NATURAL REVEGETATION OF ABANDONED CULTIVATED LAND IN THE SPANISH PYRENEES AND ITS EFFECT ON STREAMFLOW

by

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Thesis submitted to the faculty of Geosciences at Utrecht University

in Partial fulfilment of the Requirements for the Degree

Master of Science

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Final version

February 2016

ABSTRACT

Abandonment of cultivated land has been a common phenomenon in the central Spanish Pyrenees. Secondary succession causes the abandoned fields to gradually transform into forested areas and thereby impacts the hydrology. River discharges decrease, raising concerns about water availability. This study examines the change of vegetation and its subsequent influence on stream flow in the Upper Aragón basin by using a combination of satellite remote sensing and a process-based hydrologic modelling technique. A pixel based linear regression analysis was run on twelve Landsat satellite images, between the years 1984 and 2013, to determine the spatial and temporal distribution of vegetation change. With the results, the effect on stream flow was modelled using the PyCatch hydrological model in a small catchment within the Upper Aragón basin. Finally, also the effect of climate change on streamflow was modelled to determine its importance relative to the effect of succession. Analysis of the satellite imagery showed that an increase of vegetation between the years 1984 and 2013 has happened in most of the Upper Aragón basin, with most of the changes occurring beneath 1600 meter on slopes with a dominantly northeasterly aspect. The change resulted in a streamflow decrease of 87% between 1950 and 2040 in the modelled catchment, with absolutely the highest changes occurring in autumn. Under only climate change the streamflow decreased by 28% between 2005 and 2040, while vegetation changes caused a decrease of 60% between those years. The results suggest that secondary succession can influence the hydrology of an area considerably, even though the found decrease of discharge overestimates measured decreases. The impact may in some cases even be considerably larger than the effect climate change has on the hydrology of an area.

PREFACE

This Master thesis was made in partial fulfilment of the requirements for a master's degree in Earth Sciences. It is part of the Master programme Earth surface and Water at the Utrecht University. The research was conducted under the supervision of Derek Karssenberg, Elisabeth Addink and Noemí Lana-Renault.

There are several people who I would like to thank for their advice, support and optimism. First of all, I would like to thank my first supervisor Derek Karssenberg for his support, guidance and patience during the process. He often encouraged me to keep going and provided useful feedback and discussions during our meetings. I would also like to say thanks to my second supervisors Noemí Lana-Renault and Elisabeth Addink, for their feedback and advice. Special thanks to Jeanette van Rees who supervises the 'afstudeergroep' and the students that participate in that group. Many hours studying together and the weekly meetings pushed me forward. They supported me in a way no one else could. Thanks to all my friends, you often asked about my progress but also knew when to cheer me up. Thanks to my parents and brother, your continued faith and support mean a lot to me. And finally, I would like to say thanks to my biggest supporter Bob Hageman. Your unconditional love and your unfailing confidence in me, have made the difference. Without you, this work would never have been completed. I dedicate this work to you.

Merel Nije Bijvank

Hillegom, February 2016

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1 INTRODUCTION

1.1 PROBLEM DEFINITION

The Mediterranean region is in a constant battle to preserve sufficient water resources for drinking and irrigational purposes. Summers are hot and dry creating a shortage of water. Dams and reservoirs were built to ensure the availability of water all year round. Decreasing discharges in most parts of the Ebro basin over the last 50 years (Beguería et al. 2003; López-Moreno et al. 2011; López-Moreno, Beguería, and García-ruiz 2004; López-Moreno, Beniston, and García-ruiz 2008) and an increasing water demand for consumption and irrigation purposes are a concern. The water supply increasingly depends on the runoff from the Pyrenean headwaters; more than half of the runoff in the entire Ebro valley originates from the high upstream areas in the north while this only occupies 11% of the area (López-Moreno et al. 2011). A good understanding of the factors governing the decreasing trend is needed to estimate water availability in the Ebro basin for future generations. Several studies concluded that changes cannot solely be attributed to decreasing precipitation and increasing temperatures (Beguería et al. 2003; López-Moreno and Beniston 2009; López-Moreno et al. 2011; Vicente-Serrano, Lasanta, and Romo 2004). A non-climatic factor possibly explaining the negative trend is secondary succession after land abandonment in the headwaters.

Abandonment of farmland has happened in various countries in Europe, especially in mountainous areas as the Alps, Slovakian mountains and the Pyrenees (García-ruiz and Lana-Renault 2011). Since water resources are already scarce in the Mediterranean area and vegetation succession might affect water availability negatively, studying it in this particular region has a high interest. Nevertheless, other regions that were subject to abandonment might also benefit from research. Abandoned cultivated fields are subsequently invaded by herbaceous plants, woody shrubs, and finally turn into forested areas (Molinillo, Lasanta, and García-ruiz 1997). These changes influence the hydrological processes and might result in decreasing discharges of water towards the lower areas. Exactly how and where this succession took place throughout the years and what the hydrological impact is, is not fully known. A number of studies quantified with satellite imagery land use changes in the Mediterranean and noticed the succession, but did not use the data to estimate the future water supply (Lasanta and Vicente-Serrano 2012; Stellmes et al. 2013; Vicente-Serrano et al. 2004). Others did look at this future water supply, but did not specifically look at measured changes due to succession since the abandonment (López-Moreno et al. 2008).

1.2 RESEARCH QUESTIONS

The main objective of this Master research is to quantify the re-vegetation and assess its effect on changes in the water supply from the Spanish central Pyrenees with the use of satellite imagery and a spatially distributed hydrological model. The main research questions are:

1. What is the change in vegetation cover including its spatial pattern in the study area over the past 30 years after land abandonment had taken place?
2. What is the change in streamflow as the result of this vegetation change?
3. What is the effect of changes in vegetation on the streamflow compared to the effect of climate change?

1.3 OUTLINE

This thesis starts with a theoretical background of agricultural land abandonment, secondary succession that often follows it and the effects of this succession on the hydrological cycle. In the following chapter the study area, the Upper Aragón basin in the Spanish Pyrenees, is discussed. A description of the area is given followed by a review of land abandonment, succession and the hydrological changes that have happened in this area. The third chapter describes the methodology of the study, which is divided into two parts. The vegetation distribution and the vegetation change were analysed using Landsat satellite imagery, and is described in the first part. The second part of the method section describes how the change in discharge was modelled using vegetation changes from the remote sensing analysis. The results of the study are given in Chapter 5. They include an analysis of the vegetation distribution, an analysis of the temporal and spatial pattern of vegetation change and the resulting effects on the discharge. The discussion is presented in Chapter 6, in which the main findings are discussed, the main findings are compared to other studies, limitations and recommendations for future research are given. Finally the research questions are answered in chapter 7, the conclusion.

2 THEORETICAL BACKGROUND

2.1 DRIVERS OF AGRICULTURAL LAND ABANDONMENT

Land-use changes have been going on at a large spatial and temporal scale. Part of this change is caused by abandonment of cultivated land. This abandonment can be seen throughout Europe (García-ruiz and Lana-Renault 2011; Hatna and Bakker 2011), but also in other parts of the world, for example Argentina (Izquierdo and Grau 2009). It has already been documented during the Black Death around AD 1347-1352, but is a more recent phenomenon in for example Eastern Europe (Prishchepov et al. 2012). The location of the abandonment can often be linked to marginal areas, as is the case in many mountainous areas such as the Spanish Pyrenees (MacDonald et al. 2000). Drivers for the abandonment can be divided into socio-economic factors or ecologic factors (García-ruiz et al. 1996; Rey Benayas 2007). However, on a worldwide or continental scale the primary reason for farmland abandonment is harder to explain, probably because it is often driven by local reasons (Hatna and Bakker 2011).

2.2 SUCCESSION

Ecological succession is a development of an ecosystem over time, were communities and their structure are changed into new ones. It can be divided into two types: primary and secondary succession (Clements 1916). Primary succession takes place when the ground has not been colonized by a vegetation community before, for example on newly exposed sand surfaces in the dunes. Secondary succession takes place after a severe disturbance of the existing vegetation community. A disturbance can range from a natural event like a forest fire to human induced disturbances like the clearance of forest. Contrary to primary succession, secondary succession involves an ecosystem where soil layers and seeds are still in place.

Several people have written about the process of succession and there are several views on the process (Clements 1916; Gleason 1926; Tansley 1935). The traditional or classical view of succession has a deterministic nature. Clements has written one of the most popular classical theories of succession (Clements 1916). He divides the concept of succession into processes, several stages in which vegetation slowly alters the environment in a way other species can thrive. According to this view, succession ends with a stabilization of vegetation into a climax community. This climax stage is primarily determined by the climatic conditions of the area. The theory is considered deterministic in nature since, over time, it always results in the same climax community. The ecological succession model of Clements is one of the most widely used, although several people criticize it and proposed alternative models. For example Gleason's view (1926) is more stochastic. Succession depends on how seed dispersal takes place and if the seeds happen to land in a suitable environment for germination. Opposed to Clements (1916), he states that there are no regular sequences in succession, the type of vegetation that shows up next depends entirely on immigration of seeds when the environment changes. Others criticize the idea of one climax community, a monoclimax. A polyclimax theory was created by Tansley (1935). He states that more than one climax community can exist within one climatic region, depending on more local conditions e.g. topography.

The succession that occurs after the abandonment of cultivated land is a form of secondary succession. Pioneer species are the first ones to arrive when old fields are recolonized. Most of the pioneer species are grasses and weeds which grow and reproduce at a high rate. Subsequently succession typically follows a more or less standard pattern of regrowth. When the circumstances allow it, the fields transform into shrubs and finally a forest may start to develop. Secondary succession is nature's way of rebounding after a disturbance, it can however have negative effects on the water availability. Problems may especially arise in areas with a dry climate, where water is scarce for consumption and irrigation.

2.3 CONSEQUENCES OF SECONDARY SUCCESSION ON HYDROLOGICAL CYCLE

Secondary succession and other land-use changes can alter the hydrological cycle significantly. Changes of leaf area and vegetation structure are mostly the cause. Frequently noted as one of the most important changes as a consequence of succession is the increase of canopy interception (e.g. Zimmermann et al. 2013). Forest has a higher total leaf area, more vegetative layers and a thicker accumulation of litter at the surface compared to abandoned cultivated land. As a consequence less precipitation reaches the ground surface to become available as runoff. Also evapotranspiration, the sum of transpiration and evaporation, changes with ongoing succession. Evapotranspiration is higher for forest compared to earlier successional stages because of larger surface areas, increase of canopy height, lower albedo and an increase of turbulence. In this way, water can be lost to the atmosphere and does not contribute to the runoff in the area. Root water uptake also increases, but only a small fraction is retained in the plant itself used for turgor and growth while most of the water is lost into the atmosphere by transpiration.

Not only vegetation itself, but also soil properties change as a consequence of secondary succession. Soil development is dependent on climate, parental material, topography, fauna, vegetation and time. Most of the factors do not change when looking at the consequences of secondary succession, except for vegetation and time. Vegetation grows when time is given and consequently organic matter in the soil accumulates, especially in the upper part (Foote and Grogan 2010). The input of organic matter by plants affects mineral weathering which favours soil development and, at a larger time scale, increases soil thickness (Kelly, Chadwick, and Hilinski 1998). Other changes in soil properties related to this change in organic matter is an increase of the aggregate stability (Lesschen et al. 2008). Soil aggregates are groups of soil particles that bind to each other, the stability of these aggregates is e.g. important for the infiltration capacity of water. Unstable soil aggregates might break down during heavy rainfall events, especially when the soils are open to the physical impact of the raindrops. The breakdown results in the formation of a physical soil crust which hampers infiltration because pores are clogged.

In summary vegetation succession leads to a complex reaction of changes, it has an effect on the hydrological variables interception and transpiration and it can also influence soil properties like organic matter content, thickness, aggregate stability and also infiltration capacity. The effect that secondary succession after the abandonment of cultivated land has on the hydrological cycle, can be of great importance especially in regions where water is (periodically) scarce. Insight into this process of change may help to make decisions concerning water management now and in the future.

3 STUDY AREA

3.1 TOPOGRAPHY AND MORPHOLOGY

The study area is the Upper Aragón river basin, a part of the Ebro river basin in Northern Spain. The catchment of 2100 km^2, is situated against the border with France in the Spanish Pyrenees (Figure 1). The elevation is highest in the North of the area, with the highest mountain being Collarada peak which reaches 2860 m a.s.l. (García-ruiz et al. 2010). The elevation decreases towards the south with the lowest point in the south-west of the basin, beneath 500 m a.s.l. where the Yesa reservoir is located. The river Aragón, a northern tributary of the Ebro, rises near Astún in the north east of the area. From there it flows in a southern direction till Jaca, where it turns to the west and is finally interrupted by Yesa reservoir. Tributaries flowing into this river from the north are: Lubierre, Estarrún, Aragón Subordán, Veral and Esca. They cross several structural units in the area (Beguería 2006; García-ruiz et al. 2010):

I. Axial Pyrenees
II. Inner Sierras
III. Flysch sector
IV. Inner depression
V. Pre-Pyrenean Molasses

The Axial area is composed of a mix of rocks from a Paleozoic age, mostly limestone and shale (García-ruiz et al. 2010). The more southerly located inner Sierras is an overthrusted anticline composed of Cretaceous and Paleocene limestone imbedded with sandstone (Beguería 2006). The relief of this structural unit is characterized by steep cliffs. The Flysch sector is more moderately sloped, with Eocene sandstone and marls. The inner depression is the lowest part of the catchment, in which the Aragón flows from east to west. The area consists of Eocene marls which makes it vulnerable to erosion. Finally the Pre-Pyrenean Molasic area can be found south of the Aragón river, the elevation is somewhat higher than the inner depression with steep slopes. The area consists of lutites, sandstones and conglomerates (Beguería 2006).

