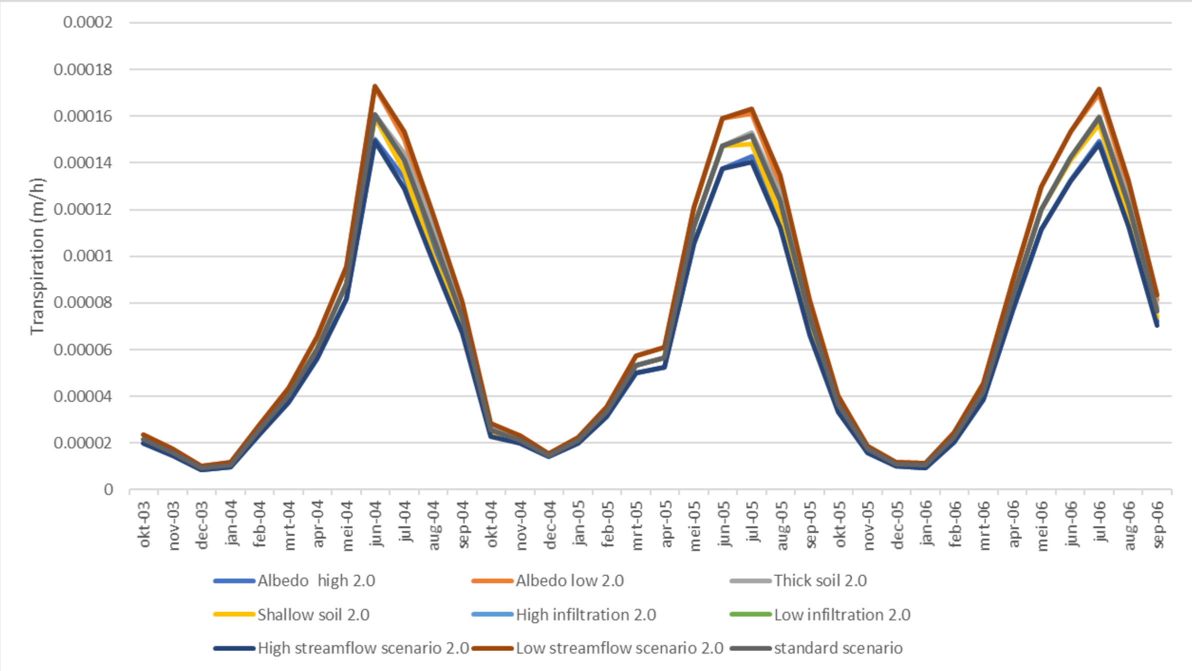

Figure 23 Average monthly transpiration (m/h) for the Arnás catchment with an LAI of 2, with nine variations in parameter values for three hydrological years (2003-2006).

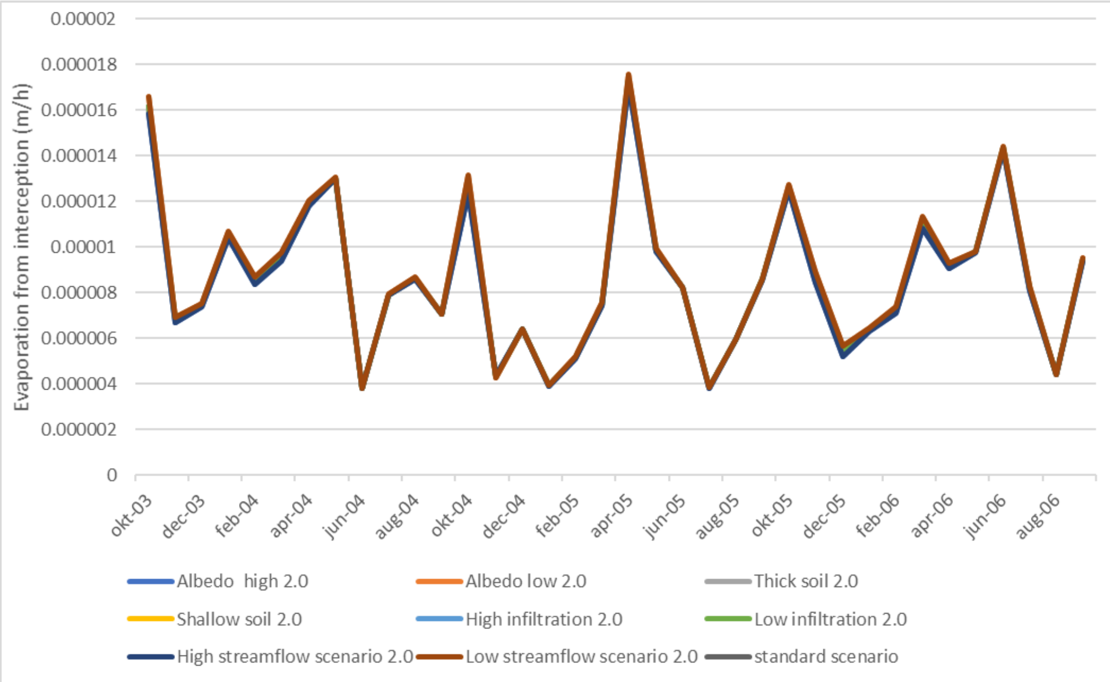

Figure 24 Average monthly transpiration (m/h) for the Arnás catchment with an LAI of 2, with nine variations in parameter values for three hydrological years (2003-2006).

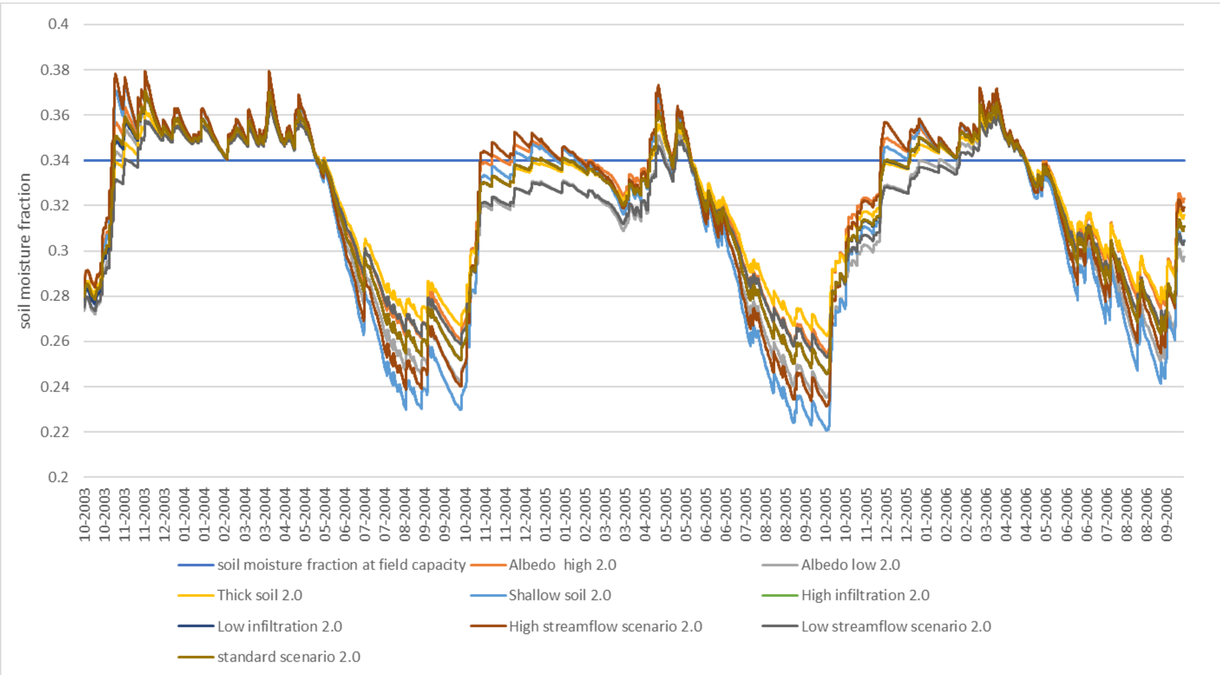

Figure 25 Average soil moisture fraction in the Arnás catchment for 9 different scenarios with LAI=2.