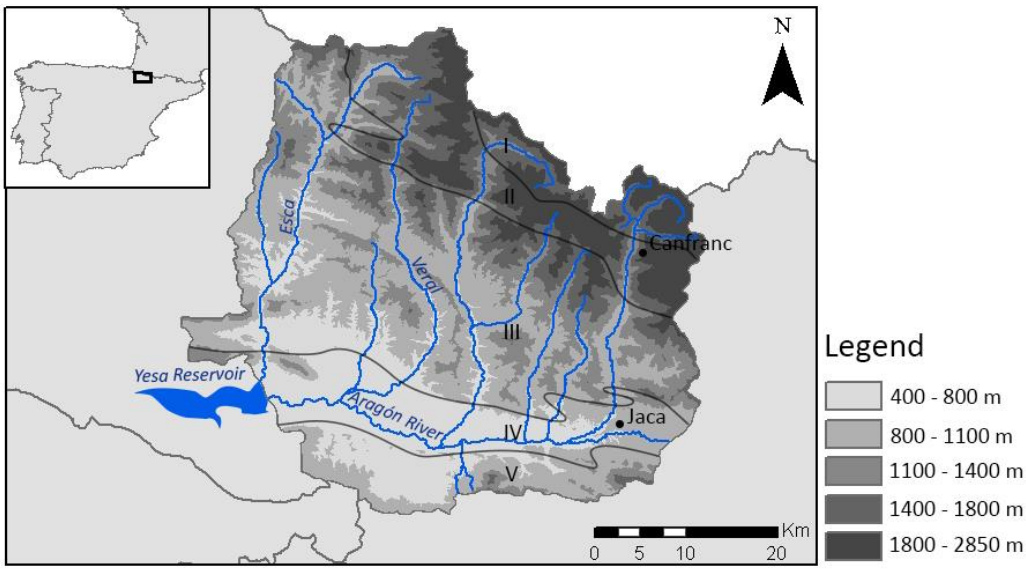


FIGURE 1. A ELEVATION MAP OF THE UPPER ARAGÓN BASIN IN THE CENTRAL SPANISH PYRENEES. THE MAIN WATER BODIES AND THEIR NAMES ARE DEPICTED IN BLUE. THE ELEVATION OF THE AREA IN GREY SHADING. THE STRUCTURAL UNITS: I) AXIAL PYRENEES, II) INNER SIERAS, III) FLYSCH SECTOR, IV) INNER DEPRESSION AND V) PRE-PYRENEAN MOLASSES

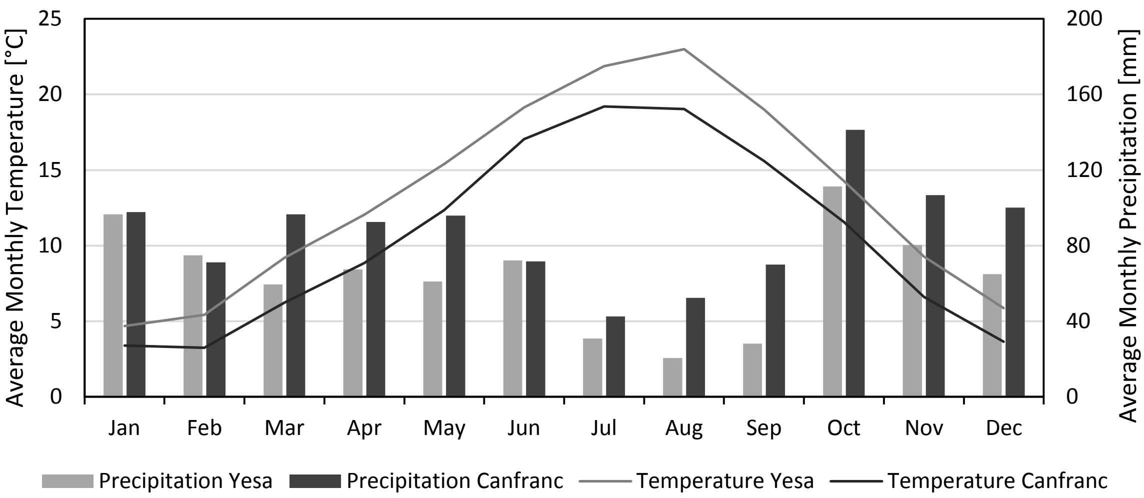


FIGURE 2. MEAN MONTHLY PRECIPITATION AND TEMPERATURE AT YESA RESERVOIR AND CANFRANC (JUNE 2008-2013) (CONFEDERACIÓN HIDROGRÁFICA DEL EBRO N.D.)

3.2 CLIMATE

The climate in the Upper Aragón area is Mountainous Mediterranean with an increasing oceanic influence towards the west. The average annual precipitation ranges from 1600 mm in the northern area, to 800 mm in the Inner depression (López-Moreno et al. 2004). This positive gradient of precipitation towards the north is the result of the positive relation between precipitation and altitude. Precipitation also has a positive gradient towards the west of the area as a consequence of the increasing oceanic influence. Most of the precipitation falls in autumn and spring, with a markedly dry period in summer. The mean annual temperature ranges from 13 °C near Yesa reservoir in the SW of the Upper Aragón basin to 10 °C near Canfranc in the NE of the area, with the highest temperatures in August and the lowest in January. The mean annual temperature in the region shows an opposite gradient to precipitation: it decreases towards the higher areas in the north and increases in a smaller amount towards the west. Both precipitation and temperature gradient can be seen when climate data of Yesa (492 m a.s.l.) in the SW and the climate data from Canfranc (1045 m a.s.l.) in the NE of the study area are compared to each other (Figure 2). The temperature is colder in Canfranc and precipitation is higher. The 0 °C isotherm is in the cold season located at a height of 1600 m a.s.l., most precipitation falls in the form of snow between the months November and May (Del Barrio, Creus, and Puigdefabregas 1990). This is important for the hydrology in the area because snow accumulates and temporally retains water, in contrary to rain which flows more or less directly towards the lower areas. The 10 °C isotherm during the warmest month is located at a height of 2,438 m and is a rough approximation for the location of the upper timberline in the Central Pyrenees (Del Barrio et al. 1990).

3.3 VEGETATION AND SOIL

Naturally the vegetation in mountainous areas as the Pyrenees show an altitudinal zonation: basal (600-900m a.s.l.), submontane (900-1100 m a.s.l.), montane (1100-1700 m a.s.l.), subalpine (1700-2300 m a.s.l.), alpine (2300-2800m a.s.l.) and subnival (>2800m a.s.l.) (Ninot et al. 2007). The exact height at which these zones occur depends on: temperature, soil properties and the incoming solar radiation. The potential vegetation in the Upper Aragón basin, consists of the *Quercus pubescens* between 800-1800m, *Pinus sylvestris* between 1200-1800m and above 1800m the *Pinus uncinata* (Lasanta-Martínez, Vicente-Serrano, and Cuadrat-Prats 2005) However, the actual vegetation distribution has become increasingly dependent on human activities. In the upper Aragón basin, cultivated lands dominated beneath the area of snowfall (1600 m), but were abandoned around the 1950s.

These abandoned fields have evolved into shrubs and forests (Beguería et al. 2003). The land cover in the upper Aragón river basin in the year 2000 is depicted in Figure 3. The inner depression is still dominated by agricultural areas with meadows and cereal crops (López-Moreno et al. 2004). On the lower slopes oak forests (*Quercus cerrioides*) alternated with scrubs can be found (Lasanta and Vicente-Serrano 2007). The montane zone is dominated by pine forests (*Pinus sylvestris*) and scrubs *(Echinospartum horridum*). The subalpine zone consists mainly of grasses (*Trifolium alpinum, Festuca rubra, Nardus stricta, Carex montana* and *Festuca eskia*) and small forests of black pine (*Pinus uncinata)* (Lasanta-Martínez et al. 2005; López-Moreno, Beguería, and García-ruiz 2002). In the highest parts of the Upper Aragón basin heterogeneity in topography and microclimate cause strong variations in cover alternating between grasslands and rocky surfaces (Ninot et al. 2007).

A relatively large variety in elevation, vegetation and parent material in the Upper Aragón basin causes a high diversity of soil types. A soil survey was performed by Navas et al. (2008) in the Arnás river catchment (284 ha) located north west of Jaca in the middle of the study area. The parent material in this part are Eocene marls and sandstones, which makes the study representative for the flysch sector, which is the major structural unit in the Upper Aragón basin. Despite the relatively small catchment and the homogenous parent material, still six soil types were distinguished in the Arnás catchment: Rendsic Leptosols, Calcaric Regosols, Haplic Kastanozems, Haplic Phaeozems, Calcaric Fluvisols and Eutric Gleysols (Navas et al. 2008). The authors found a difference between the physical properties of the soils that were facing north-east, covered with forest, and the south-west facing slopes that were covered with shrubs. The forested north-east facing slopes had better developed soils, tended to have a higher infiltration capacity and higher water retention. In the upper Aragón basin south facing slopes usually have a poor soil function compared to the north facing slopes (García-ruiz et al. 2010).

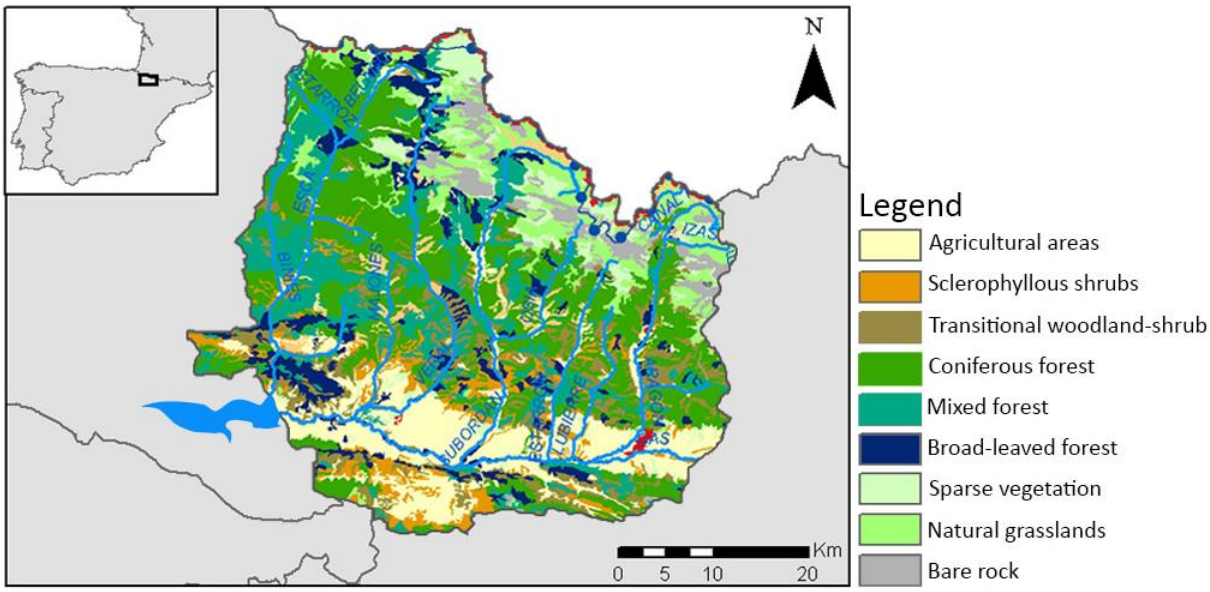


FIGURE 3. VEGETATION/LANDUSE MAP OF THE UPPER ARAGÓN BASIN (CONFEDERACIÓN HIDROGRÁFICA DEL EBRO N.D.)

3.4 Secondary succession after land abandonment in the Upper Aragòn Basin

Changes of land-use in the Aragón basin has strongly been affected by changes in socio-economic activities. A shift can be seen from a traditional system to a more modern and recent one (Lasanta-Martínez et al. 2005). The traditional agricultural system in the Pyrenees consisted of husbandry and cultivation (García-ruiz and Lasanta-Martínez 1990). Sheep were the dominant livestock in the area, and produced wool and meat used by the local population. A system of transhumance was used to benefit from the high pastures above the treeline; during summer time sheep could stay in these high summer pastures, and adapted easily to the steep sloped surfaces in the area. They were moved to lower flat areas in the Ebro basin when snow began to fall in the beginning of the winter. Cultivated area had increased at the end of the 19th century to support the population growth in the Pyrenean area during that time (García-ruiz et al. 1996). The increasing pressure for food resulted in an extension of the cultivated area into more marginal regions with topographic unfavourable conditions. Terraced fields, the so called “articas” and sloping fields were common (Lasanta-Martínez 1988).

The traditional system began to collapse around the 1950s, when people started to move towards city centres, import of products became more profitable and tourism in the area started to increase. The resultant changes ranged from decreases in sheep and abandonment of cultivated slopes to an increase of irrigated agriculture in the flat lower areas. Lasanta-Martínez (1988) determined the areas which were historically cultivated and then abandoned, using aerial photographs from 1957 and 1981 (Table 1). More than half of the land had already been abandoned by 1957. These were mostly areas with unfavourable conditions, such as steep slopes and high altitudes. The abandonment can also be linked to distance and accessibility to villages, a significantly higher percentage of abandonment took place in areas situated further than 1 km from villages (Lasanta-Martínez 1988). Another 7% of the historically cultivated land was abandoned between 1957 and 1981.

TABLE 1. ABANDONED CULTIVATED LAND IN RELATION WITH TOPOGRAPHIC FACTORS (LASANTA-MARTÍNEZ 1988)

		1957				1981			
	Historic surface	Cultivated Space		Abandoned Space		Cultivated Space		Abandoned space	
	ha	ha	%	ha	%	ha	%	ha	%
Exposure									
N	2805	870	31.02	1937	69.00	573	20.40	2233	79.61
E/W	5877	2571	43.75	3305	56.25	2110	23.90	3768	64.10
S	10752	3260	30.32	7491	69.68	2597	24.15	8157	75.85
Open	1073	837	78.00	237	22.00	812	75.68	262	24.32
Slope									
-5%	3105	2981	96.00	123	4.00	2982	96.04	121	3.96
5 – 10%	1511	729	48.25	783	51.75	640	42.36	872	57.74
10 – 20%	4811	2246	46.75	2562	53.25	1687	35.07	3125	64.96
20 – 40%	9353	1550	16.57	7803	83.43	777	8.31	8576	91.69
+40%	1727	32	1.85	1697	98.15	9	0.52	1719	99.48
Altitude									
-900m	3228	1874	58.05	1354	41.95	1660	51.42	1568	44.58
900 – 1200m	7614	2589	34.00	5026	66.00	1964	25.79	5649	74.21
1200 – 1500m	9117	2991	32.81	6126	67.19	2450	26.87	6666	73.13
+1500m	548	85	15.51	463	84.49	18	3.28	530	96.72

Land abandonment after cultivation that took place in the Mediterranean region, has resulted in secondary succession. Plant colonization starts when fields are abandoned and its status depends on time since abandonment, ecological conditions and the human activity before and after abandonment (Molinillo et al. 1997). The succession in the central Pyrenees usually takes place in the following order (Molinillo et al. 1997):

I.	Shortly after abandonment:	Invasion of herbaceous plants
II.	After 10/15 years:	Some woody shrubs
III.	Between 10 – 35 years:	Woody shrubs spread and cover
IV.	Between 35 – 60 years after abandonment:	Shrubs retreat, herbaceous plants expand
V.	After >60 years :	Young trees

These authors found that the succession after abandonment of cereal stubble or meadows is slightly different, however converges after 15 years. Weeds and shrubs quickly colonize the abandoned cereal field, while there is more competition in the abandoned meadows where fodder species dominate. These species were often still present in the seed bank of the soil, which enables them to emerge relatively quickly (Lasanta and Vicente-Serrano 2007). Variability in succession can also arise due to effects of the topography. Soil moisture is less on sunny slopes, subjecting vegetation to water stress and thereby limits growth (Lasanta and Vicente-Serrano 2007).

3.5 Water availability in the central Spanish Pyrenees

3.5.1 Discharge regime

As a consequence of relatively high temperatures and moderate to low precipitation, water is scarce in the Mediterranean region especially during the summer. This causes strains on the water availability during this period. Water availability can be seen as the amount of water available for consumption for domestic, industrial and agricultural purposes. In this study the term water availability is used as an equivalent for river discharge. To ensure water availability year round, reservoirs were build. When making projections for the availability of water in the future, hydrologic trends are important to assess.

The discharges of streams in the Upper Aragón basin show a strong seasonal variation. This variation is important because it may cause water shortages in certain months of the year, while in other months the water availability is still sufficient. The seasonality of the river flow in the Upper Aragón basin depends on several factors, e.g. relative influence of the ocean and the melting of the snow reserves (López-Moreno et al. 2004). A variety of regimes are present in the Aragón river basin, depending on the factor which has the most influence. Here we analysed the flow regimes of the rivers Esca, Veral and Aragón at Sigués, Biniés and Jaca gauging stations, respectively (Table 2).

Table 2. Gauging station characteristics (López-Moreno and García-Ruiz 2004)

Gauging station	River	Height m a.s.l.	Drainage Area km^2	Area above 1600 m a.s.l. %	Mean annual discharge m^3/s
Sigües	Esca	497	506	7.76	11.19
Biniés	Veral	640	161	22.49	4.24
Jaca	Aragón	773	238	47.23	6.79

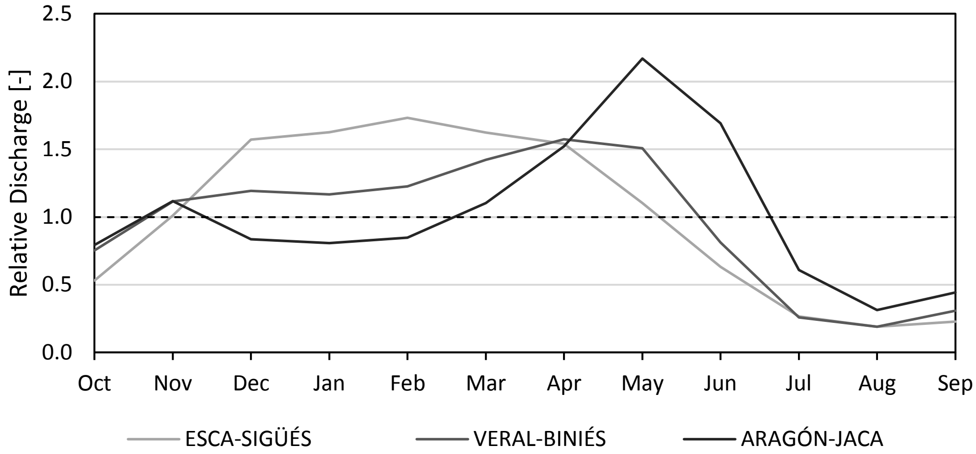


FIGURE 4. RELATIVE DISCHARGE REGIMES AT VARIOUS LOCATIONS IN THE UPPER ARAGÓN RIVER BASIN (DATA: MINISTERIO DE AGRICULTURA, ALIMENTACIÓN Y MEDIO AMBIENTE)

An oceanic regime dominates in the western part of the catchment, where the Esca river flows from the North into Yesa reservoir (López-Moreno et al. 2004). The high flows are between January and April as a consequence of active fronts above the Atlantic (Figure 4). The lowest flows are from July to September, when snow reserves are depleted and precipitation is low. The discharge regime of the Veral near Biniés shows a slightly different pattern. The high flows occur later in the year between March and May, the lowest flows are again from July to September but with a second reduction of the flow in February. The discharge regime of the Aragón near Jaca in the west of the Upper Aragón basin has high flows between April and the middle of May, which is later in the year compared to the other two stations. The low flows are between July and September and a second low flow period is visible around February. This shows that in general two patterns in the discharge regimes can be observed from west to east: 1) The high flows occur from west to east progressively later in the season, which is also observed by other studies (López-Moreno and García-ruiz 2004). It differs from March in the east to May in the western part; and 2) The relative discharge around February becomes less. This spatial pattern in discharge can be related to the oceanic influence and snow accumulation and melt (López-Moreno and García-ruiz 2004). At the Sigüés gauging station 8% of the upstream area is located above 1600 m a.s.l., this is 22% at Biniés and 47% at the Jaca gauging station (Table 2). Between November and April the 0°C isotherm is located at 1600 m a.s.l. (García-Ruiz, Puigdefabregas-Tomás, and Creus-Novau 1986), so more precipitation falls in the form of snow in the eastern part of the Upper Aragón basin compared to the western part. This explains the relative low discharges in February at Jaca compared to the other two stations. The shift in the highest annual discharge towards the end of spring can be attributed to the time it takes to melt these snow reserves. Since altitudes are higher and snow reserves larger in the eastern part, the snow reserve is larger and peak discharge occurs later.

3.5.2 YESA RESERVOIR

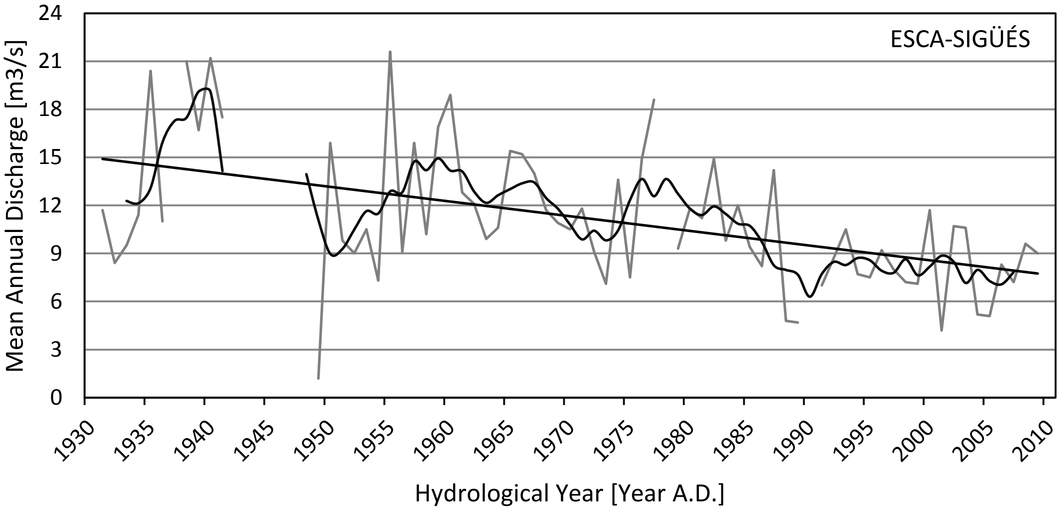
The Mediterranean is one of the many regions in the world depending on reservoirs to ensure water availability year round. The reservoirs hold the water during the wet season, to release it when precipitation becomes scarce in summer. They are usually built in mountain areas, with better geological and climatic conditions to build dams, and they supply the lowlands (interior plains and coastal regions), where the demand of water is the highest. A reservoir in the Upper Aragón basin is Yesa, located in the south west. It was built in 1959 to supply water to irrigational areas in Bardenas via the Bardenas Canal (López-Moreno et al. 2004). A large dam of 74 m high was built to retain a total volume of 470 hm^3 water, but this volume was reduced to 450 hm^3 by 1986 due to siltation (López-Moreno et al. 2004). Water input comes from Aragón and Esca river, which contribute respectively 1019 hm^3 and 353 hm^3 a year with most of the input in autumn and spring (López-Moreno et al. 2002). Outflowing water is distributed between the Aragón river and Bardenas Canal. From October to April discharge is highest in the Aragón river, while from May to September the discharges are higher in the Bardenas Canal to irrigate the fields during the driest months (López-Moreno et al. 2002).

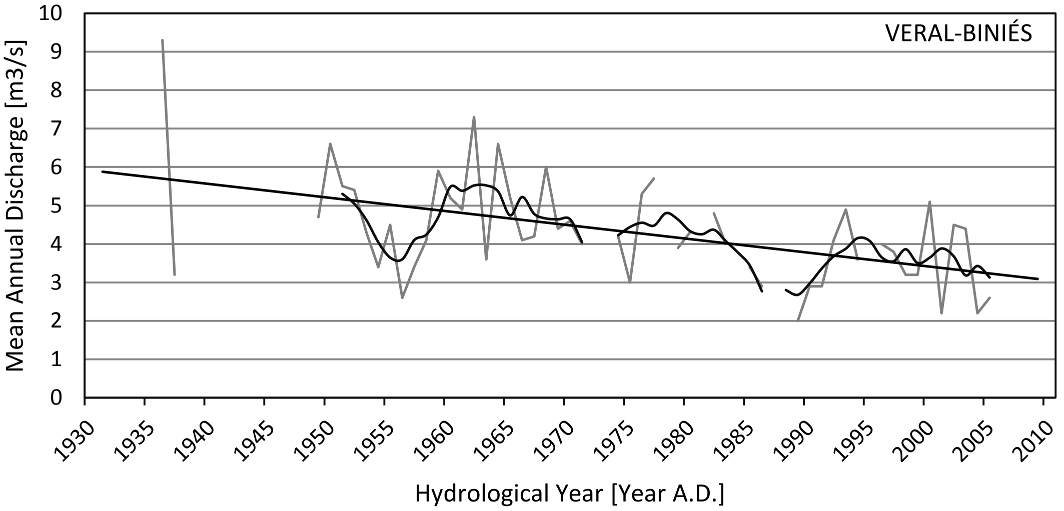
3.5.3 DECREASING DISCHARGE OF RIVERS

Discharge data of the Esca, Veral and Aragón rivers show a decreasing trend over the past decade (Figure 5). This change in discharge pattern can be the result of changes in the climate of the area, but also the result of secondary succession. A significantly increasing trend for annual temperatures in the Ebro river basin has been found (López-Moreno et al. 2011; Vicente-Serrano et al. 2004). Especially the northern part of the Ebro river basin, where the Pyrenees are located, showed a strong increase of more than 0.3 °C per decade since 1950 (López-Moreno et al. 2011). The increase of temperature in the Upper Aragón basin is the largest in summer, but also winter and spring show a significant increase (López-Moreno et al. 2011). Autumn is the only season which shows no significant positive or negative trend. In the Pyrenees and the Iberian mountains the annual positive trend is expected to continue, with temperatures increasing 1.5 – 2 °C over the period 2021-2050 and 4 °C over the period 2051-2080 according to the A1B1 emission scenarios (López-Moreno et al. 2011). The positive trend has a negative influence on the water availability, because an increase of temperature increases also evapotranspiration: the sum of evaporation and transpiration from vegetation. More evapotranspiration means that less water is available as runoff. The higher temperatures also cause the 0°C isotherm 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. 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 and García-ruiz 2004).

A second factor besides temperature which might influence the discharge pattern of an area significantly is precipitation. Multiple studies concluded that annual precipitation in the Aragón river basin and the rest of the Spanish Pyrenees did not change in a significant ($\alpha<0.05$) manner (López-Moreno et al. 2008; Vicente-Serrano et al. 2004), however significant negative trends in the Pyrenees were found for the months of February, March and June (López-Moreno et al. 2008). Others concluded that in some parts of the Spanish Pyrenees annual precipitation did decrease in a significant manner (López-Moreno, Beguería, and García-ruiz 2006). There was no clear consistency between studies and some already pointed out the high variability in magnitude and the direction of change (López-Moreno et al. 2006; López-Moreno and Beniston 2009).

Despite the lack of a clear trend in the precipitation, a significant decreasing trend of discharge in the central Pyrenees can be observed (Beguería et al. 2003; López-Moreno et al. 2011, 2008). The change of temperature or other climatic factors is not sufficient to explain trends in the discharge regime, so also non-climatic factors have to be assessed (Beguería et al. 2003; López-Moreno et al. 2011). One of the factors that could possibly explain this trend is the ecological succession on previously cultivated areas in the Central Pyrenees. This succession influences several hydrological processes which can reduce the runoff in an area. This study addresses the question to what extend secondary succession might influence the discharge pattern.





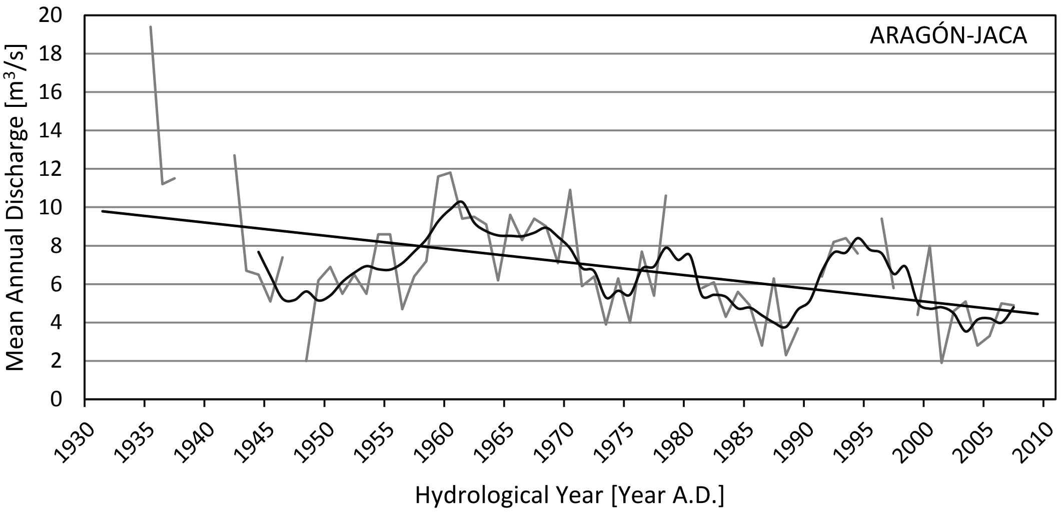


FIGURE 5. MEAN ANNUAL DISCHARGES (GREY) AND A FIVE YEAR MOVING AVERAGE (BLACK) SHOWING A NEGATIVE TREND (DATA: MINISTERIO DE AGRICULTURA AND ALIMENTACIÓN Y MEDIO AMBIENTE N.D.).

4 DATA AND METHODS

4.1 VEGETATION CHANGES IN THE UPPER ARAGÓN RIVER BASIN

4.1.1 DATA ACQUISITION AND PREPARATION

LANDSAT IMAGE ACQUISITION AND PREPARATION

Remote sensing is widely used in various research fields, e.g. urban planning, geology, meteorology and physical geography. It enables the study of surfaces or objects without direct interference by using sensors mounted on e.g. aircrafts or satellites. Landsat imagery was used in this study because it provides a freely available long term data record with a relatively high spatial resolution. The complete Upper Aragón river basin falls within the tiles path 199 row 30 and path 200 row 30 of the Landsat world reference system two (WRSII). A database of Landsat satellite imagery of Landsat 4 till 8 was created from the period 1984 – 2013, with TM, ETM+, OLI and TIRS sensors that have a 30m resolution in the visible and near infrared regions. From the ETM+ sensor aboard Landsat 7 only the images with the SLC-on (1999-2003) were used, because the failure of the scan line corrector after 2003 caused data losses. From 2003 and onward until the arrival of Landsat 8 data, satellite images produced by the TM sensor aboard Landsat 5 were used again. Only summer images were assessed to ensure vegetation cover is relatively high, cloud cover is low and the area is not covered by snow. They were acquired near an anniversary date, between 20th of July and the 20th of August, to reduce phenological effects and effects resulting from differences in solar position. When multiple images were available close to this date, the image with the best quality in terms of lowest cloud cover was used.

A total of 12 Landsat satellite images were downloaded in GEOTIFF format from the website of the United States Geological Survey (TABLE 3). Among these images were 8 Landsat TM images, 3 Landsat ETM+ images and 1 Landsat OLI/TIRS image. Pre-processing of satellite data is needed to prepare data for analysis and reduce scene to scene variability of factors like solar position, atmosphere and geometry. Various files are included when an image is downloaded, important are the individual band files and the metadata file. All the bands with a spatial resolution of 30 m were stacked into a single file using Erdas Imagine software. All the acquired images were processed to the level of a standard terrain correction by the USGS (L1T) using ground control points and a digital elevation model. The geometric accuracy was visually checked between the stacked images and no additional geometric correction steps were performed.

The stacked images consist of digital numbers (DN), which are un-calibrated pixel values. Radiometric correction transfers these DN into actual reflectance values. This correction was done in two steps for the images produced by the Landsat Thematic Mapper sensor (TM) and the Landsat Enhanced Thematic Mapper sensor (ETM+). First,

TABLE 3. CHARACTERISTICS OF THE AQUIRED LANDSAT SATELLITE IMAGERY USED IN THIS STUDY.