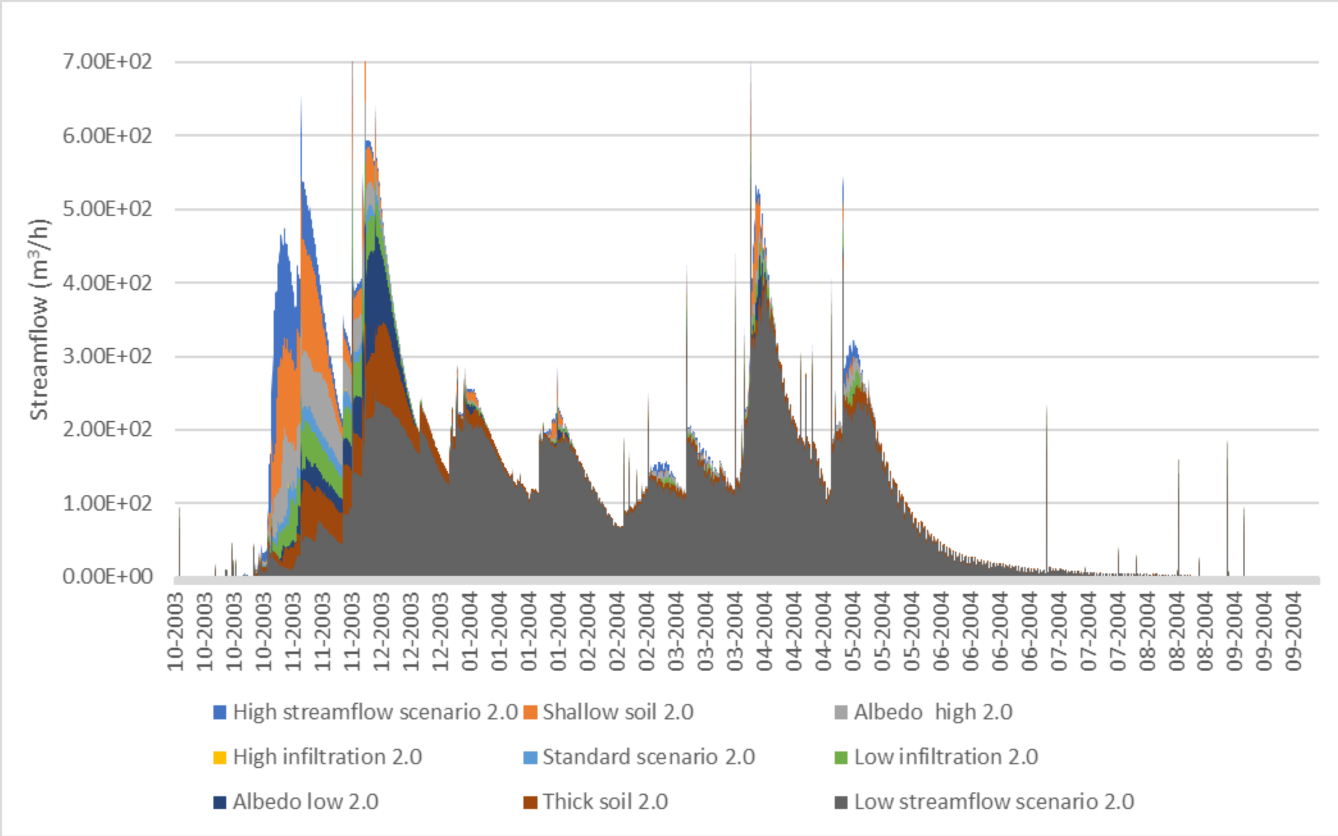

Figure 26 Hourly streamflow for 9 different scenarios with an LAI of 2 for the 2003-2004 hydrological year.

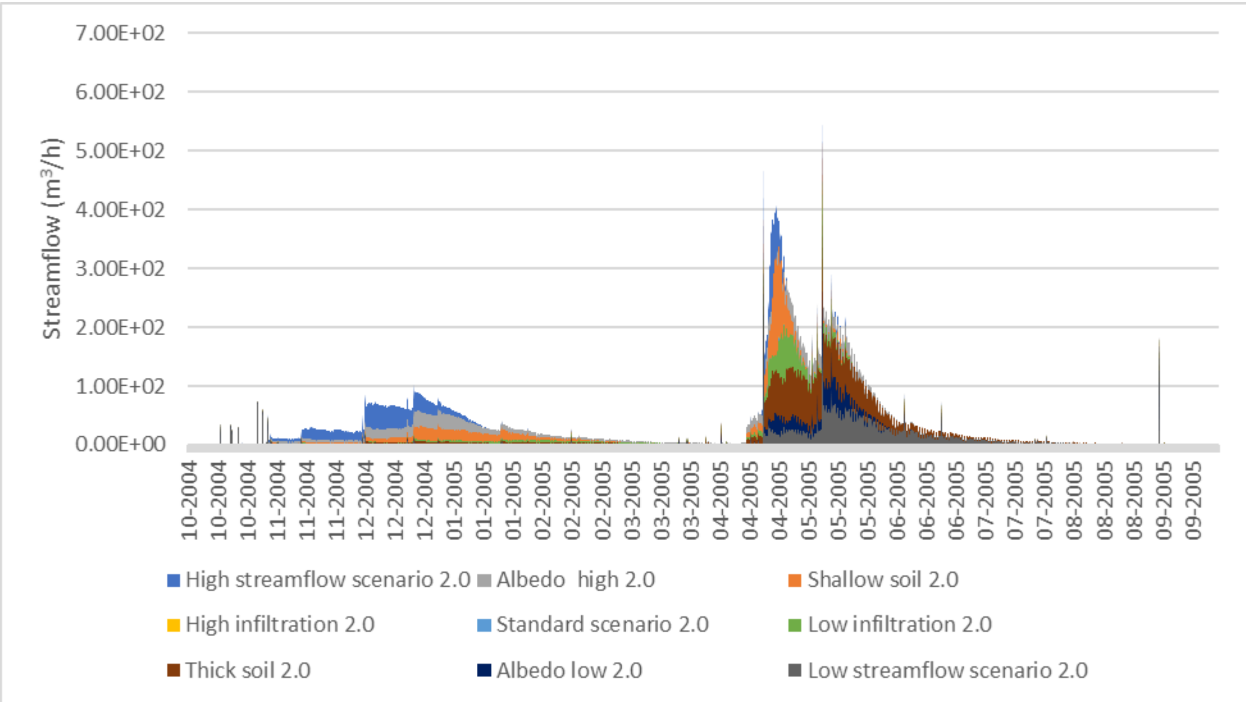

Figure 27 Hourly streamflow in the Arnás for 9 different scenarios with an LAI of 2 for the 2004-2005 hydrological year.

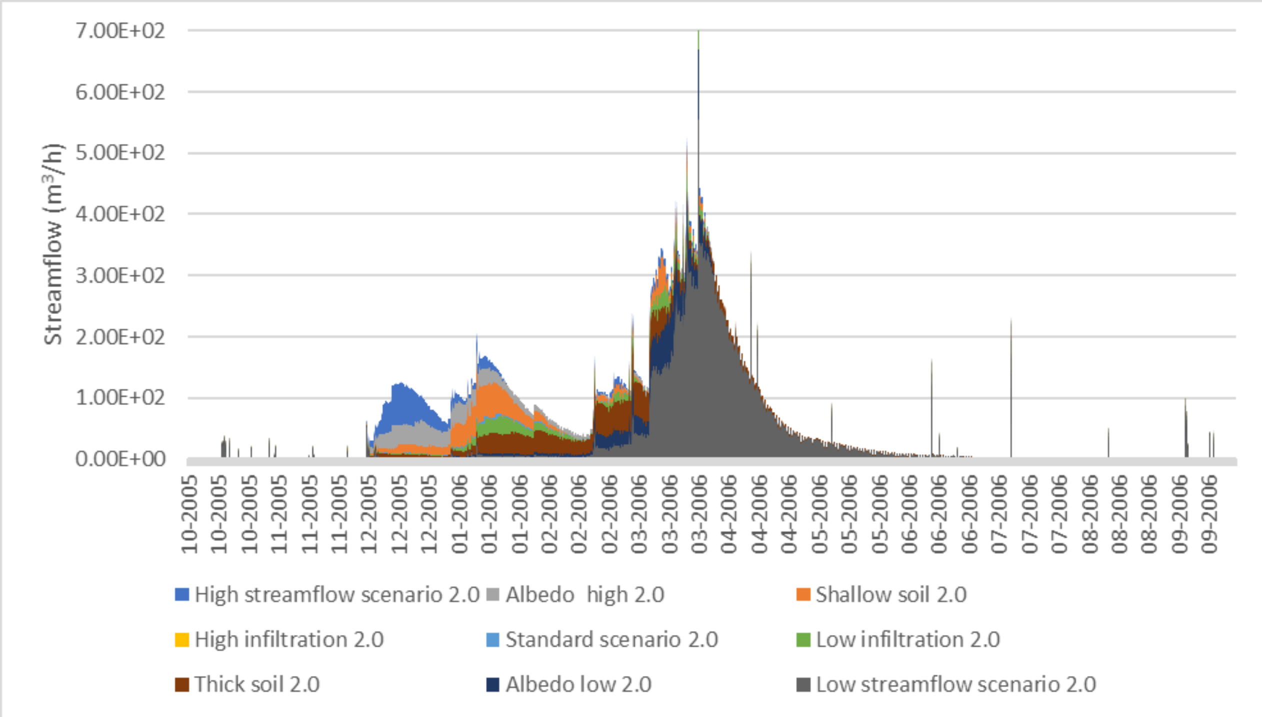

Figure 28 Hourly streamflow in the Arnás for 9 different scenarios with an LAI of 2 for the 2005-2006 hydrological year.