Acquisition date	Satellite	Sensor	WRS-2 Path/Row	Quality
20-08-1984	Landsat 5	TM	199/30	Medium
20-08-1987	Landsat 5	TM	200/30	Medium
27-07-1990	Landsat 5	TM	200/30	Low
22-07-1991	Landsat 4	TM	200/30	Medium
30-07-2000	Landsat 7	ETM+ (slc on)	200/30	Good
11-08-2001	Landsat 7	ETM+ (slc on)	199/30	Good
14-08-2002	Landsat 7	ETM+ (slc on)	199/30	Good
31-07-2003	Landsat 5	TM	200/30	Good
11-08-2007	Landsat 5	TM	200/30	Good
27-07-2010	Landsat 5	TM	199/30	Good
30-07-2011	Landsat 5	TM	199/30	Low
11-08-2013	Landsat 8	OLI/TIRS	200/30	Good

a correction for the sensitivity of the sensor which transfers DN into radiance values (W m^{-2} steradians^{-1} µm^{-1}) (Chander, Markham, and Helder 2009) was performed:

$$L_\lambda = \frac{L_{max\ \lambda} - L_{min\ \lambda}}{Q_{cal\ max} - Q_{cal\ min}} * (Q_{cal} - Q_{cal\ min}) + L_{min\ \lambda} \tag{1}$$

Where L_λ is the radiance for a specific spectral band [Watt/(m^2 * sr * µm)], Q_{cal} [DN] is the quantized calibrated pixel value, $Q_{cal\ min}$ [DN] is the minimum quantized calibrated pixel value (typically 1) and $Q_{cal\ max}$ [DN] the maximum quantized calibrated pixel value (typically 255), $L_{min\ \lambda}$ [Watt/(m^2 * sr * µm)] is the spectral radiance that is scaled to $Q_{cal\ min}$ and $L_{max\ \lambda}$ [Watt/(m^2 * sr * µm)] is the spectral radiance that is scaled to $Q_{cal\ max}$. All the values were obtained from the Level 1 product metadata file, a summary of these values is listed in Appendix 1. Subsequently radiance values were converted to Top-of-Atmosphere reflectance, also called at sensor reflectance, as follows (Chander et al. 2009):

$$\rho_\lambda = \frac{\pi * L_\lambda * d^2}{E_{sun\ \lambda} * \cos(\theta_S)} \tag{2}$$

Where ρ_λ [-] is the is the top of atmosphere reflectance for band λ, d [astronomical units] is the earth sun distance, $E_{sun\ \lambda}$ [Watts/(m^2 * µm)] is the mean exoatmospheric solar irradiance for band λ and θ_S [°] is the solar zenith angle (equals the sine of the solar elevation angle). Values for d and $E_{sun\ \lambda}$ were obtained from Chander et al. (2009) and θ_S was obtained from the metadata file.

In contrary to its predecessors, the Landsat 8 Operational Landsat Imager (OLI) sensor can directly convert the downloaded band data from DN's to TOA reflectance values, instead of first to radiance values. It uses scaling factors provided in the metadata file for the conversion to TOA reflectance as follows (U.S. Geological Survey 2013):

$$\rho_\lambda = \frac{M_\rho Q_{cal} + A_\rho}{\cos(\theta_S)} \tag{3}$$

Where R_λ [-] is the is the top of atmosphere reflectance for band λ, M_ρ is the multiplicative rescaling factor for band λ, A_ρ is the additive rescaling factor for band λ, Q_{cal} [DN] is the quantized calibrated pixel value and θ_S [°] is the solar zenith angle (equals the sine of the solar elevation angle).

Top-of-Atmosphere reflectance reduces the scene-to-scene variability by accounting for differences in the solar zenith angle, the distance to the sun and the mean exo-atmospheric solar irradiance. It does not remove any atmospheric effects, as scattering and absorption. Clouds and their shadows were manually removed from the dataset, because they interfere with optical remote sensing techniques when studying the earth surface. Other atmospheric influences were assumed to be negligible, because pseudo invariant features showed no clear change throughout the scenes and absolute correction methods might make image series less spectrally similar (Schroeder et al. 2006). Finally all the scenes were transformed into the reference coordinate system WGS84 zone 30 and resampled to the same location and cell size of 30m by 30m with the nearest neighbour method and cropped to the study area.

OTHER DATA

Other data that was used in the analysis and interpretation of vegetation change, were a digital elevation model of the Upper Aragón basin and the Corine Land Cover map. The digital elevation model (DEM) was used to assess the spatial pattern of the change and its relation to topography. The elevation data was obtained from the National Center for Geographic Information (CNIG) website. The DEM with a 25m resolution had been subtracted from PNOA's orthophotographs (National Aerial Orthophotography Plan). The data was transformed to the reference coordinate system WGS84 zone 30 and resampled to a pixel size of 30m using ArcMap to match the satellite imagery.

The Corine Land Cover 2006 seamless vector data was used to mask out areas which are still cultivated and areas without vegetation. The vector data was obtained from the website of the European environmental agency (European Environment Agency n.d.). A subset of the vector data was made and it was transformed to the reference coordinate system WGS84 zone 30. The alignment of the various classes was visually checked with the Landsat satellite image of 2013. The classes artificial surfaces, agricultural areas and water bodies of the original map were merged into one class to create the mask of the non-natural areas. In order to correct for small misalignments a buffer zone of 60 meters was created outside the non-natural area in order to ensure the removal of it from the analysis. The vector dataset was subsequently conversed to a raster data set and resampled to match the pixel size of the satellite imagery.

4.1.2 EXPLORATORY ANALYSIS OF THE SPATIAL DISTRIBUTION OF VEGETATION

In order to explore the spatial distribution of vegetation from the Landsat satellite imagery, first an indicator for vegetation had to be found. Vegetation has a characteristic reflection pattern, caused by leaf pigments, cell structure and water content. It is studied thoroughly by e.g. Knipling (1970) so it now can be used in remote sensing research. The dominant factor controlling the leaf reflectance in the visible domain (0.4 – 0.7 µm) are the leaf pigments; chlorophyll-a and chlorophyll-b. These pigments cause absorption of the light in the blue and red part of the spectrum, with the result that vegetation has a relatively high reflection in green. Cell structure is the dominant factor causing the high reflectance in the near infrared part of the spectrum. It is the result of multiple reflections inside the leaf structure as a consequence of differences in refractive indices of the cell walls and the space between the cells. In the short wave infrared (SWIR) region reflection is dominated by water content of the vegetation and is generally lower than the reflection in the NIR. Vegetation indices are developed to express this characteristic spectral signal of vegetation as a single number. The most widely used is the normalized difference vegetation index (NDVI), a ratio between the reflection in the red and NIR part of the spectrum:

$$NDVI = \frac{\lambda_{NIR} - \lambda_{RED}}{\lambda_{NIR} + \lambda_{RED}} \tag{4}$$

The value ranges between -1 and +1, where λ_{NIR} is the reflection in the near infrared region and λ_{RED} is the reflection in the red region. NDVI gives an impression of vegetation abundance and its status. The reflectance values of band 3 (red) and 4 (near infrared) are used to calculate the NDVI for all the individual images except the images produced with the OLI/TIRS sensor, where band 4 (red) and band 5 (near infrared) are used. All the satellite images were transformed to NDVI values to get an idea of its spatial and temporal pattern. The band designations of red and near infrared differs slightly between the Landsat TM, ETM+ and OLI sensor, the effect of this difference on the NDVI is assumed to be negligible. Finally a subset of the satellite images that contains the study area was created.

The exploratory analysis was done visually but also in relation with topographic factors in order to assess the influence of topography on the distribution of vegetation in the area. To test this, NDVI values of the naturally vegetated zones were compared to topographic factors. The range of elevations was divided into 8 classes from an elevation of 400m with an increase of 200m per class. The aspect was divided into 9 classes, 8 classes with a difference of 45° between each class and one class for area which was considered flat. And, slope was divided into 8 classes from 0° with an increase of 5° per class. The mean and standard deviation of NDVI in these classes were calculated using the ArcMap Zonal statistics tool. In the calculation agricultural areas were excluded with the created mask of the Corine Land Cover map, because the study focuses on areas which are currently naturally vegetated. The change of the mean and standard deviation between the classes gives an impression of the natural and anthropogenic distribution of vegetation in relation with topography.

4.1.3 Transforming NDVI data into LAI

Like other vegetation indices NDVI is often related to physiological vegetation parameters. It has proven to be correlated to variables such as photosynthetic activity, canopy structure and leaf area index (Gamon et al. 1995). For that reason NDVI change might be an indicator of succession. The NDVI needed to be transformed into a biophysical parameter in order to quantitatively measure the change of vegetation and to be able to use it subsequently as input in a hydrological model. The Leaf area index was chosen to use since it is important factor in the interception and evapotranspiration process.

Leaf area index (LAI) can be defined as the total one-sided leaf area per ground area (Chen and Cihlar 1996). LAI can be estimated using direct and indirect measurement techniques. Direct measurement techniques such as harvesting of leaves or the use of litter traps, are time consuming and sometimes disrupt the natural environment. More frequently is opted for quick and less disruptive indirect techniques, e.g. hemispherical photography or the LAI-2000 plant analyser. These measurement techniques are however methods for in the field, cannot go back in time to assess changes of succession and are not spatially continuous. Another option is to estimate LAI with the use of satellite imagery. Several global and regional LAI products have already been developed with use of satellite imagery (Liang, Li, and Wang 2012), one of the most commonly used is the MODIS LAI product. However the relatively low spatial resolution and lack of a long-term record makes it not suitable for this study. Therefor the LAI was retrieved out of the Landsat satellite imagery. This can be done e.g. by linking field measurements to vegetation indices with a regression model (Chen and Cihlar 1996; Chen et al. 2002; Curran, Dungan, and Gholz 1992), however no known field data of LAI was available for the Upper Aragón basin. This significantly limited this study to the use of relatively simple methods of LAI retrieval out of Landsat satellite imagery. Finally a simple linear relation was chosen to transform all the NDVI images to leaf area index (Yin and Williams 1997):

$$LAI_i = LAI_{max} \frac{NDVI_i - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \tag{5}$$

With 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. A number of assumptions were made: 1) The NDVI of a bare field corresponds to a LAI of zero, 2) the maximum NDVI corresponds to a maximum LAI, 3) the relation between NDVI and LAI does not differ between species, location and over time and 4) the relation between LAI and NDVI is linear. The NDVI-LAI relation tends to saturate at high LAI values, however beneath an LAI of approximately 3 to 4 a linear relation might be sufficient (Brantley, Zinnert, and Young 2011; Wang et al. 2005).

The $NDVI_{min}$ value was obtained by selecting 10 bare fields on the 1984 and 2013 image and calculating the average NDVI value. The $NDVI_{max}$ was obtained by taking the 99 percentile value of the 2013 image. The LAI_{max} was assumed to be the maximum LAI of a *Pinus sylvestris* forest in de Mediterranean. Poyatos, Llorens & Gallart (2005) studied a plot in the Pyrenean area and estimated a maximum LAI of 2.4 m^2 m^{-2} for a stand with the oldest trees about 60 years old. Other LAI values of the *Pinus sylvestris* can be found in a study of Breuer, Eckhardt and Frede (2003), they range between 1.1 – 7.2. However, these values were measured in Sweden, Germany, Estonia and the United Kingdom and therefore might not be representative for this species in the Mediterranean region, so the LAI_{max} was assumed to be 2.4 m^2 m^{-2} in 2013. When the transformation resulted in negative LAI values, the negative values were set to zero.

4.1.4 PIXEL-BASED TREND ANALYSIS

Changes of the Leaf area index were assessed using a regression model. This was done with Curve Fit, an extension for ArcMap downloaded from the USGS site (De Jager and Fox 2013). It uses pixel based linear or nonlinear regression techniques on a series of raster layers to obtain an unique model for each pixel. The outputs are maps of the model parameters estimates and optionally also errors. The change of LAI is expected to be high in early stages of succession and is expected to diminish over time, eventually reaching an equilibrium. This could mean that a non-linear regression model is a better predictor of LAI changes during succession than a linear model. Nonetheless, a linear regression model was chosen to use because the model seems to fit the data well over the measurement period, 1984 till 2013, and it allows for a simple interpretation compared to non-linear models. Also, the initial stages during succession are not recorded with the Landsat satellite imagery, which makes it difficult to determine the actual shape of the LAI curve with time. The linear model has the form:

$$\mathrm{y}(\mathrm{x}) = \mathrm{a}x + \mathrm{b} \tag{6}$$

where y is the Leaf area index [-],x is the date [year A.D.], a is the fitted slope parameter and b is the fitted intercept parameter. The output of the regression are maps of the slope parameter (parameter a), the intercept parameter (parameter b) and of the R-squared value. The process was repeated several times to fill in the gaps of missing data due to clouds when they were present for only one of the years. The slope parameter can be used as an estimate of the LAI change over time, but the intercept parameter of the regression model has no real meaning. In addition to the parameters, the year when the LAI is zero was calculated (LAI zero). This value can give an indication of the year the fields were abandoned, however the use of a linear model might underestimate this value. The year in which the LAI was zero can be calculated using equation (8).

$$\mathrm{x}_0 = \frac{-\mathrm{b}}{a} \tag{7}$$

Where x_0 is the date [year A.D.] that the Leaf area index is zero.

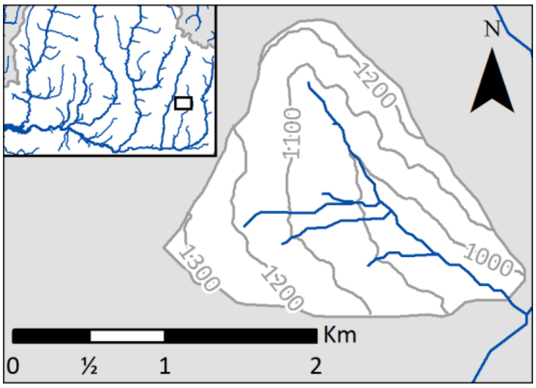
The spatial pattern of the slope parameter and the LAI zero was analysed, as well as their relation with topographic factors: altitude, slope, and aspect. The R-squared map was checked to identify recent land-use changes, a low r-squared value might indicate a sudden change in NDVI.

4.2 MODELLING CHANGES IN DISCHARGE DUE TO SECONDARY SUCCESSION

4.2.1 MODELLING CATCHMENT

Due to computational limitations the whole Upper Aragón basin could not be used for modelling. Instead the Arnás catchment, a small catchment in the Upper Aragón basin, was used. It is a tributary of the Lubbiere river, located in the eastern part of the Upper Aragón basin. The catchment covers an area of 2.84 km^2, with elevation ranging between 910 and 1430 meters a.s.l.. The area is known to be cultivated with cereal crops and was progressively abandoned since the 1950s (Lana-Renault et al. 2011). The current land cover mainly consists of shrubs, with some forested areas on the northeast facing slopes (Lana-Renault et al. 2011). A summary of the characteristics of the catchment can be found in Table 4. The catchment is an experimental site where various studies have been carried out (e.g. Lana-Renault et al. 2011; Navas, Machín, and Soto 2005; Seeger, Errea-Abad, and Lana-Renault 2005). It was also used by Lana-Renault and Karssenberg for calibrating the PyCatch model (Lana-Renault and Karssenberg 2013).

TABLE 4. CHARACTERISTICS OF THE ARNÁS CATCHMENT (LANA-RENAULT ET AL. 2014; NAVAS ET AL. 2008)



Basin Characteristics	
Elevation Range	910 – 1340 m
Catchment Area	2.84 km^2
Mean annual temperature	10 °C
Mean annual precipitation	926 ± 180 mm
Mean annual reference evapotranspiration	1088 ± 31 mm
Geology	Eocene Flysch
Soil	Regosols and Cambisols

4.2.2 PyCatch model description

The dynamic hydrological PyCatch model consists of various process-based distributed hydrological model components developed by Lana-Renault and Karssenberg (2013). The model is specifically built for simulating the effect of secondary succession after cultivation on the stream flow. It is built with the PCRaster Python language, which combines the high level language of Python with the spatio-temporal functionality of PCRaster (Lana-Renault and Karssenberg 2013). The model has modular components, which makes it relatively easy to adapt or add functions. Each of these modules are combined in a dynamic modelling framework.

Figure 6 gives the structure of the various components in the PyCatch model. It contains the processes: interception, evapotranspiration, infiltration, storage and flow. Precipitation can get intercepted by vegetation or it can reach the soil surface were it is temporarily stored. How much of the precipitation is intercepted by vegetation is determined with the canopy gap fraction, which is a function of the leaf area index and the light extinction coefficient. Evapotranspiration can bring water back into the atmosphere. The potential evapotranspiration (E_P, [m h^{-1}]) was calculated with the use of the Penman-Monteith equation (Allen et al. 1998):

$$\mathrm{E}_P = \frac{1}{\lambda}\left(\frac{\Delta R_n + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}\right) \quad (8)$$

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} °C^{-1}] is the specific heat of the air, e_s [Pa] is the saturated vapour pressure, e_a [Pa] is the actual vapour pressure, r_a [h m^{-1}] is the aerodynamic resistance, r_s [h m^{-1}] is the surface resistance [h m^{-1}] and γ [Pa °C^{-1}] is the psychometric constant. The soil heat flux is ignored in the PyCatch model. Water stored at the surface can infiltrate into the ground or become surface runoff. The infiltration of water is described by the Green-Ampt model for potential infiltration (Green and Ampt 1911):

$$f_p(\mathrm{t}) = K_s\left(1 + \frac{\psi(\phi - \theta_i)}{\mathrm{F}}\right) \quad (9)$$

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, θ_i [-] is the initial moisture content of the soil and F [m] is the cumulative infiltration. In this formula the depth of ponding is assumed to be negligible, because it most likely becomes surface runoff. The lateral movement of water in the subsurface (Q_g, [m h^{-1}]) is modelled using Darcy's Law, routed over the local drainage direction (LDD) network (Lana-Renault and Karssenberg 2013):

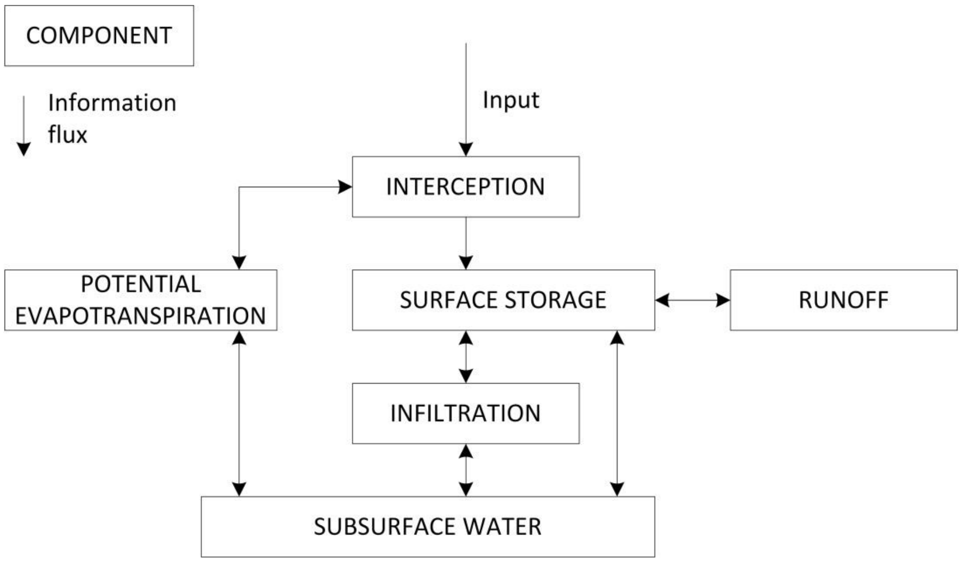


FIGURE 6. DIAGRAM SHOWING THE MODULAR STRUCTURE OF PYCATCH AND THE FLOW OF INFORMATION BETWEEN THE COMPONENTS (LANA-RENAULT AND KARSSENBERG 2013)

$$Q_g(\mathrm{t}) = K_s \cdot L \cdot G \cdot i \tag{10}$$

Where L [m] is the cell length, s [-] is the slope to the downstream cell and G [m] is soil water storage. The subsurface water can seep upward when the storage capacity of the soil is exceeded. It is added to the water available at the soil surface. Water on the surface might result in overland flow which is also routed over the LDD.

4.2.3 DATA ACQUISITION AND PREPARATION

The input data needed to run the PyCatch model ranges from meteorological data to vegetation parameters, soil parameters and other. The data was obtained from the Landsat satellite imagery, a meteorological station in the Arnás catchment, a digital elevation model and from literature. The main input variables and parameters of the PyCatch model are listed in Table 5.

METEOROLOGICAL DATA

The meteorological data was obtained from a meteorological station within the Arnás catchment. Air temperature [°], precipitation [mm], wind [m s^{-1}], relative humidity [-] and shortwave radiation [W m^{-2}] data of the hydrological year 2005-2006 was used. The data was already checked for missing values and prepped for a time step of one hour by Lana-Renault and Karssenberg (2013). This meteorological data was used for all the modelled years to eliminate changes in the streamflow due to changes in climate. Spatial variations in the meteorological variables are assumed to be negligible because of the limited size of the catchment. The used temperature and precipitation input can be found in Appendix B.

TABLE 5. MAIN INPUT VARIABLES AND PARAMETERS OF THE PYCATCH MODEL. PARAMETER VALUES ARE BASED ON LANA-RENAULT AND KARSSENBERG (2013).

Input variables and parameters		Unit
Meteorological inputs		
Precipitation	-	mm h^{-1}
Incoming shortwave radiation	-	W m^{-2}
Air temperature	-	°C
Air relative humidity	-	–
Wind speed	-	m h^{-1}
Vegetation parameters		
Leaf Area Index (LAI)	-	–
Maximum interception storage per LAI	0.00032	m
Albedo	0.27	–
Vegetation height	-	m
Maximum stomatal conductance	0.0067	m h^{-1}
Soil parameters		
Regolith thickness	2.25	m
Limiting point fraction	0.276293	–
Wilting point fraction	0.1	–
Field capacity fraction	0.327306	–
Soil porosity fraction	0.5	-
Saturated conductivity groundwater	30	m day^{-1}
Ksat	0.3	m/h
Others		
Digital elevation model	-	m
Maximum surface storage	0.001	m
Latitude, longitude	(42.645, 0.6)	°

PARAMETERS ESTIMATED FROM SATELLITE IMAGERY

The main input parameter for the PyCatch model derived from the Landsat satellite imagery is the LAI. It was modelled per pixel using a linear regression model as described in the paragraph Pixel-based trend analysis. The model was constrained by predefined boundary conditions. The LAI varies from zero (0.0001), when no vegetation is present, to the estimated maximum LAI of a *Pinus sylvestris* stand (2.4 m^2 m^{-2}). A minimum value of 0.0001 for the LAI was used instead of zero, because a value of zero causes problems in the PyCatch model.

Subsequently, the vegetation height was estimated using the modelled LAI. Generally a positive relation exists between the LAI and the height of vegetation (Luo et al. 2015; Yuan et al. 2013). A linear relation was used, based under the assumptions: 1) when LAI is zero, plant height is zero, 2) when LAI reaches its maximum, plant height is 18m (Breuer et al. 2003) and 3) the relation between LAI and vegetation height is the same for all vegetation types during succession in the Arnás catchment. There are however some limitations to this method. A study by Yuan et al. (2013) showed that a power function provides the most significant fit, but it was followed by the linear model. And also some studies indicated that that the relation between vegetation height and LAI differs per vegetation type (Yuan et al. 2013).

OTHER PARAMETERS

Other parameters in the Pycatch hydrological model are kept constant spatially and temporally. Vegetation parameters were mostly the same as used in the study by Lana-Renault and Karssenberg (Lana-Renault and Karssenberg 2013). The values used in the model correspond to a shrub environment so the output of the discharge data of the hydrological year 2005-2006 could be compared to the actual discharge data of that year.

The vegetation parameter values used in the hydrological model; interception storage per leaf area, albedo, and vegetation stomatal conductance, can be found in Table 5. Soil parameters were also obtained from the study by Lana-Renault and Karssenberg (2013) and can be found in Table 5.

4.2.4 MODEL SETUP

The PyCatch model cannot be run continuously for the entire successional time because of computational limitations. Instead the model was run every 30 years: 1950-1951, 1980-1981, 2005-2006, 2040-2041. Instead of running the model for 2010-2011 it was run for the hydrological year 2005-2006 because the meteorological data comes from that year and the modelled discharge can be compared to the measured discharge. In order to remove the effects of choosing an initial moisture content, a period of three months is used as a spin-up period. Since the catchment is relatively small, this is likely to be enough.

Main output of the PyCatch model is the discharge at the output location of the Arnás catchment. The performance of the PyCatch model was tested by comparing the modelled discharge of the hydrological year 2005-2006 with measured discharge data from that year. Comparison was done visually and also quantitatively by calculation of the Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970):

$$NSE = 1 - \frac{\sum_{t=1}^{n}(Q_o - Q_p)^2}{\sum_{t=1}^{n}(Q_o - \bar{Q}_o)^2} \tag{11}$$

With Q_o the observed discharge values [m^3], $\bar{Q}_o$ the mean of the observed discharge values and Q_p the predicted discharge values [m^3]. Finally, the change of the discharge pattern was analysed visually by comparing the total daily and monthly discharge values over the modelled years to assess the influence of succession on streamflow.

4.2.5 CLIMATE CHANGE SCENARIO

The relative influence of climate change on the streamflow was tested in a scenario where the temperature and precipitation input was changed but the vegetation input was kept the same. The PyCatch model was run for the hydrological year 2040-2041, with new temperature and precipitation values while vegetation parameters stayed equal to the hydrological year 2005-2006. The output was compared to the previous model runs of PyCatch model in 2005-2006 and 2040-2041 in order to assess the influence of climate change on streamflow and assess its influence relative to succession.

The projected changes of temperature and precipitation in the study area were estimated using several studies which use regional or global climate models to assess climate change (López-Moreno et al. 2011; Ribalaygua et al. 2013). The temperature shows a clear tendency and is expected to rise towards the end of the 21st century, but the trend of precipitation is less conclusive (López-Moreno et al. 2011; Ribalaygua et al. 2013). The change of temperature is expected to be most pronounced in summer, followed by spring and autumn (Ribalaygua et al. 2013). Values which were used for the climate change scenario can be found in Table 6. The values were based on Ribalaygua et al. (2013) and an A2 emission scenario. For temperature a different change in temperature over the different seasons was chosen. For precipitation the change was kept constant over the year.

TABLE 6. ESTIMATED CLIMATE CHANGE IN THE ARNÁS CATCHMENT OVER THE PERIOD 2005-2040 AS USED IN THE PYCATCH MODEL.

Period	Change temperature	Change precipitation
July – September	+1.50 °C	-5%
October – December	+1.00 °C	-5%
January – March	+0.75 °C	-5%
April – June	+1.00 °C	-5%

5 RESULTS

5.1 SPATIAL VEGETATION PATTERN IN THE UPPER ARAGÓN BASIN

An exploratory data analysis is used to study patterns and characteristics of the NDVI dataset. The average NDVI value of the study area is 0.60 in 2013. Without the inclusion of non-natural areas as water bodies, urban areas and agricultural fields the NDVI is 0.64. Low NDVI values can be found in the south of the study area along the river Aragón and in the northeast (Figure 7). The low values correspond to the location of Yesa reservoir where values are below zero and to the agricultural fields in the central depression and the rocky areas with the highest elevation of the study area where NDVI values are slightly above zero. High NDVI values are more distributed throughout the area, but a concentration of high values can be found in the northeast around the areas with a high elevation.

To get an impression of the range of NDVI values of vegetated areas, the NDVI of bare fields ($NDVI_{min}$) and of fully vegetated forest areas ($NDVI_{max}$) were estimated. The $NDVI_{min}$ value was obtained by manually selecting 10 bare fields on the 1984 and 2013 image and calculating the average NDVI value. The average NDVI value of 10 bare fields in 1984 is 0.12 (SD= 0.008) and in 2013 is 0.16 (SD = 0.027). The difference may arise due to the influence of moisture content on NDVI or due to radiometric or atmospheric differences. The NDVI value of a dense forest is expected to correspond to the 99th percentile, which is 0.83 for the 2013 image.

Multiple graphs were made of the NDVI in 2013 vs the topographic factors (Figure 8). Several observations can be made from the figures regarding the relation of the topographic factors versus the vegetation status of the study area. First, the NDVI increases with elevation to a maximum around 1400m and decreases above this elevation. The mean NDVI in the 1200 – 1400m class is 0.73 opposed to mean NDVI values around 0.5 in the lowest and highest elevation classes. Second, the NDVI is highest in areas with a north-eastern aspect and lowest in areas with a southern aspect. The mean NDVI in these classes differs respectively from 0.67 to 0.62. Finally, NDVI increases with an increasing slope to maximum around 30° and decreases for a steeper slope. The mean NDVI in the class 30° - 35° is 0.67 opposed to mean NDVI values lower than 0.60 for the flattest and steepest areas. The optimal vegetation status can be found on the shady areas with a relatively steep slope and elevation between 1200 and 1600 meter. The primary topographical factor controlling vegetation status is elevation, effects of slope and aspect are respectively less important.

Overall the vegetation status in 1984 is in the same way controlled by topographical factors as the vegetation status in 2013. The NDVI is highest in areas with a north-eastern aspect, a slope between 30° and 35° and a height between 1200 and 1400. Again the elevation seems to have the most effect, followed respectively by slope and aspect. Overall an increase of the NDVI values could be observed from 1984 to 2013, the average value of the naturally vegetated area increased from 0.44 to 0.64.