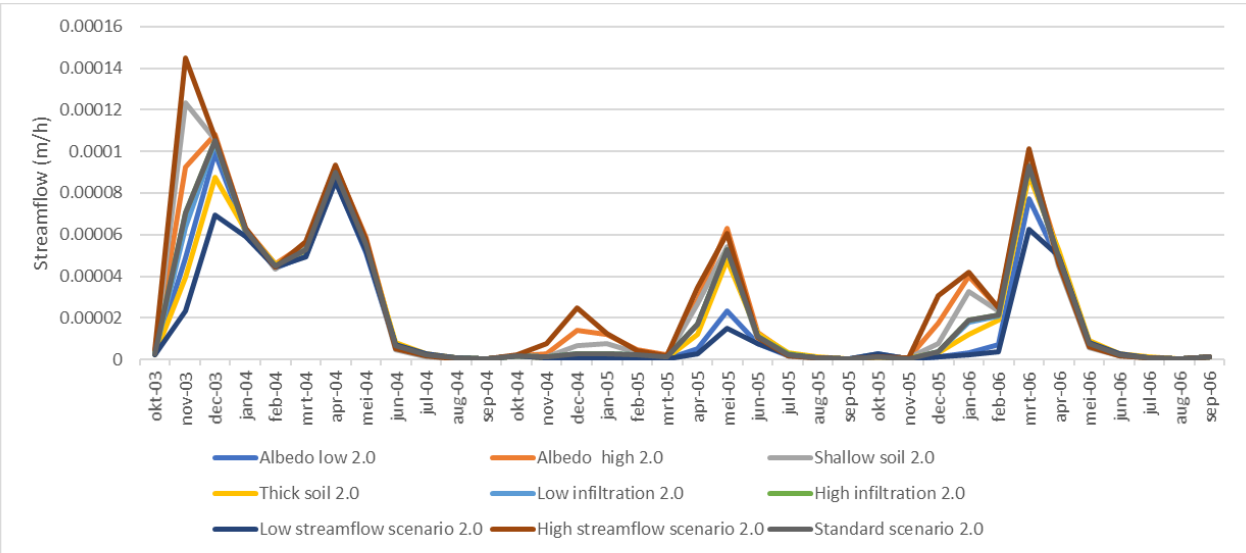

Figure 29 Average monthly streamflow in the Arnás (m/h) for the Arnás catchment with an LAI of 2, with nine variations in parameter values for three hydrological years (2003-2006).

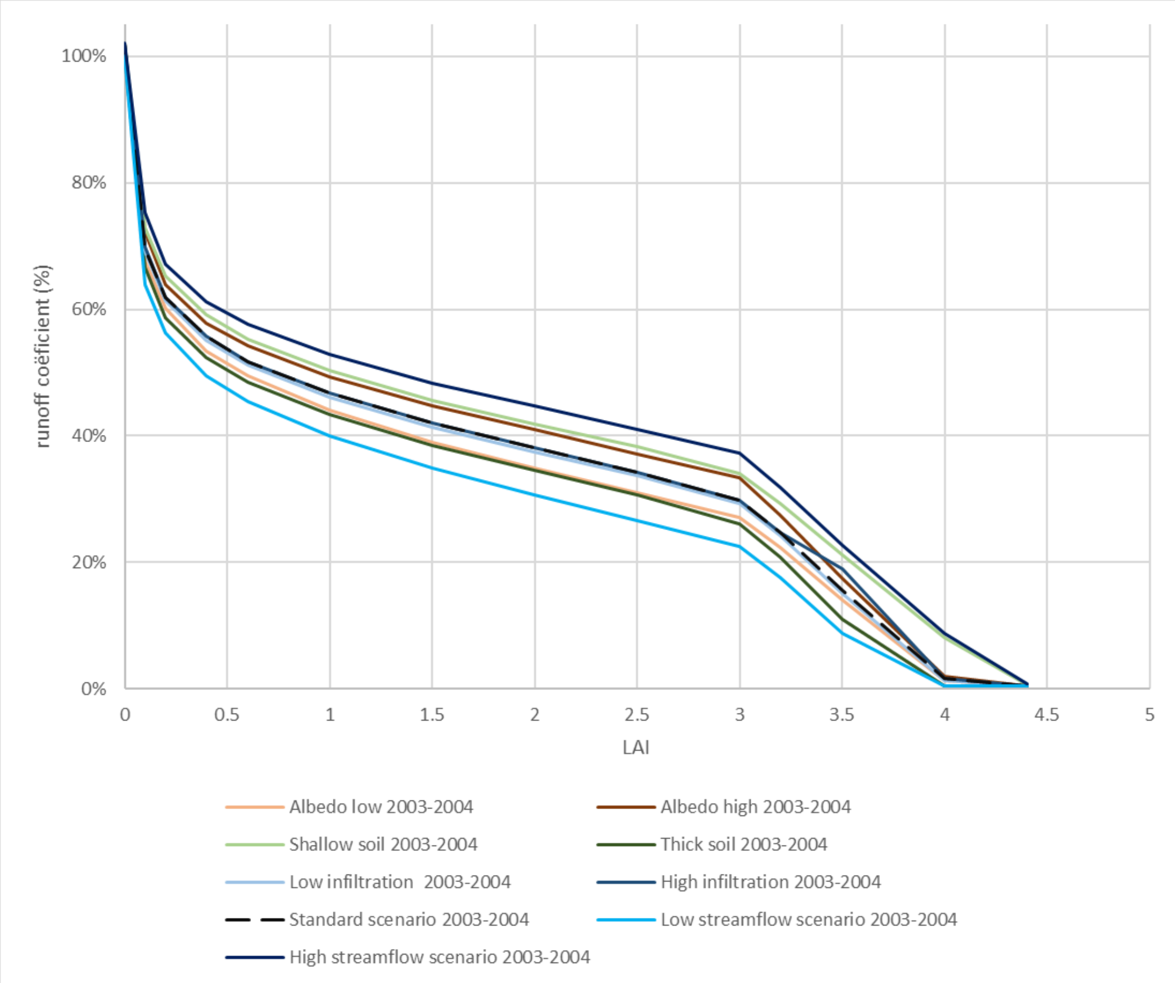

Figure 30 The relation between runoff coefficient and LAI in the Arnás for nine different parameters scenarios for the 2003-2004 hydrological year.

4.3 Vegetation growth in the Upper Aragon basin

By applying a non-linear regression model on 12 LAI maps, vegetation growth for the 1950-2050 period in the Upper Aragon Basin was simulated. Because of the uncertainty in translating NDVI maps into LAI maps, two different transformation methods were used (see Section 3.4.1).
One of the three parameters of the regression model is *x0*, which is the starting year of the vegetation growth. Results for *x0* using the linear LAI-NDVI transformation are depicted in figure 31. According to the model most of the vegetation in the area started growing after 1960. Figure 32 shows the average LAI increase for the Upper Aragon Basin in the 1950-2050 period using the two NDVI-LAI conversion methods. The linear method leads to higher LAI values than the non-linear method. The maximum difference can be up to 1 point in LAI. But the general graph is the same: There is a fast increase in the period 1970-1990, after this vegetation growth slows down and trends to a constant LAI value. Figure 33 shows the same as figure 32 but this time minus and plus one standard deviation.

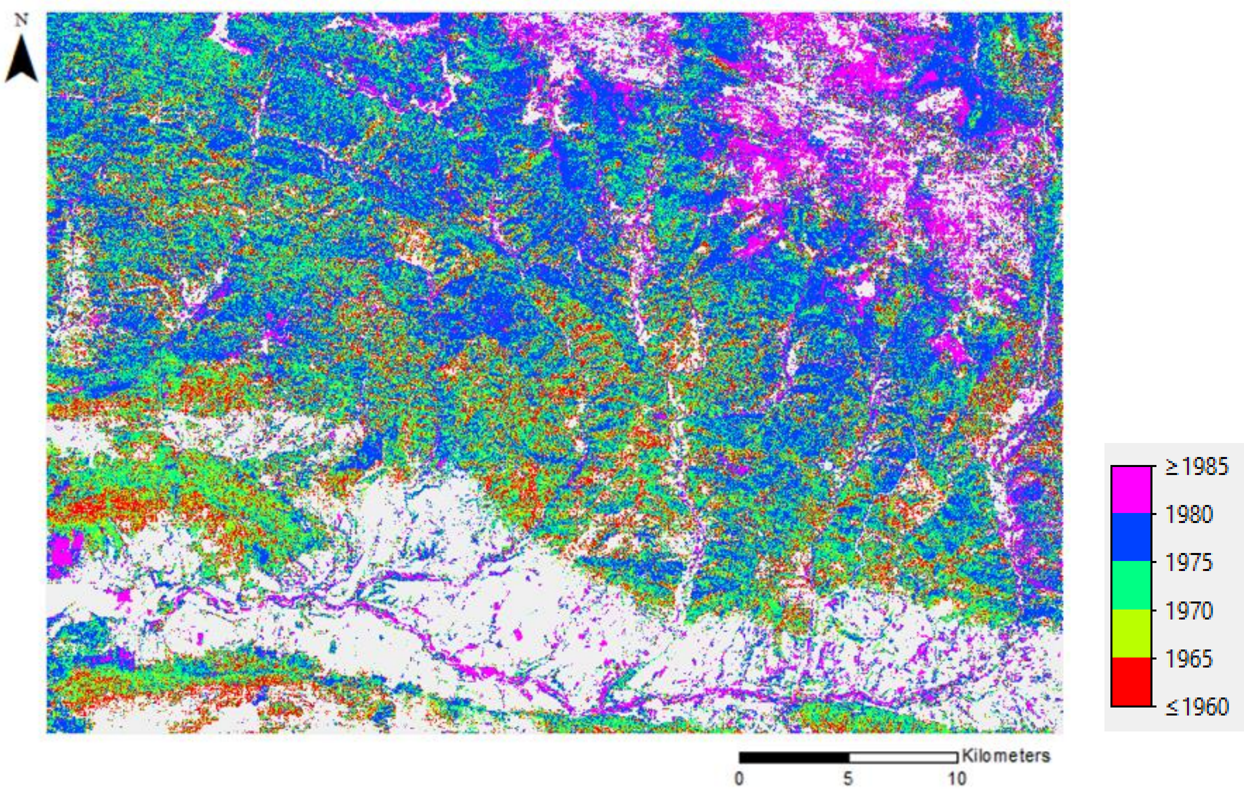

Figure 31. Starting year of vegetation growth (x0) according to the regression model, for the linear NDVI-LAI conversion with LAImax=4.5. The white points represent missing values, which means that fitting the regression equation at these points was unsuccessful.