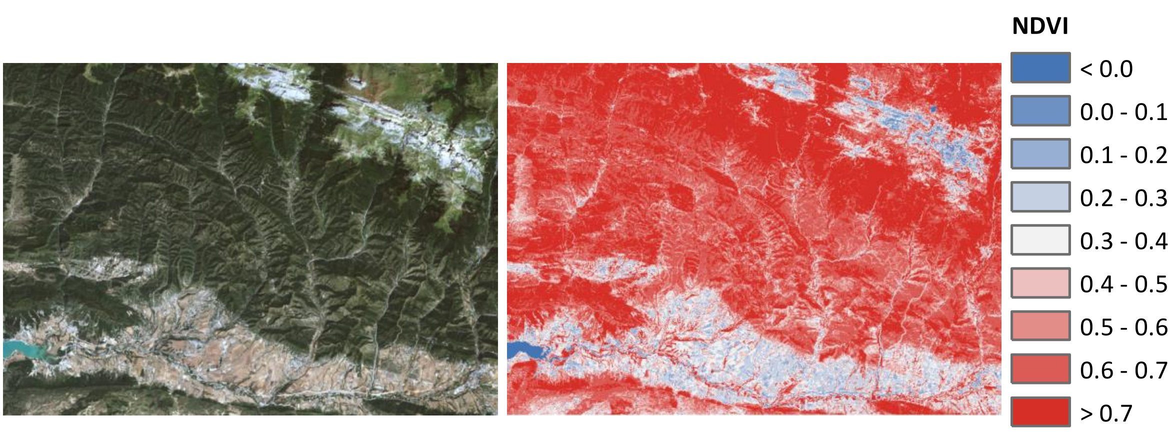


FIGURE 7. UPPER ARAGÒN BASIN IN 2013. LEFT, NATURAL COLOURS; RIGHT, NORMALIZED DIFFERENCE VEGETATION INDEX

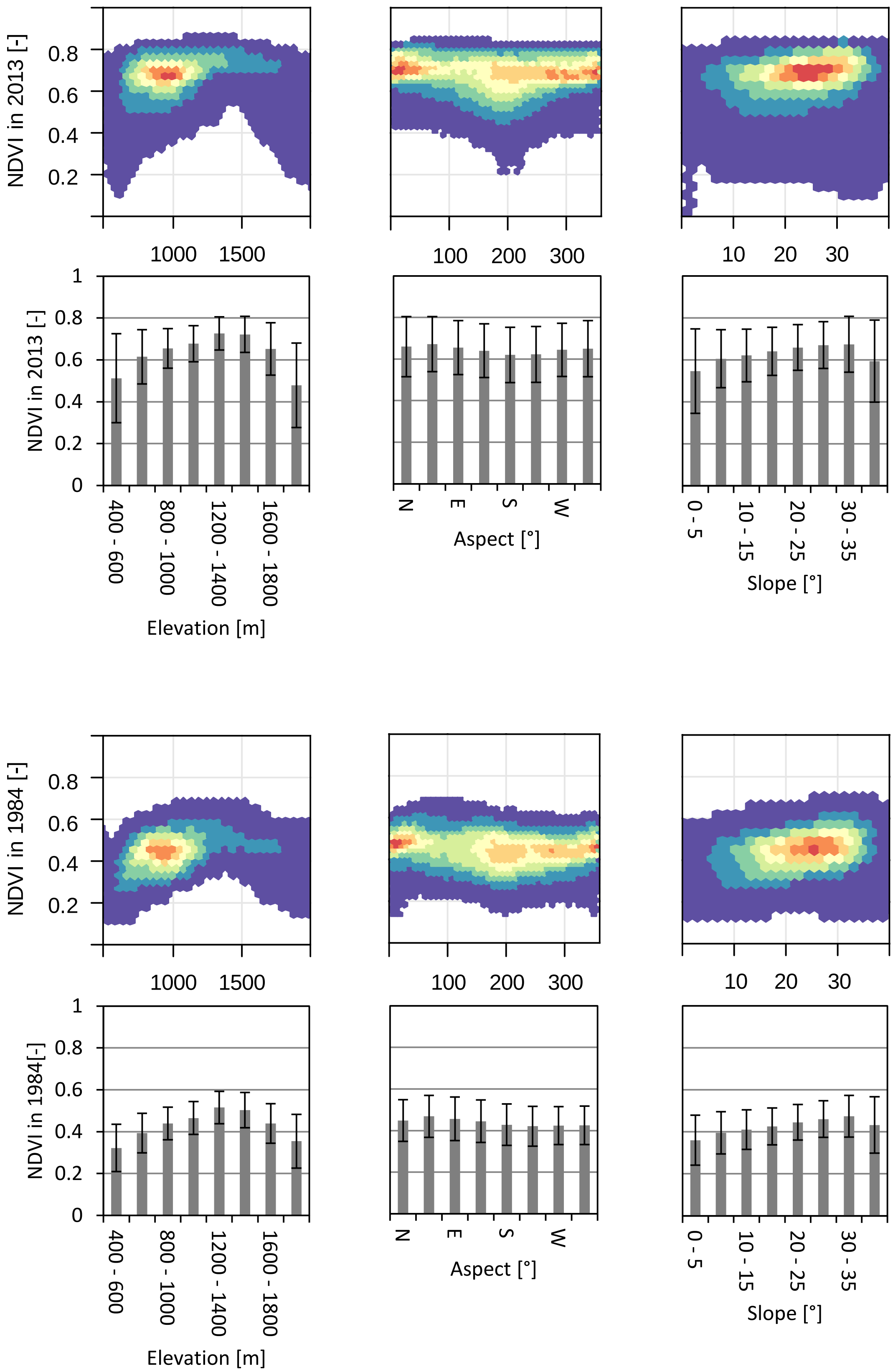


FIGURE 8. NDVI IN 2013 AND 1984 RELATED TO THE TOPOGRAPHICAL FACTORS. THE COLOURS IN THE CHART WITH THE HEXAGONAL LATTICE STRUCTURE REPRESENT THE NUMBER OF PIXELS (COUNTS) FALLING IN EACH HEXAGONIC REGION. NON NATURAL VEGETATED AREAS ARE EXCLUDED FROM THIS ANALYSIS USING THE CORINE LANDCOVER MAP OF 2006 (VERSION 16). THE MINIMUM AND MAXIMUM COUNTS IN THE HEXBINPLOTS ARE NOT THE SAME, THE ELVATION PLOTS RANGE FROM 200 TO 22000 COUNTS, THE ASPECT PLOTS RANGE FROM 200 TO 5000 COUNTS AND THE SLOPE PLOTS RANGE FROM 200 TO 24000 COUNTS.

5.2 Temporal changes of vegetation after abandonment of cultivated land

5.2.1 NDVI-LAI transformation

The NDVI was converted to a physical parameter LAI to assess changes in the vegetation of the Upper Aragón basin. The previous paragraph gave the average NDVI for a bare field in 1984 and 2013 and the maximum NDVI in 2013. In the conversion the average bare field value, 0.14, was assumed to correspond with a LAI of zero. The maximum NDVI was also determined in the previous paragraph, 0.83, which was assumed to correspond with the maximum LAI of 2.4 found in literature. NDVI was accordingly converted to LAI with the relation:

$$LAI_i = 2.4 * \frac{NDVI_i - 0.14}{0.83 - 0.14} \tag{12}$$

Were $NDVI_i$ [-] is the NDVI value at pixel i and LAI_i [-] is the resulting leaf area index value at pixel i. The results of the transformation for the years 1984, 2002 and 2013 can be seen in Figure 10.

5.2.2 Observed temporal changes of vegetation

A linear regression model of time versus LAI was used to assess the change of vegetation in the study area. The spatial pattern of this change can be visualized with a map of the regression slope and a map of the year the LAI becomes zero (Figure 11). The mean change of LAI per year in the study area is 0.017 (SD= 0.0088). Without the inclusion of non-natural areas as water bodies, urban areas and agricultural fields this change is 0.018 (SD= 0.0069). The lowest values of LAI change, close to zero or even negative, are located in the central depression around the agricultural areas, waterbodies, and in the high areas in the north eastern part of the study area. The highest values are more spread throughout the study area. However, some clusters of high values can be found around Yesa reservoir, around the areas with a high elevation and in and around the central depression. The second parameter to be looked at, is the year in which the LAI is zero. The standard deviation of this parameter is 30474 for the whole study area, and is 19500 when non-natural areas are excluded. The high value indicates a large spread in the data, making the mean value not representative for the data. The median LAI zero is 1926 for the whole study area and 1920 when only natural areas are considered. The lowest values can be found in the north eastern part of the study area next to the areas with a high elevation and at the location of Yesa reservoir. The highest values can be found in the central depression, other agricultural areas and in the part with the highest elevation of the study area.

Secondly the trend of LAI change over time (slope parameter) was assessed in relation to topographical factors. Several charts were made to assess the relation between the regression slope or the time at which the LAI was zero in relation with topographical factors: elevation, aspect and slope of the Upper Aragón basin (Figure 9). The change of LAI per year decreases with increasing elevation. The highest increase of LAI per year of 0.020 can be found at an elevation between 600 and 800 meters. The lowest change of LAI per year can be found in the areas with the highest elevation, which have had an increase in LAI of 0.011 per year. The regression slope was the lowest in areas with a south eastern aspect and highest in areas with a north western aspect, respectively differing from 0.017 to 0.021. The slope of the area seems to have a less profound effect on the LAI change per year. The highest change can be found in areas with a slope between 20 and 25 degrees, 0.018. However, the change of LAI per year is almost the same for all slope classes. The intercept of the linear regression was inversely related the same way as the regression slope. This makes sense, because for every fitted pixel in the research area, the x-values (years) are the same and are close together. So in general when the regression slope is high, the intercept value will be relatively low. And when the regression slope is low, the intercept value will be relatively high. The average year the LAI was zero was not assessed in relation to topographic factors since a large spread of the data makes the mean value less representative for the data.

R-squared was calculated to look at the percentage of variance explained by the simple linear regression model. The mean R-squared value for the linear regression in the whole area under study is 0.54. The R-squared when only non-natural areas are considered is 0.31, and 0.61 when only the naturally vegetated areas are considered. When also the high elevated areas are excluded from the naturally vegetated area, this value would be even higher. R-squared does not indicate if the selected regression model, in this case a linear model, is appropriate; for this also the residuals should be evaluated. This was done for several locations in the study area. A random residual pattern suggests that the linear model is appropriate, in the case of a non-random pattern a non-linear model might be a better fit. In Figure 12 the fit of the linear regression is assessed at several locations in the study area. Looking at the graphs the linear model seems to describe the LAI change over time reasonably, instead of point 3. This is also confirmed by the residual plot, it shows an inverted U-shaped non-random pattern. Point 4 and 5 seem to also have a moderate inverted U-shaped residual pattern.

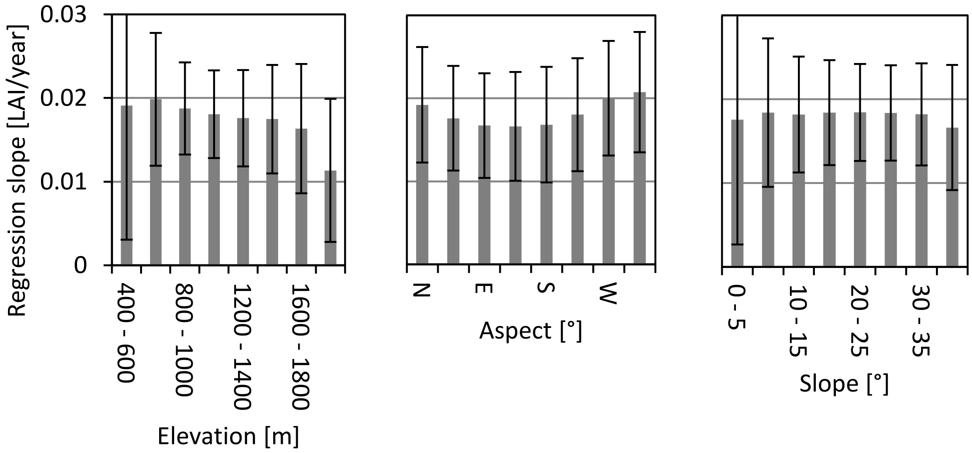


FIGURE 9. SLOPE OF LINEAR REGRESSION ANALYSIS, IN RELATION WITH TOPOGRAPHY. BARS DISPLAY THE AVERAGE SLOPE IN THE CATEGORY AND ERROR BARS GIVE THE STANDARD DEVIATION.

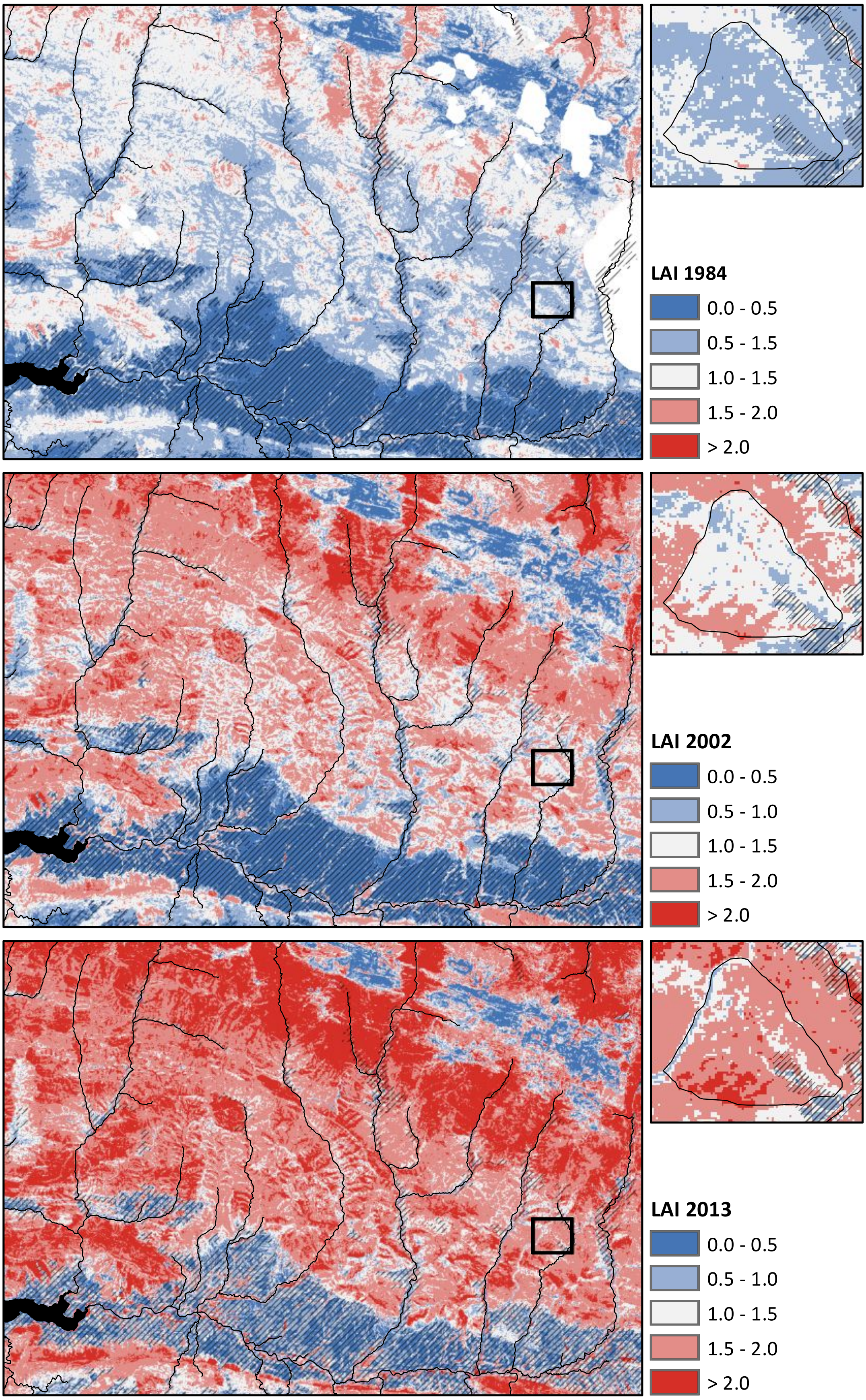


FIGURE 10. LAI IN THE YEARS 1984, 2002 AND 2013. THE NDVI FROM LANDSAT IMAGERY WAS CONVERTED TO LAI USING EQUATION (12.