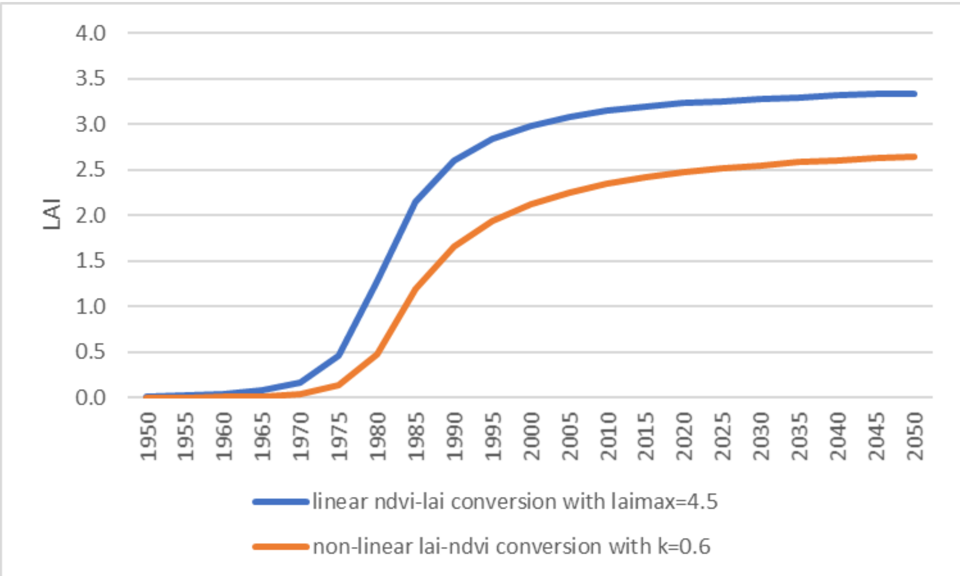

Figure 32 Average vegetation growth from 1950 to 2050 in the Upper Aragon Basin according to the regression model, for two different NDVI-LAI conversion methods.

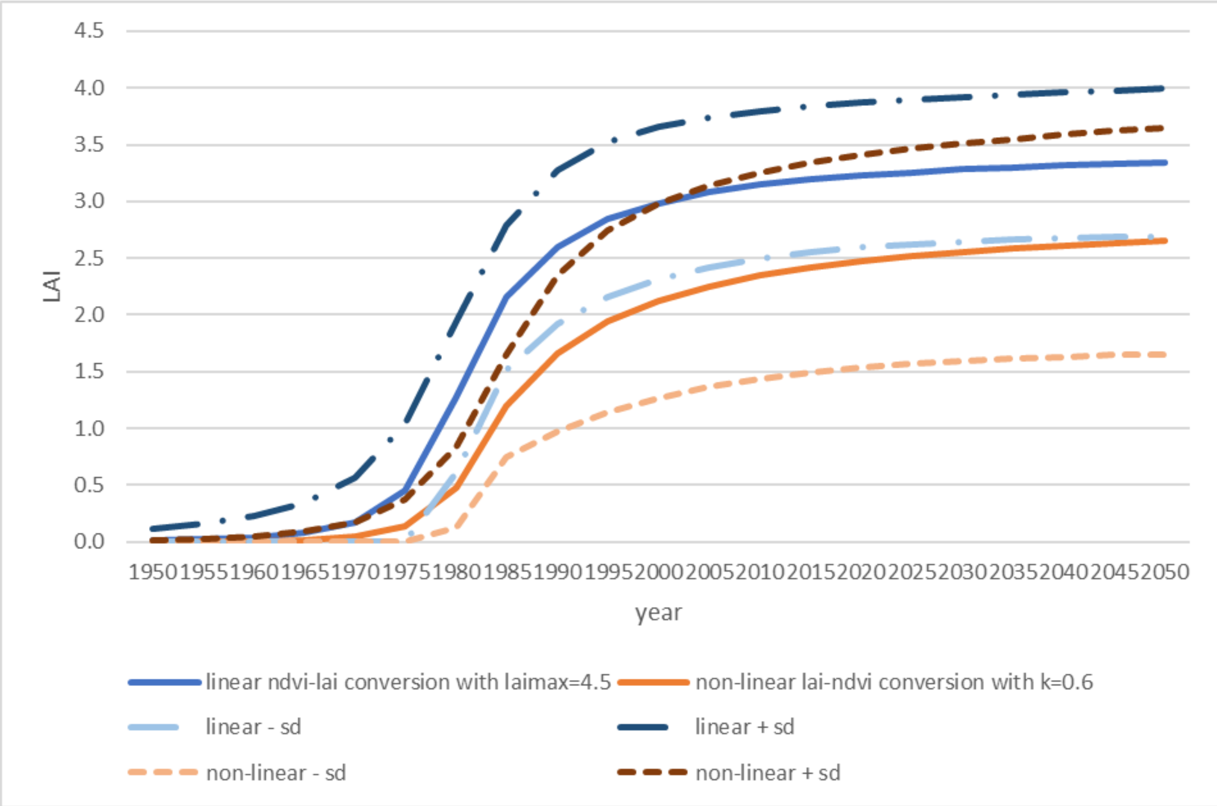

Figure 33 Average vegetation growth in the Upper Aragon Basin from 1950 to 2050 according to the regression model, for two different NDVI-LAI conversion methods. Including the standard deviations.

4.4 Hydrological consequences of vegetation growth in the Upper Aragon Basin

Figure 34 shows the impact of the average vegetation growth in the Upper Aragon Basin on the yearly runoff coefficient for the three hydrological years and the two NDVI-LAI conversion methods. There is a stark decrease in the 1960-1990 period and after this the runoff coefficient becomes constant. There is quite a big difference in runoff coefficient depending on the hydrological year (2003-2006) and NDVI-LAI conversion method. For example: In 1980 the runoff coefficient ranges between 3 and 41%.

When we combine this uncertainty in the vegetation growth, with the uncertainty in the parameter values (albedo, infiltration, soil thickness) on streamflow we can create two extreme scenarios: one where the decrease in streamflow is largest and one were the decrease in streamflow is smallest. Figures 35, 36, 37 show this for each year hydrological year. Although there is a large uncertainty in the amount of streamflow, especially up to 1990, the general pattern is the same. For all graphs you see that after the year 1990 decrease in runoff coefficient becomes small and eventually stops.

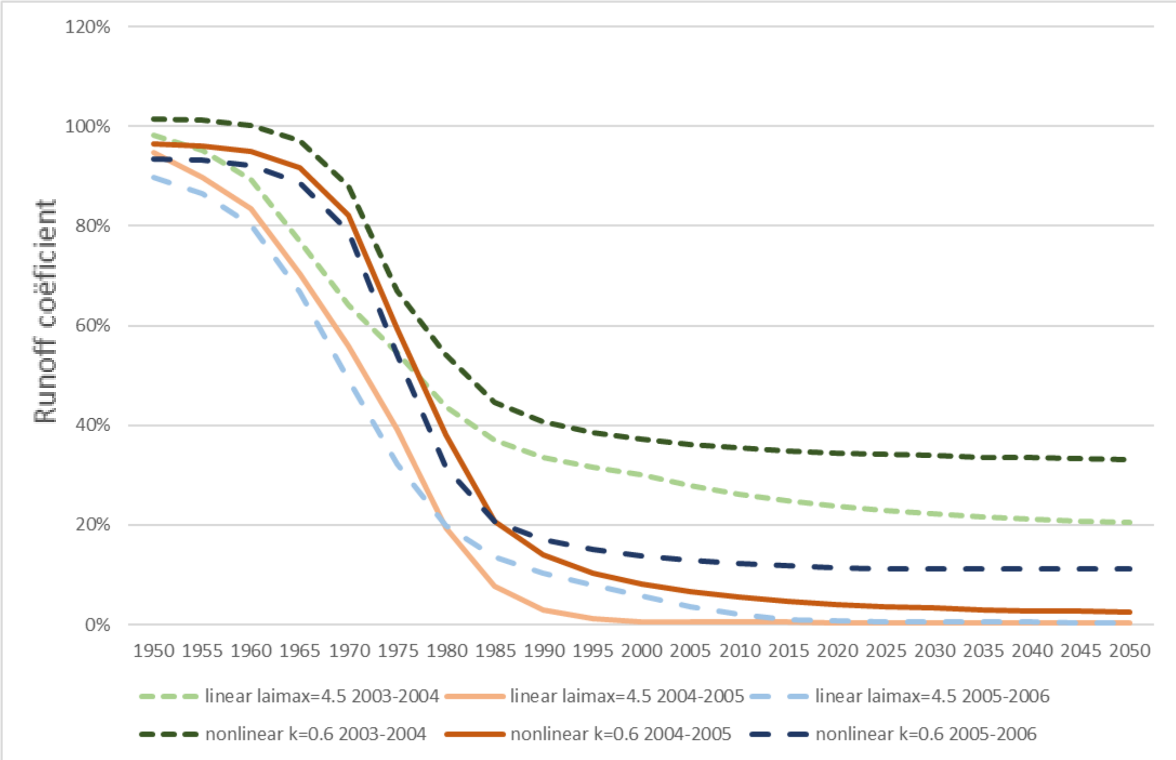

Figure 34 Yearly runoff coefficient during the 1950-2050 period in the Upper Aragon Basin, for each of the three hydrological years (2003-2006) with two different NDVI-LAI conversion methods.