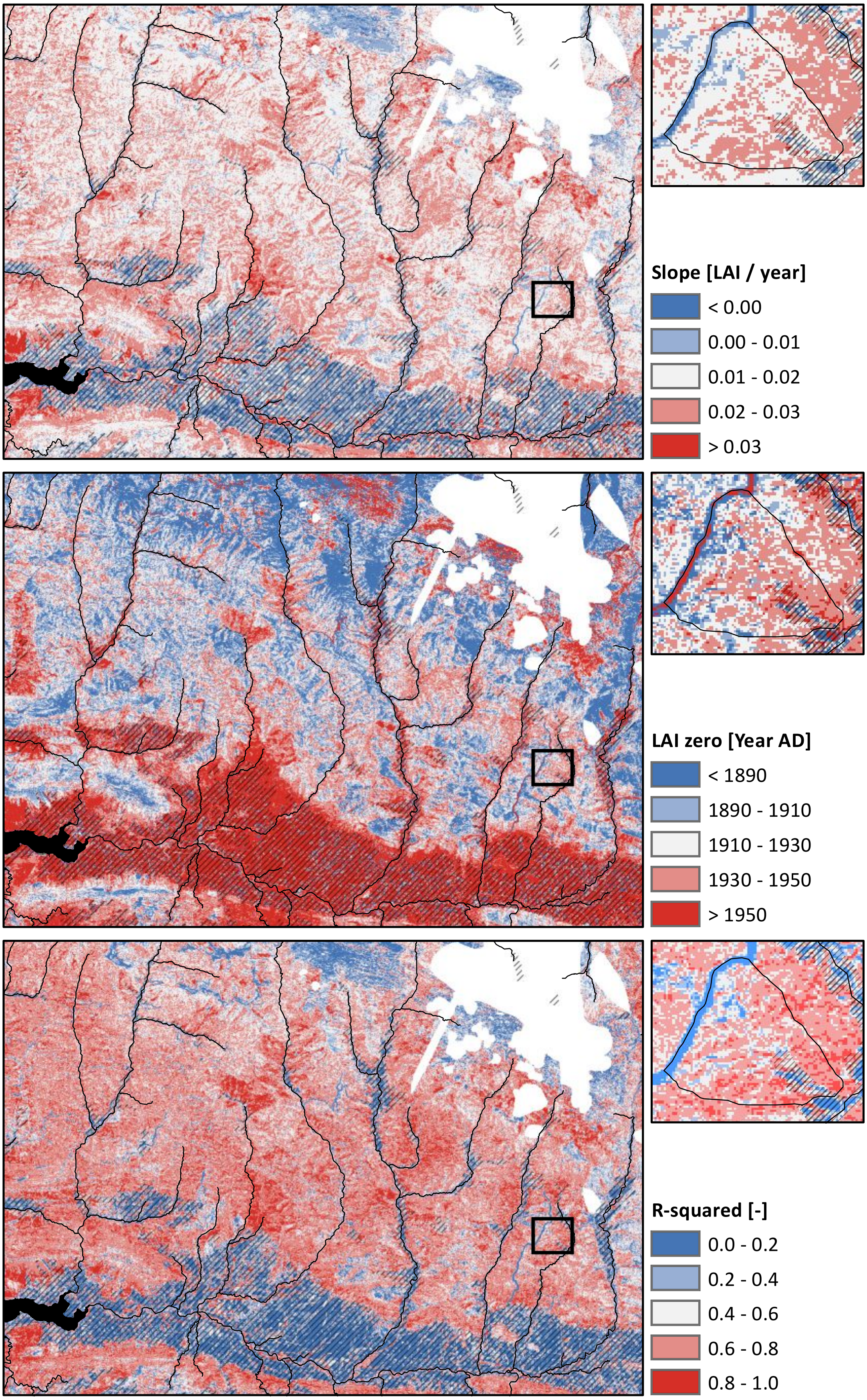


FIGURE 11. LEAST SQUARE LINEAR REGRESSION PARAMETERS. THE SLOPE OF THE REGRESSION, THE YEAR IN WHICH THE LAI BECOMES ZERO (CALCULATED WITH SLOPE AND INTERCEPT PARAMETER), AND THE R-SQUARED VALUE. WHITE AREAS ARE MISSING DATA, BECAUSE CLOUDS WERE PRESENT FOR MORE THAN ONE YEAR.

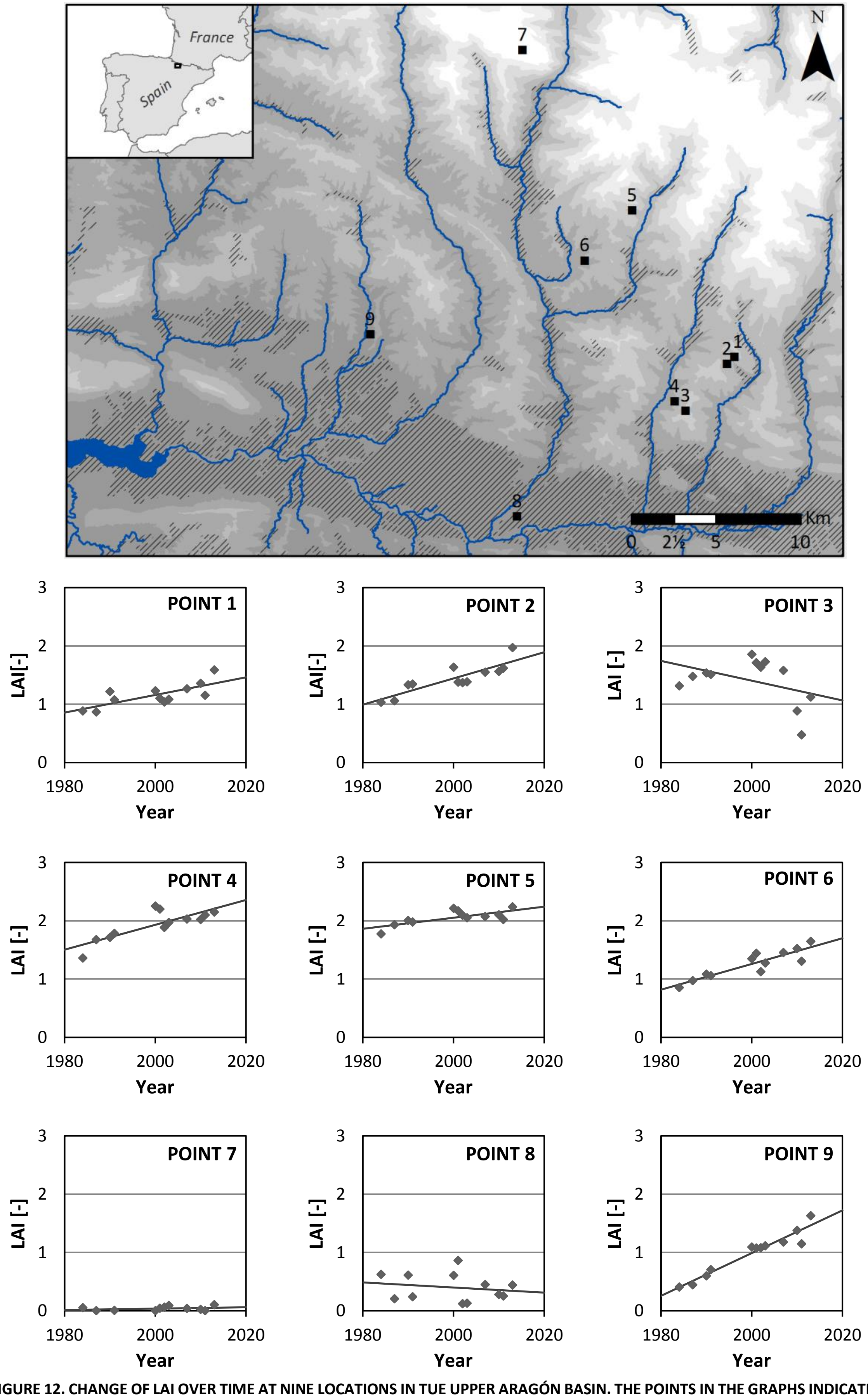


FIGURE 12. CHANGE OF LAI OVER TIME AT NINE LOCATIONS IN TUE UPPER ARAGÓN BASIN. THE POINTS IN THE GRAPHS INDICATE THE LAI VALUES OBTAINED FROM SATELLITE IMAGERY. THE LINE IN THE GRAPHS IS THE FITTED LINEAR REGRESSION MODEL.

5.3 Discharge changes as a consequence of secondary succession

5.3.1 Modelled discharge compared to measured discharge

The difference between the modelled and measured discharge in the hydrological year 2005-2006 was assessed in order to estimate the performance of the PyCatch model. The closer the modelled values are to the measured discharge values, the higher the model performance. Discharge values at the outlet of the Arnás catchment are compared to the modelled discharge annually, monthly and daily to study the differences on several temporal scales.

Figure 13A shows the measured daily discharge in the Arnás catchment compared to the modelled daily discharge. The general pattern of the discharge seems to be simulated relatively well. However, overall the model tends to underestimate the discharge values. The observed total discharge in the hydrological year 2005-2006 was 698812 m^3, while the modelled discharge in the same year was 608390 m^3. Especially the peak flows resulting from large rainfall events are underestimated, e.g. events at the 1st of December 2005, 1st January 2006, 19th February 2006 and the 11th March 2006. This becomes also visible in a scatterplot of the measured versus modelled discharge, Figure 14. Looking closely at the high discharge events reveals that overall the rising limb of the modelled graph seems to be less steep than the one of the measured graph.

The measured monthly discharge compared to the modelled monthly discharge can be seen in Figure 13B. The difference between the measured and modelled discharge is largest in the month December were the modelled discharge overestimates the actual monthly discharge by 58558 m^3 (68%). The absolute difference is the least in the month August, were the model underestimates the discharge with 2877 m^3 (80%). Overall the discharge is underestimated, except for the months November 2005, December 2005 and April 2006. Over the whole year the difference in discharge seems to be the largest in the winter months and smallest in summer. The absolute difference between modelled and measured values is 180950 m^3 in winter (October – March) and 94333 m^3 in summer (April – September). However relatively the difference in modelled and measured discharge is larger in summer (underestimation of 27%), compared to winter (underestimation of 8%).

The Nash-Sutcliffe model efficiency was calculated to assess the predictive power of the hydrological model (Nash and Sutcliffe 1970). The values can range between 1 and -∞, with 1 corresponding to a perfect fit of the model to the observed values and a value below zero indicating that the observed mean is a better predictor than the model itself. For the whole hydrological year 2005-2006, an efficiency of 0.15 was found for the hourly discharge, an efficiency of 0.34 for the total daily discharge and an efficiency of 0.79 for the total monthly discharge. The Nash-Sutcliffe efficiency for hourly and daily modelled discharge values is relatively low. According to Moriasi et al. (2007) a Nash-Sutcliffe efficiency value beneath 0.5 is considered unsatisfactory. Given the aim of this research, the unsatisfactory results of the hourly and daily values does not have to pose any problems. An efficiency value of 0.79 for the total monthly discharge values is considered very good (Moriasi et al. 2007) and is more important for assessing changes in discharge over a timescale of decades. Low values are partly caused by the large absolute difference between modelled and measured values during high discharge events, e.g. events at 1st of December 2005, 19 February 2006 and 11 March 2006. And also by the chosen interpolation method of measured discharge values when dealing with missing data.

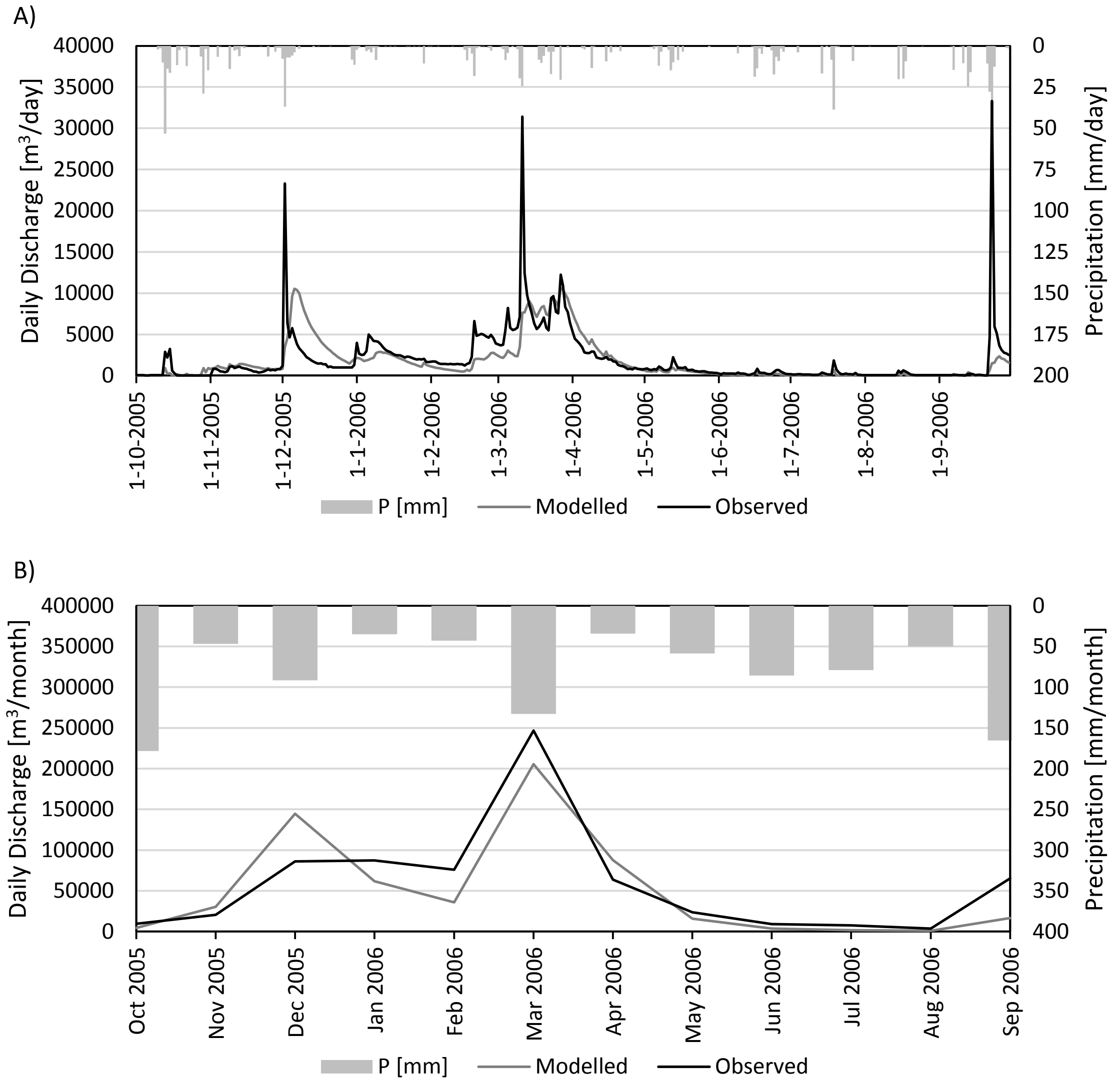


FIGURE 13. OBSERVED DISCHARGE IN THE ARNÁS CATCHMENT IN THE HYDROLOGICAL YEAR 2005-2006 COMPARED WITH THE MODELLED DISCHARGE. A) DAILY DISCHARGE. B) MONTHLY DISCHARGE

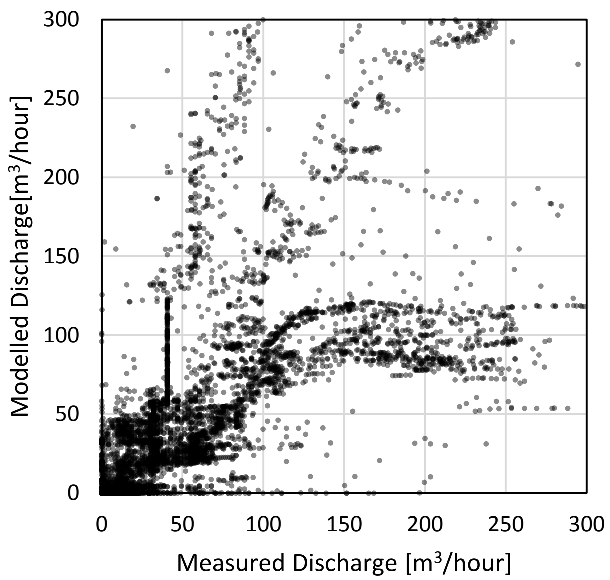


FIGURE 14. SCATTERPLOT OF THE MEASURED DISCHARGE AT THE OUTLET OF THE ARNÁS CATCHMENT VERSUS THE MODELLED DISCHARGE.

5.3.2 CHANGES IN DISCHARGE DUE TO SECONDARY SUCCESSION

The discharge of the Arnás catchment was modelled with the PyCatch model in order to estimate changes due to secondary succession. The modelled discharge for the hydrological years 1950-1951, 1980-1981, 2005-2006 and 2040-2041 is displayed in Figure 15. The annual change in discharge as well as the monthly change are discussed.

Figure 15a shows the annual discharge predicted with the PyCatch model at the outlet of the Arnás catchment. The total annual discharge went from 1794086 m^3 in the year 1950 to 241955 m^3 in 2040, a decrease of 1552131 m^3 (87%). Most of this decrease already happened from 1950 to 1980, a decrease of 41% in 30 years. The amount of change diminished after this period, over the period 1980-2005 and 2005-2040 the discharge respectively decreased by 452213 m^3 (43% over 25 years) and 366435 m^3 (60% over 35 years).