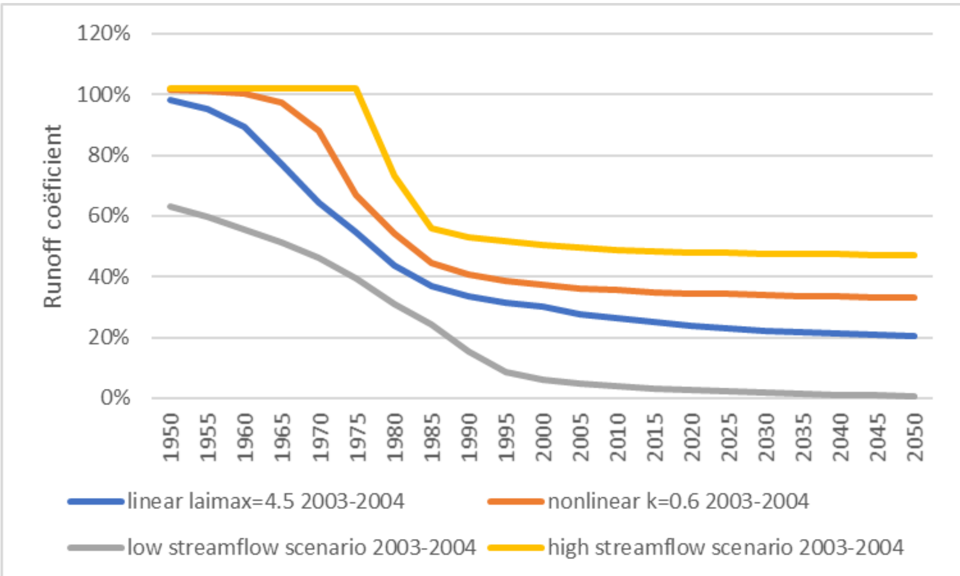

Figure 35 Average yearly runoff coefficient during the 1950-2050 period in the Upper Aragon Basin, for the 2003-2004 hydrological year with two different NDVI-LAI conversion methods. Also included are the runoff coefficient for the high streamflow scenario and low streamflow scenario.

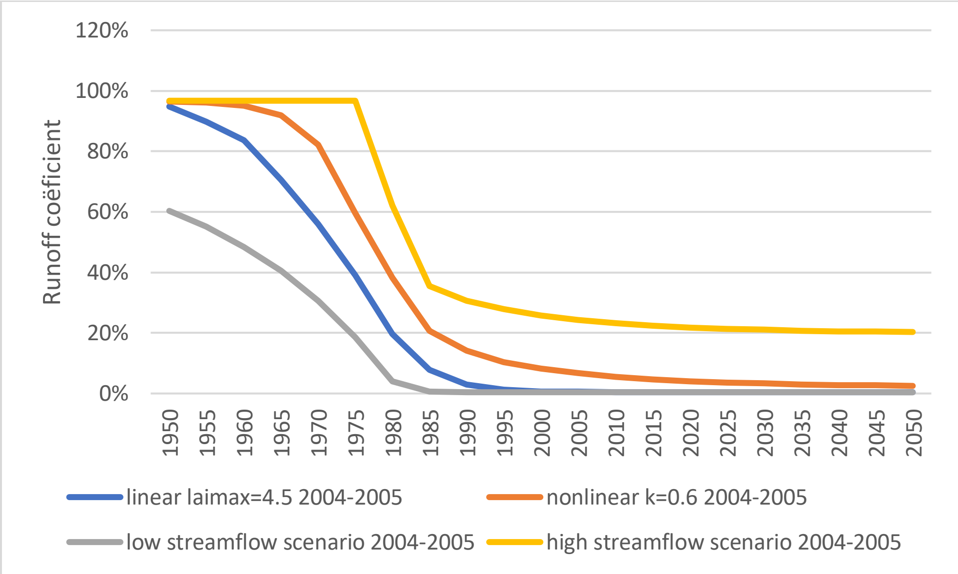

Figure 36 Average yearly runoff coefficient in the Upper Aragon basin during the 1950-2050 period, for the 2004-2005 hydrological year with two different NDVI-LAI conversion methods. Also included are the runoff coefficient for the high streamflow scenario and low streamflow scenario.

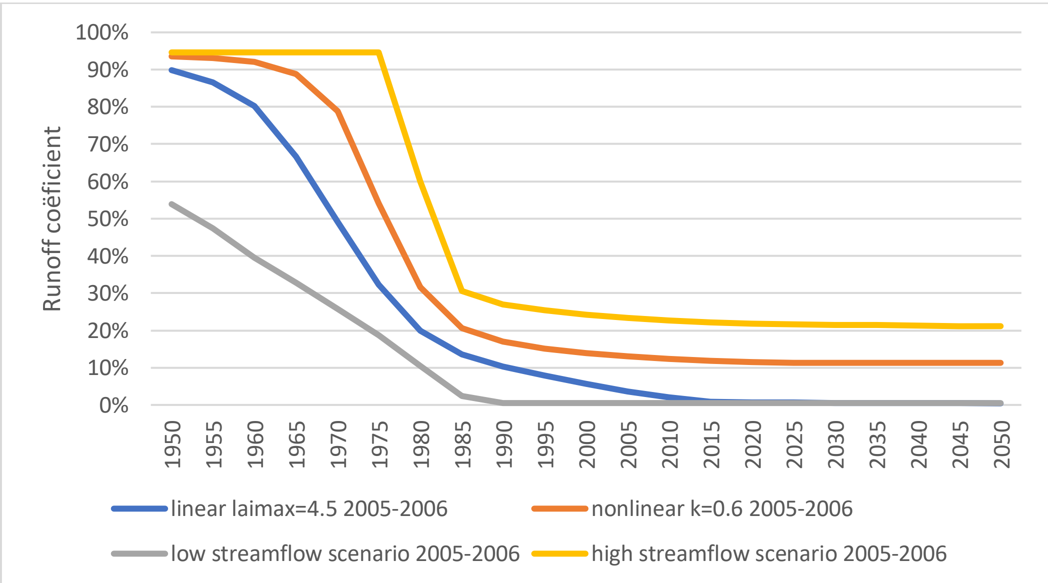

Figure 37 Average yearly runoff coefficient during the 1950-2050 period in the Upper Aragon basin, for the 2005-2006 hydrological year with two different NDVI-LAI conversion methods. Also included are the runoff coefficient for the high streamflow scenario and low streamflow scenario.

5. Discussion

5.1 How are streamflow, interception, evapotranspiration and soil moisture in the Arnás catchment (a sub-basin of the UAB) influenced by vegetation growth?

To assess the effect of vegetation growth on the hydrology of the Arnás catchment, we ran the PyCatch hydrological model with different LAI inputs (0-4.4). This way we could draw a relationship between LAI and hydrological fluxes (streamflow, evapotranspiration, soil moisture). Results suggest that the hydrology of the Arnás catchment is strongly influenced by the presence of vegetation. Even a small vegetation growth from 0 to 0.1 point in LAI leads to a very large increase in evapotranspiration in summer and thus a very stark decrease in summer streamflow, which becomes almost non-existent in that period for all LAIs above 0.1. Also, when LAI is above 0.1 streamflow has a characteristic seasonal pattern with almost no streamflow in summer, high streamflow in autumn, a dip in winter, then again high streamflow in spring. When LAI is close to zero this seasonality does not exist, and in this case, streamflow seems to be directly linked to rainfall depth.

Looking at the soil moisture fraction it seems that streamflow for all LAI's above 0 streamflow is the result of subsurface flow, because there is only streamflow when soil moisture is close to field capacity. García-Ruiz et al., (2008) compared the streamflow in three neighboring catchments the Upper Aragon Basin, including the Arnás catchment, with different types of vegetation and soil: The Arnás (mostly schrubs), Araguas (25 percent badlands) and San Salvador (forest). They found that in the forested catchment streamflow is mostly the result of baseflow, while in the other two catchments Horton overland flow is more important, which means that in the Araguas and Arnás catchments streamflow response is connected to rainfall depth and maximum rainfall intensity. In the San Salvador catchment streamflow response is linked to antecedent rainfall and baseflow. Comparing this to our results, it seems that in our case all streamflow is related to sub surface flow for all LAI's above 0.1. Which means that it hydrologically behaves like a forested catchment. This might be unrealistic for a catchment with very low LAI values. In view of the results of García-Ruiz et al., (2008) one would also expect Horton overland flow to happen in our catchment. This might be caused by the choice of our soil thickness value; a thinner soil would respond more directly to rainfall and thus might be more realistic. Also, it could be that the Pycatch model has difficulty realistically mimicking Horton overland flow. What is important to note though is that in our simulation there are no large areas with bare ground, vegetation is evenly distributed over the catchment. Often after abandonment certain parts of the catchment are vegetated while other parts are still bare, and these bare areas play a large role in the generation of runoff. This is also suggested by research by Cosandey et al. (2005) who, looking at results from several catchments in southern France, concluded that soil vs. covered soil was a far more important factor than forest vs. any other type of vegetation in predicting runoff response.

After the strong quasi-exponential decrease in streamflow for the small LAI values, the decrease becomes more gradual and roughly linear after LAI=1. Every further increase in LAI will result in less streamflow, with the largest decrease occurring in autumn. The higher the LAI value the later streamflow will start in the wet season because it takes longer for the soil moisture to reach field capacity. When LAI keeps increasing further, also spring streamflow will be affected. When LAI becomes larger than 3, streamflow goes down fast. When a catchment has reached the vegetation cover of a forest (LAI=4) streamflow in the whole year has become practically zero.

The reason an increase in LAI leads to less streamflow is because it increases evapotranspiration, which is the result of an increase in transpiring surface and increased interception. Going from an LAI of 0 to an LAI of 1 is a relatively large change and thus there is a much stronger increase in evapotranspiration then there is for the larger LAI values (1-4). The sudden stronger decrease in streamflow after LAI=3 is probably the result of the sudden increase in vegetation height and a decrease in albedo. An increase in vegetation height leads to higher transpiration rates as a result of the change in the roughness of the transpiring surface. When LAI was below 3 vegetation height was always below 1.5 meters, but when LAI has reached a value of 4 vegetation height has increased to 9.3 meters. We also implemented a decrease in albedo for LAI values above 3. This also leads to a higher transpiration rate and thus lower streamflow.

Using three hydrological years also provided interesting insights, because how the hydrological fluxes are influenced by vegetation growth is also dependent on climate. García-Ruiz et al. (2008) found that the Araguas catchment (badlands) had the highest yearly runoff coefficient (0.69), followed by 0.25 for the Arnás (shrubs) and 0.12 for the San Salvador (forest) for the 2005-2006 year. These numbers roughly correspond to our results (average yearly runoff coefficient) although it is difficult to compare because we do not know the exact LAI of the catchments used by Garcia-Ruiz (2008). Furthermore, our research shows that determining a runoff coefficient of a catchment based on one single hydrological year has limited meaning. In our case the runoff coefficient was very different for the 2003-2004 hydrological year, compared to the other two years. It showed that not only the amount of rainfall but also the timing matters. Rainfall in autumn will lead to a higher level of soil moisture in the same year and will thus increase streamflow, while rainfall in summer will evaporate but also lead to an increase in soil moisture levels that will lead to more streamflow in autumn of the next hydrological year. Whatever the LAI of a catchment, when field capacity is reached all catchments (bare ground or forested) respond the same way to rainfall. So, the effect of revegetation becomes especially significant when soil moisture is low in autumn due to dry summer or a lack of rainfall in autumn. After the first year the catchment with LAI=4 never reaches field capacity again, and soil moisture fraction keeps decreasing. It might be that the initial soil moisture at the start of the 2003-2004 year was unrealistically high for this LAI and the model needed a longer "spin up period" to reach realistic values.

Bosch & Hewlett (1982) compared 94 catchments and drew a relationship between the percentage of surface area forest that was removed and the amount (mm) of streamflow increase as a result of this. According to their research changing a grass covered catchment into one completely covered by pine trees results in an average 400 mm decrease in streamflow. Turning a grass covered catchment into one covered by a deciduous forest causes a decrease of 250 mm and going from a grass cover to a shrub cover results in a decrease of 100 mm. It is difficult to compare these numbers to our results. The catchments studied by Bosch & Hewlett (1982) had all different catchment characteristics and also different amounts of yearly precipitation. It would be more interesting when we knew the amount of discharge relative to the amount rainfall. Although, even then there are large differences in rainfall-runoff coefficient going from one year to the next. In our study going from a grass covered catchment (somewhere around LAI=0.6) to a forested catchment (LAI=4) for the first year would result in a decrease of roughly 460 mm in yearly discharge. The same change in the other two years would result in a decrease of around 250 mm, even while the first and third year have the same amount of rainfall.

Andréassian (2004) applied a similar approach and compared 136 paired watersheds in order to find the relation between annual streamflow and percentage of treated watershed (Reforested or deforested), both in mm and in percentage of flow. Only looking at the 100 percent treated watersheds, there is a large range in results varying between 0 and 40 percent decrease in streamflow. In our model predictions the highest LAI values resulted in a complete drying up of the river flow, which means the decrease is a lot larger than 40 percent. This suggest that our calculations might overestimate the effect of vegetation on streamflow. The large variation in effects of reforestation found in the study of Andréassian (2004) might also mean that "percentage of treated watershed" is not the best predictor of change in annual flow. It might me better to connect it to factors more directly connected to evapotranspiration like LAI, sapwood area or basal area as suggested by the authors themselves.

5.2 What is the uncertainty in these calculations and what is the sensitivity of the model outcomes to certain soil and vegetation parameters (hydraulic conductivity of the topsoil, albedo and soil thickness)?

Because it is difficult to determine the exact input values for the soil and vegetation parameters in the hydrological model that would best mimic vegetation growth, we ran eight additional scenarios. Albedo, saturated conductivity of the topsoil and soil thickness were increased or decreased by 25 percent relative to the standard scenario.

Albedo impacts streamflow by changing the amount of radiation that is absorbed by vegetation and soil, which in turn determines how much water can evaporate. This explains why the increase in albedo results in an increase in streamflow while the lower albedo results in a decrease. Our results show roughly a 3.5 percent (absolute) difference in runoff coefficient between the standard scenario and the high or low albedo scenario for all LAI values. This means that for higher LAI values (lower streamflow) the impact of albedo is relatively larger than for lower LAI values. How does this compare to changes in LAI value? For small LAI values, the difference in runoff coefficient is comparable to that of albedo changes. For example, in 2003-2004n increase in LAI from 0.2 to 0.25 changes the runoff coefficient from 62 percent to 60 percent. An increase of 25 percent, from 2.0 to 2.5 leads to the runoff coefficient decreasing from 38 percent to 34 percent. And going from LAI =3 to LAI=3.75 causes the runoff coefficient to decrease from 30 percent to 9 percent. So, the impact of a 25 percent decrease in albedo is comparable to that of a 25 percent increase in LAI. This holds up to an LAI of around 3. When LAI values reach values above 3.0, the impact of changes in LAI on runoff coefficient becomes considerably larger than that of albedo. Change in streamflow as a result of a change in albedo is primarily the result of changes in transpiration. The amount of evaporation from interception is not impacted, probably because it is already limited by the amount of water that can be hold in interception storage. The impact of albedo on streamflow is largest in autumn, just like that of LAI, because streamflow happens when the soil is saturated which is controlled by how much water transpires in summer. Using 25 percent lower and higher albedo values means that our albedo input varied between 0.135 and 0.294. In the field (Europe and North America), values between 0.02 and 0.44 have been measured (Breuer 2003), so our 25 higher and lower values are still realistic.

The second parameter value that we changed was the hydraulic conductivity of the topsoil, which controls how fast water can infiltrate. When the hydraulic conductivity is low, more water will stay on the surface and can turn into runoff. A high hydraulic conductivity will lead to more precipitation infiltrating and this will cause a rise in soil moisture. The effect of increasing or decreasing the hydraulic conductivity of the topsoil with 25 percent in our study had only a small effect. Maybe because it primarily impacts the timing of streamflow (lower infiltration leading to a faster streamflow response), and not so much the amount of streamflow. Only in the first hydrological year a decrease in hydraulic conductivity leads to a very small decrease in the amount of streamflow. In the other years the effect is almost zero. What is important to keep in mind is that the saturated conductivity of a soil has a very large range and can vary over 10 orders of magnitude. This means a change of 25 percent, which is large change for albedo and soil thickness, is only a small change for hydraulic conductivity. Using a larger range in hydraulic conductivity would me more ideal.

The third parameter of interest is the soil thickness. It determines the amount of water that can be stored in the subsurface, and thus how long it takes before field capacity is reached and streamflow starts. Depending on the LAI value a 25 percent change in soil thickness results in a change in yearly streamflow ranging from 0.7 to 6.5 percent, depending on year and LAI. Only looking at the last two years it ranges between 0.2 and 3.2 percent. The impact is again, like that of LAI and albedo, largest on autumn streamflow because it takes longer for the thick soil to become saturated than for a thin soil. The soil thickness parameter is especially interesting, because a thicker soil is considered as a long-term result of vegetation recovery (N. Lana-Renault et al., 2011). Our research suggests that an increase in soil thickness (from thin soil to thick soil scenario), as a result of vegetation recovery, could lead to a 13 percent decrease in yearly streamflow. Only looking at the second two years this is only 6.5 percent. According to our research vegetation recovery leads to a complete drying up of the river flow. So, the effect of vegetation growth would be a lot larger than that of an increase in soil thickness.

In order to assess the uncertainty in our predictions we also ran a high and low streamflow scenario combing the effects of the three parameters. Figure 30 and appendix A show the effect on the yearly runoff coefficient. Depending on the LAI and hydrological year this can be somewhere between 4 and 8 percent. The effect of the low and high flow scenario on streamflow is large; for example, in 2003-2004 the "low flow" scenario with an LAI of 1.0 has a 40 percent runoff coefficient, while for the "high flow" scenario LAI needs to increase to 2.6 to get the same runoff coefficient.

5.3 What is the change in vegetation cover in the Upper Aragon Basin for the period 1950-2050?

The next part of our research consisted studying temporal trends in vegetation growth in the Upper Aragon Basin. In order to estimate the level of increase in leaf area index (LAI) in the Upper Aragon Basin, 12 NDVI maps created by Nije Bijvank (2015) were used. We transformed these NDVI maps into LAI maps using two NDVI-LAI transformation methods, a linear and non-linear one. For each of the pixels on the LAI maps a non-linear vegetation growth formula was fitted. This resulted in maps of the parameters of this non-linear growth model: *c*, *x0*, *k*. These maps are then used as input in the same vegetation growth formula, to calculate LAI values for the 1950-2050 period.

Our results show that the linear method leads to higher average LAI values than the non-linear method. This difference can be up to 1 point in LAI, depending on the year. Both methods result in very low LAI values until 1960, a fast increase in the period 1970-1990, followed by a slowing down, eventually reaching a constant LAI. In 1960 LAI is around 0, while in 2050 the LAI has reached a value of 3.4 for the linear method and 2.6 for in the non-linear method. As shown by the relatively large standard deviation there is a large spatial variation in LAI values for each year. This is to be expected because there are large differences vegetation growth due to factors like (former) land use, elevation, slope and aspect which all influence vegetation growth.

Fitting of the model was not successful in all datapoints, and that does also influence our results. This is due to the non-linear regression model we used. Only in the cases where the 12 LAI input values show a clear increase over time, fitting was possible. So, when LAI fluctuates too much or shows a decreasing trend the model is not able to make a fit. Fitting datapoints in the lower lying valley was probably impossible because of the human and agricultural activity in this area, and thus no increase in vegetation through the years. Also, in the areas with a high elevation fitting was imposable due to there being very little vegetation. Riverbeds also cause missing values. For other areas the reason of exclusion is less clear. In the Arnás catchment LAI probably fluctuated too much. So, our average growth value is clearly an overestimation of the actual average vegetation growth. Or at least is not a depiction of vegetation change in the complete Upper Aragon Basin but only of the area situated between 1000 and 1600 meters.

Vegetation growth has happened in many parts of the UAB and is often associated with land use change. For example in the Borau value, a sub-basin of the UAB, Lasanta-Martínez et al. (2005) found that land use had changed in 52.5% of the area between 1957 and 2000. This resulted in an increase of scrubland and woodland. This is in line with our research because we also found a large increase in vegetation in the second half of the 20th century. The findings of Vicente-Serrano, Lasanta, & Romo (2004) are easier to compare to our results, than those by (Lasanta-Martínez et al., 2005), because they used changes in NDVI to map vegetation growth. They examined NDVI increment in the UAB for the 1980-2000 period. An upward trend was found, going from an average NDVI value of 0.5 in 1981 to an average value of 0.57 in 2000. If we would apply our two NDVI-LAI transformation methods to these numbers, this would mean an increase from an LAI of 1.2 to one of 1.6 using the non-linear method and an increase from 2.4 to 2.8 using the linear method. According to our research LAI increased from 0.5 to 2.1 using the non-linear method and an increase from 1.3 to 3 using the linear method. So, according to them the LAI increase in this period is around 0.4, while according to our calculations it is around 1.6. So, the increase in LAI according to our calculations is a lot larger. Also, our 1980 values seem low in comparison. Moreover, they suggest a linear trend while we see a slowing down in vegetation growth.

According to our results the whole revegetation seems to be completed in around 60 years. When considering the process of secondary succession in the area, according to literature grasses start growing the first year, and it takes 10 to 35 years for shrubs to cover the whole area, and young trees start growing after 60 years. This suggests that it takes longer for the Upper Aragon Basin to reach its maximum LAI than what can be concluded from our predictions. Also, several authors have pointed out that a large proportion of land abandoned several decades ago in the UAB is still in the primary stages of secondary succession. Fields are partly covered in shrubs and will in the future probably evolve into areas with more developed forest stands. Moreover, increasing temperatures will make it possible for forests to grow at higher elevations which will also lead to more vegetation growth in the future (J.M. García-Ruiz et al., 2011).

5.4 What is the effect of the change in vegetation cover on streamflow in the Upper Aragon Basin?

The average LAI value of each year (1950-2050) of vegetation growth in the Upper Aragon basin was coupled to the average streamflow for that LAI calculated with the PyCatch model for the Arnás catchment. This provided us with a temporal trend in vegetation growth for this period. According to our results there is a large decrease in streamflow in this period, from a runoff coefficient ranging between 90 and 100 percent in 1950 to one ranging between 3 and 41 percent in 1990 for the standard scenario. Although there is a large level of uncertainty in our results, the general picture is the same for all scenario's: a large decrease before the year 2000 after which streamflow becomes constant, due to vegetation growth being completed.

In the Upper Aragon Basin a decrease in river discharge has been measured in the 20^{th} century. Nije Bijvank included the river discharge measured at three stations in the UAB for the period 1930-2010 in her report. If we assume the downward trend found between 1930 and 2010 is representative of the whole 1950-2050 period, this would mean there is a decrease in discharge in the Esca, Veral and Aragón rivers of respectively 66, 71 and 88 percent for the 1950-2050 period. Of our six standard scenarios (3 years, two NDVI-LAI relations), the most conservative one predicts a decrease for this period of 67 percent, while the most extreme scenario would result in an almost 100 percent decrease. Especially when assuming that the 'drier' hydrological years (2004-2005, 2005-2006) are representative for the 1950-2050 period, decrease would be a lot larger than that of the three rivers mentioned above. Using the 2003-2004 year as input seems to give more comparable results. What is also different is that the decrease in discharge in these rivers seems to be linear, while we saw a sudden decrease from 1960 onwards and then a slowing down. Besides, we only incorporated the effect of vegetation growth on streamflow and did not include other factors like climate change. Although we did not explicitly include climate change in our model, we based the vegetation growth on satellite images. And the vegetation growth recorded on these images could have been partly influenced by climate change. According to Vicente-Serrano et al. (2004) vegetation growth in the Upper Aragon Basin is at least partly the result of an increase in temperature. But apart from this we did not asses the effect of changes in temperature and precipitation on the hydrology of the UAB.

According to López-Moreno et al. (2008) part of the decrease in streamflow in this region can be attributed to climate change. They analyzed data from 18 weather stations for the 1950-2050 period in the central Pyrenees and found that precipitation has a negative significant trend in February, March, and June. Potential evapotranspiration increases in February, March, June, July, and August. Mean annual evapotranspiration also goes up. The changes in precipitation and evaporation cause a significant negative trend for the annual water balance and for the months February and March, and insignificant negative coefficients from June to September. Beguería et al. (2003) found no significant trends in climate between 1945 and 1995. All climatic changes were attributed to climatic fluctuations: cycles of 15–20 years where precipitation and temperature varied between one standard deviation above or below the average values. They found no evidence of a clear annual climatic trend since the mid-20th century. Because there was a reduction in water yield by about 30% between 1945 and 1995 they attributed this completely to land use changes (Beguería et al., 2003).

Most other authors consider changes in streamflow to be a result of both climate and land-use changes. López-Moreno et al. (2008) found that the trend in discharge shows a steeper gradient than what would be expected on the basis of climate change, suggesting the key role of plant regeneration in abandoned agricultural areas. López-Moreno et al. (2014) compared the effect of a hypothetical evolution of land cover with the effect of climate change projections in the UAB for the 2021-2050 period. They found that changes in land cover caused a decrease of 16 percent in annual flow, while the combination of climate and land use change will lead to an almost 30 % decrease in annual runoff. This implies that the effect of land cover changes is larger than the effect of climate change. In a study area in the Pyrenees east of the UAB decrease in streamflow was found in three catchments between 1987 and 2009 (Buendia et al., 2016). The decrease in discharge was different in all three rivers as a result of different catchment characteristics. In the river Flamisell a reduction of 27% in comparison to

1987 was observed, with land use changes accounting for 16% of the total decrease. A 20% runoff reduction was estimated for Talarn, of which 37% is attributed to land use changes. Last, in Escaló, the reduction in runoff was 10%, 6% of which could be explained by the change in land use. The catchment with the most afforestation (Talarn) showed the largest impact of land use change on streamflow (36 percent), while the catchment with the least (Escaló) impact was smallest (6 percent).

Apart from climate change, another factor that was not included in our research is the effect of snowfall and snowmelt. López-Moreno et al. (2008) found a negative trend in snow accumulation at high altitudes. This can be explained by recent shifts in atmospheric circulation over the Iberian Peninsula (López-Moreno & Vicente-Serrano, 2007). Increase in temperature also causes the 0°C future to shift towards a higher elevation, which reduces the amount of precipitation that falls as snow. López-Moreno et al. (2008) estimated that in the Spanish Pyrenees the warming can lead to a reduction of the area above the 0°C isotherm up to 34% by the end of the 21st century, limiting snow accumulation. These changes in snowfall are very important because snowmelt is the main source of spring runoff. In terms of water availability this results in a decrease of the flows in spring and shift of the high flows to earlier in the year (López-Moreno et al., 2004).

The abovementioned changes in streamflow are especially important because they impact the inflows in Pyrenean reservoirs. Not only the annual incoming water volume is affected but also the seasonal distribution of inflow. According to our model predictions vegetation growth has the largest impact on autumn streamflow and after this on spring streamflow. Other authors have pointed to the expected decrease in spring streamflow due to the changes in snowpack, snowfall and snowmelt, which means that more streamflow happens earlier in the year.

5.5 Suggestions for further research

One of the problems of our research is that there is much uncertainty in our NDVI-LAI conversion, indicated by the large differences in results between our linear and non-linear methods. Both these conversion equations are an educated guess, because although we know that at higher LAI values the NDVI curve tends to become saturated, we do not know what this curve should actually look like in our case (Bierkens et al., 2008). A solution to this problem would be to start again with the original satellite images and use a different method to find LAI values, like the Enhanced Vegetation Index (EVI), to evade the saturation problem. In comparison to NDVI, EVI was found to be more linearly correlated with green leaf area index (LAI) in crop fields, and less prone to saturation in temperate and tropical forests (Jiang et al., 2008).

Our results show an initial very low LAI value in 1950, followed by a fast increase after which a constant LAI value is reached. This might be unrealistic and is partly the result of the fact that vegetation change for the 1950-2050 period is based on only 12 Landsat images. The first image of the study area is from 1984, while we know land abandonment already started in the first half of the 20th century. Another point of interest is the vegetation growth model itself. An example of what the fitting of the vegetation growth equation through one pixel looks like is depicted in figure 38. Whatever the values that are put in the model, it always assumes a strong initial increase in vegetation growth, which then diminishes over time eventually reaching a constant value. Modeling constant or decreasing LAI is not possible. What is also unrealistic is that it results in there being practically no vegetation in the whole UAB before 1960.

Using a different vegetation growth model might give better results in the future. Because the regression model needs to describe vegetation over a long period, based on only 12 datapoints collected in a short period, it is difficult to determine what model is needed to accurately describe the vegetation change in the UAB. The linear method of Nije Bijvank, (2015) had its limitations, but it did not result in missing values. The non-linear model used by us and by Bänziger (2016) also turned out to not be ideal, as we have described above. So, in further research, attention should be focused on finding a regression equation that can more accurately describe vegetation growth in this region, and that does not result in missing values in case of constant vegetation or vegetation decrease.

There are also a few technical issues with the Landsat images that might need improvement, for further information on this see the discussion of Nije Bijvank (2015). Part of this could be fixed by using the Enhanced Vegetation Index as we described above.

Also, certain parts of our hydrological modeling could be improved. We only changed certain vegetation parameters when simulating revegetation, while we kept the soil parameters constant. In future research it would be better to also asses changes in soil as a result of vegetation change. Another issue with the hydrological modeling is that, according to our results, almost all streamflow for all scenarios seemed to be the result of sub surface flow. Better ways to model Horton overland flow need to be sought to more realistically describe the hydrological fluxes in the Upper Aragon basin.

Finally, one of the downsides of our approach that needs mentioning is that we took the average LAI in the UAB of each year (1950-2050) and coupled this to average yearly streamflow. It would have been preferable to couple the LAI of each pixel of each map to a runoff value, and then take the average of all runoff values.

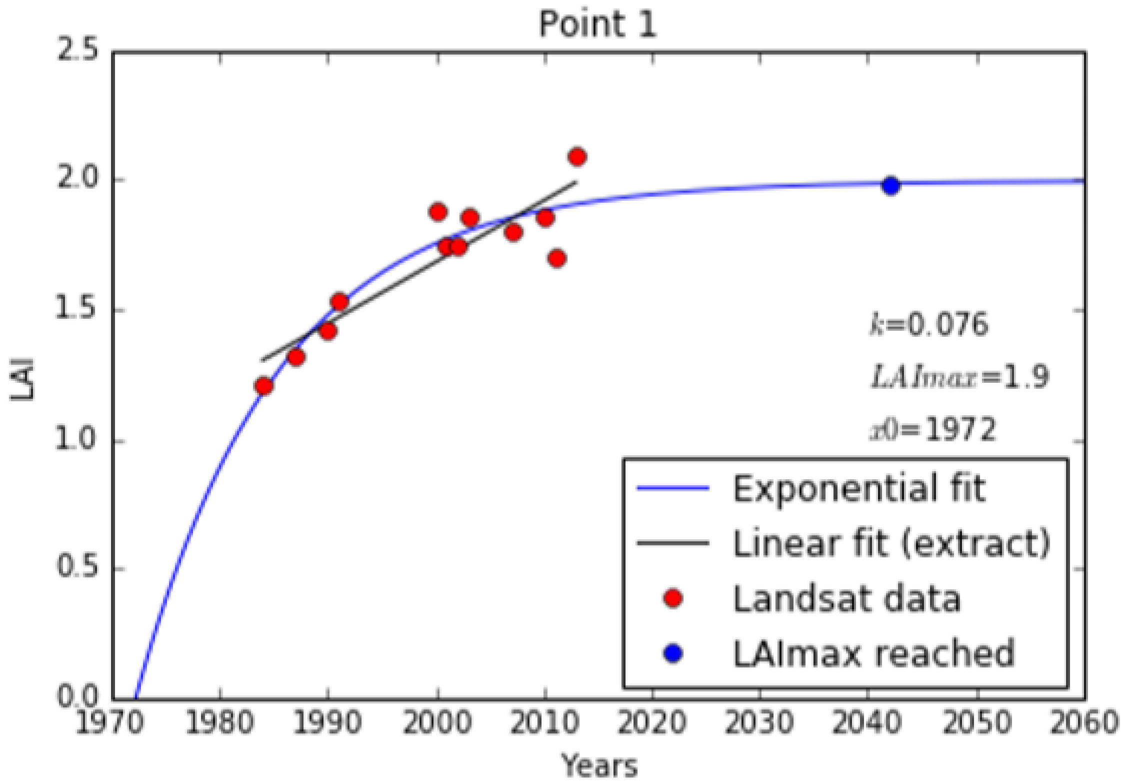

Figure 38 Change of LAI over time in one pixel of the UAB as modeled by (Bänziger, 2016). *The blue line depicts the non-linear fit as used in our research. The red dots represent the LAI values that were used as input in the regression formula.*

Conclusion

During the 20th century agricultural lands were abandoned in many parts of the Mediterranean, including the Upper Aragon Basin. The revegetation that follows land abandonment can impact streamflow in several ways. First, an increase in vegetation causes an increase in interception and transpiration. Furthermore, soil properties like soil depth and permeability can change, depending on the land use before abandonment. Although revegetation will influence land cover and soil properties, literature shows that it can take several decennia before both vegetation and soil characteristics of a revegetated area match the ones of a natural forest.

The effect of vegetation growth on hydrological fluxes in the Upper Aragon Basin was assessed by running the Pycatch model for the Arnás catchment, a sub catchment of the UAB. To simulate vegetation growth LAI input values ranging from 0 to 4.5 were used as input. Other vegetation parameters where also changed by coupling these to the LAI values. The results show that vegetation growth has a large impact on stream flow. The decrease in streamflow is largest for small LAI values, especially going from 0 to 0.1, which results in the almost complete drying up of summer streamflow. After the LAI of around 1 the decrease becomes more gradual and after the LAI of 3 streamflow decrease becomes stronger again. After the impact on summer streamflow, it is autumn streamflow that is mostly affected by the increase in vegetation. Because streamflow is so clearly connected to the soil moisture reaching field capacity, it seems that almost all streamflow is the result of subsurface flow. The differences in yearly runoff coefficient for each of the hydrological years show that the amount of yearly streamflow is not only connected to the amount of rainfall but also very much to the seasonality of the rainfall.

Because it is difficult to determine the exact input values for the soil and vegetation parameters in the hydrological model that would best mimic vegetation growth, we ran eight additional scenarios. Increasing soil thickness with 25 percent has roughly the same impact as decreasing albedo by 25 percent. The impact of a 25 percent lower or higher saturated conductivity turned out be almost neglectable. Thicker soil (which might accompany vegetation growth after abandonment) can result in an absolute difference in yearly runoff coefficient in the range of 6.5 to 13 percent, which is relatively small compared to the effect of vegetation change in the case of complete reforestation.

A strong increase in vegetation in the Upper Aragon Basin was found between roughly 1960 and 2000, after which vegetation increase became very small. Before 1960 there was almost no vegetation according to our calculations. The linear NDVI-LAI relation resulted in significantly higher LAI values than the non-linear NDVI-LAI relation. The difference in results between the linear and non-linear NDVI-LAI relation shows that a more accurate method is needed to determine LAI based on satellite images. Comparing our results to other research shows that the vegetation growth we found is probably an overestimation compared to the real situation. Also, more vegetation was probably present before 1960. Part of the overestimation can be attributed to the non-successful fitting of the regression model through data points that do not show a clear increase in LAI. Another downside of the model is that it always assumes a strong increase in LAI and then a slowing down, which is may not be realistic for the type of vegetation growth in the UAB.

The strong level of vegetation growth results in a strong decrease in streamflow. In 1950 the runoff coefficient is between 90 and 100 percent, while in 1990 this has decreased to somewhere between 3 and 41 percent for the standard scenario, depending on the hydrological year. When using the 2004-2005 hydrological year (which had very little rainfall) to project past and future streamflow, vegetation recovery results in an almost complete drying up of the river flow in 1990. When streamflow projections are based on the 2003-2004 year (higher initial soil moisture levels and more rainfall), the runoff coefficient is still 41 percent in 1990. Apart from the amount of rainfall, the rainfall pattern is also very important for projecting future streamflow, considering the large differences in results between the first and third hydrological year.

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Appendices

Appendix A

Absolute difference in yearly runoff coefficient compared to the standard scenario, for the low and high streamflow scenario during three hydrological years.