Figure 15b shows the monthly discharge at the outlet of the Arnás catchment. The discharge decreased in all months between the years 1950 to 2040. The decrease was the largest in September, with the river flow decreasing 236823 m^3 (99.0%) between 1950 and 2040. Also the months October and November had a large change of the total discharge, with respectively a decrease of 224427 m^3 (98.9%) and 220264 m^3 (99.4%) of the annual discharge between 1950 and 2040. Note that in terms of percentage November had the largest decrease of all the months. The lowest absolute decrease can be observed in the month June, 45628 m^3 (96%). In terms of percentage the lowest decrease was in the month April, with a 55.2% (75284 m^3) decrease between 1950 and 2040.

Figure 15c shows the absolute decrease in discharge between 1950 and 2040 per month. In December and from January to March, the discharge decreased the most between 2005 and 2040. From April to October the discharge decreased the most between the hydrological years 1950 and 1980. In only the month November the discharge decreased the most between the years 1980 and 2005. Especially the from October to December a remarkable shift in the timing of the highest decrease can be observed from early on in the succession to the later years of succession. Overall, in summer the discharge seems to have decreased the most in the early years of succession.

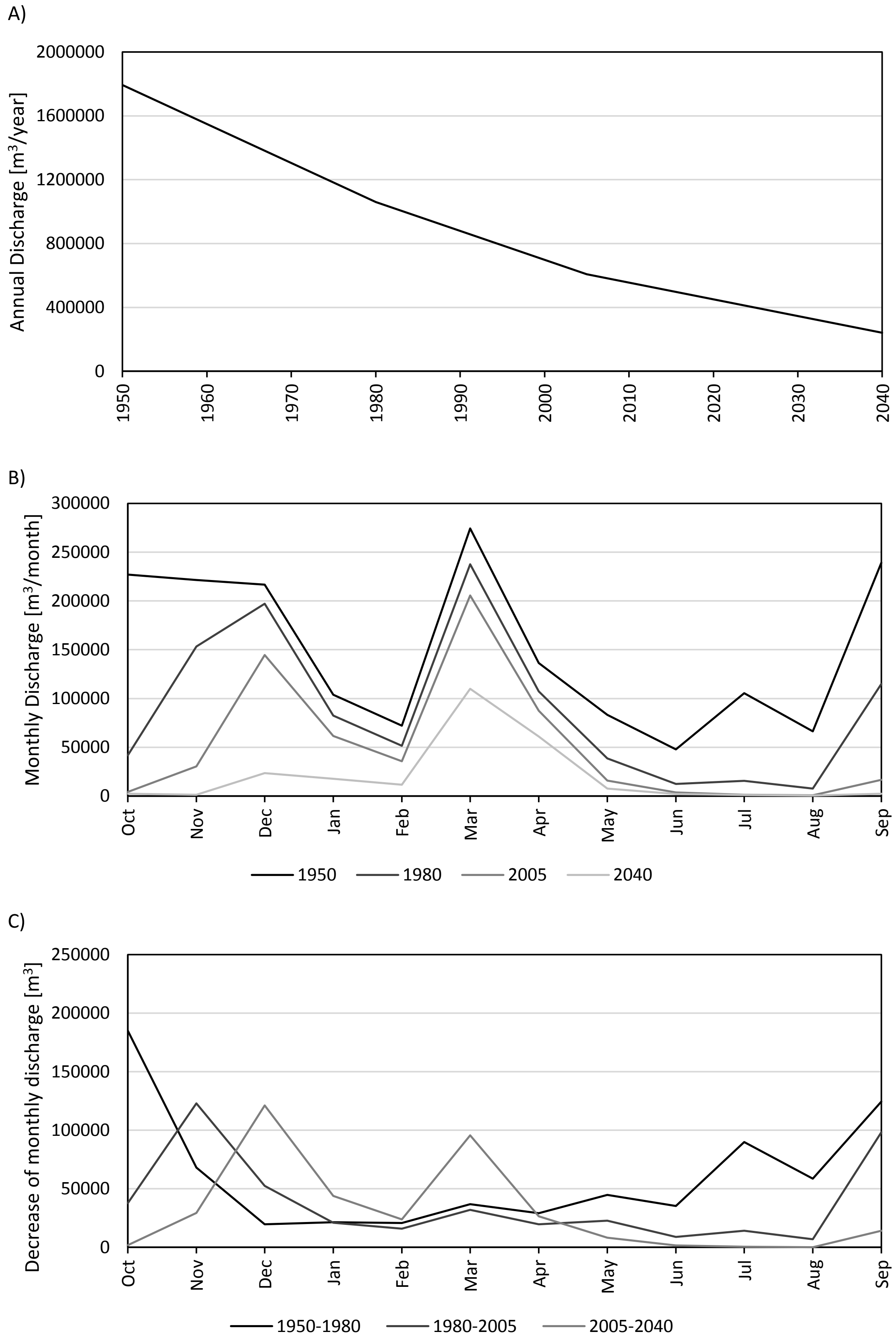


FIGURE 15. MODELLED DISCHARGE FOR THE HYDROLOGICAL YEARS 1950-1951, 1980-1981, 2005-2006 AND 2040-2041. A) ANNUAL DISCHARGE, B) TOTAL MONTHLY DISCHARGE, C) DECREASE OF MONTHLY DISCHARGE IN QUBIC METER BETWEEN THE MODELLED HYDROLOGICAL YEARS.

5.4 INFLUENCE OF CLIMATE ON DISCHARGE RELATIVE TO SECONDARY SUCCESSION

Figure 16 shows the discharge pattern of the 2040 climate change scenario (2040 CC) with the 2040 succession scenario and the 2005 scenario. The 2005 scenario had the same vegetation input as the 2040 CC scenario, but different temperature and precipitation input. The discharge diminished from 0.61 hm^3 $year^{-1}$ to 0.44 hm^3 $year^{-1}$ under the influence of climate change, a decrease of 28% in 35 years (0.17 hm^3). Under the influence of climate change, the largest decrease of discharge was in the month December with a decrease of 67541 m^3 (47%) between 2005 and 2040. In terms of percentage change, November experienced the largest decrease (73%, 22332 m^3). The smallest decrease, absolutely and in terms of percentage, of discharge was in the month August with a decrease of 69 m^3 (9%). Overall, the largest decrease in terms of volume was in winter, while the lowest decrease of discharge was experienced in summer. However, in terms of percentage the decrease was highest in autumn (70%) and lowest in spring (13%).

The annual discharge between the hydrological years 2005-2006 and 2040-2041 decreased twice as much for the succession scenario compared to the climate change scenario. The relative difference between the scenarios was largest in the months November to February, with a larger decrease of streamflow due to succession than due to climate change. Only August showed a higher decrease of discharge between 2005 and 2040 under the influence of climate change scenario, and was the month with the lowest relative change. Winter had the highest absolute and relative difference between the scenarios, with a 97969 m^3 (65%) lower decrease in the climate change scenario. The two scenarios had an almost similar response in summer, with the lowest absolute and relative difference between the two. The discharge was 982 m^3 (21%) higher in the climate change scenario compared to the succession scenario. It seems that, especially for periods of high discharge, the absolute discharge differs between the two scenarios. Relatively the highest difference corresponds to the months with the highest relative decrease in the succession scenario, with the exception of September. Overall the influence of climate change on the discharge between the hydrological years 2005-2006 and 2040-2041 is considerably less than the influence of succession.

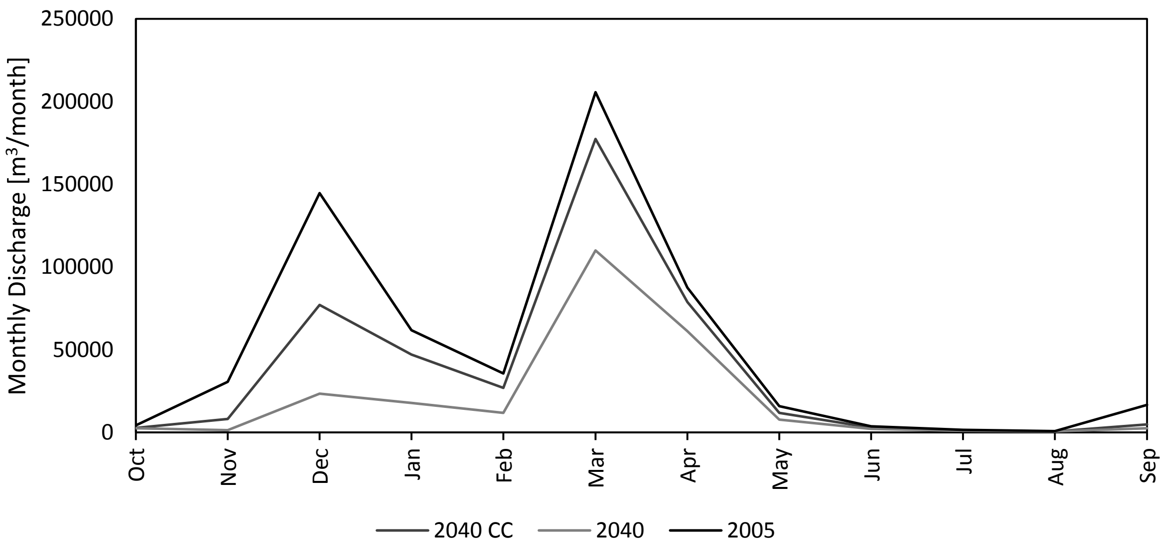


FIGURE 16. MODELLED MONTHLY DISCHARGE FOR 2005, 2040 WITH CHANGING VEGETATION PARAMETERS (2040) AND IN THE YEAR 2040 WITH CHANGING PRECIPITATION AND TEMPERATURE (2040 CC).

6 DISCUSSION

6.1 SPATIO-TEMPORAL CHANGE OF VEGETATION IN THE UPPER ARAGÓN BASIN

Twelve Landsat satellite images were downloaded and subsequently used to detect the change in vegetation between 1984 and 2013 in the Upper Aragón basin. A radiometric correction was performed and clouds removed in order to remove their interference with the data. No additional geometric or atmospheric correction steps were performed. The reflectance values were transformed to NDVI in order to assess the distribution of vegetation. An exploratory analysis of the spatial distribution of the natural vegetation cover in the Upper Aragón basin was performed. Subsequently the values were transformed into Leaf Area Index using a simple linear relation in order to quantitatively model spatio-temporal changes in vegetation with a pixel based linear regression model. The spatial pattern of this change was analysed by visual interpretation of the slope parameter of the regression analysis and a comparison of this parameter with topography.

This study has shown that the highest NDVI values were located in the northern part of the Upper Aragón basin and lowest values in the central depression. The low values are the result of dryness in the agricultural fields during the summer months (Lasanta and Vicente-Serrano 2012). Of the naturally vegetated areas, selected with the use of the Corine Land Cover map 2006 (European Environment Agency n.d.), the NDVI is highest in montane areas at an altitude in the range of 1200 to 1400 m, a north-eastern aspect and a slope between 30° and 35° degrees. Generally, for naturally vegetated areas, there is a positive relation between NDVI and slope, a positive relation between NDVI and elevation and a negative relation between NDVI and aspect in terms of the incoming solar radiation. These results are consistent with patterns found by Lasanta, Vicente-Serrano and Romo (2004) in the Upper Aragón. They found a significant positive correlation in the summer between NDVI and elevation, NDVI and slope and a significant negative correlation between incoming solar radiation and NDVI. They however also showed that this relation between NDVI and topography is not constant throughout the year, with even changes of the direction of the relations between topographic factors and NDVI happening throughout the year. In this study altitude seems to have the most pronounced effect on NDVI of the topographic variables.

The cause of the observed relation between topography and NDVI is likely to be mainly temperature and moisture related. Vegetation biomass generally increases with elevation, but decreases significantly after it reaches an altitude of 1600 meters because of unfavourable temperatures for growth. Del Barrio et al. (1990) indicated that 1600 m is the approximate altitude where temperatures are low enough for a stable snow cover to be present during most of the winter season explaining the change of NDVI found in this study. This change from an increase of NDVI with altitude to a decrease was also found by Lasanta et al. (2004). A higher NDVI in areas with a northern aspect can be related to moisture availability. Temperatures are lower on the shady northern hillside compared to areas with a southern aspect, causing more moisture to be available which benefits vegetation growth. However a part of the difference can also be caused by the historic agricultural practices of the area, as noted before by Améztegui et al. (2010). Most agriculture was found on hills with a southern orientation (Améztegui et al. 2010), continued agricultural practices negatively affect the status and fertility of the soil. This hampers succession after abandonment and therefor might still influence the recent vegetation distribution in the area. The high NDVI values for areas with a north-eastern aspect coincide with soils with a higher nutrient and water availability found by Navas et al. (2008) in the area. The more eroded and more stony soils that are present on southern slopes limit the development of vegetation. So the explanation of the current vegetation distribution seems to be a combination of natural factors (light, temperature, nutrient status of soil) and anthropogenic factors including afforestation, deforestation, grazing of animals and other factors caused by human influence.

After the analysis of the vegetation distribution, the NDVI was converted to LAI. With a linear regression model of time versus LAI, the amount of change was estimated. Almost all of the Upper Aragón basin had an increase of LAI, which is confirmed by several other studies (Lasanta and Vicente-Serrano 2007, 2012; Vicente-Serrano et al. 2004). The average increase of the LAI is 0.018 per year in the naturally vegetated areas of the study area. Spatially the increase was higher in areas around the central depression, just above the river valleys and some isolated high values close to the mountain peaks. In relation with topography high values were located in areas between the 600 and 800 meter a.s.l. and a north-western aspect. The slope of an area did not seem to have a clear relation with the change of LAI over the years.

Vicente-Serrano, Lasanta and Romo (2004) performed a similar analysis in the Upper Aragón basin. They found the highest vegetation changes in areas with elevations between 1000 and 1600 meter. The results of our study show also a decrease in the amount of vegetation change above 1600 meter, related to climatic constraints above this altitude on vegetation regrowth. However contrary to Vicente-Serrano, Lasanta and Romo (2004), the high values are mainly located below 1000 meter. This difference can be explained by the use of 1) an annual integrated series by Vicente-Serrano, Lasanta and Romo (2004), while this study made use of a summer series and 2) the use of the whole upper Aragón basin, while this study eliminated areas that were not naturally vegetated such as agricultural fields. Areas close to the central depression are more likely to experience changes in vegetation compared to areas higher and further from urbanization, which can explain the high values found in this study at low altitudes. However this does not mean that secondary succession occurred at these locations; these high values are more likely due to other causes. For instance, the area north of the Yesa reservoir has a high regression slope (>0.03), but also has a high LAI zero (>1950), the year A.D. that the Leaf area index is zero. This indicates a more recent change than secondary succession after land abandonment in the 1950s. This possible explanation is confirmed when looking at areal images of the area north of the Yesa reservoir where the regular vegetation patterns indicate artificial revegetation.

The high values found for vegetation change in areas with a NW aspect coincide with results found by Poyatos, Latron and Llorens (2003) in the Cal Rodo catchment against the Spanish Pyrenees east of our study area. Améztegui et al. (2010) also found a higher increase of vegetation on northern slopes compared to southern slopes. This difference can be due to higher moisture availability during summer months on the northern sides (Navas et al. 2008), but also by the previously noted more shallow and stony soils on the southern sides which hampers succession. On the other hand this difference can also arise due to artificial causes. Most of the agricultural practices were concentrated on the southern hillsides, which depleted soils and in turn hampers regrowth of vegetation (Améztegui et al. 2010). The lack of a clear relation between slope and vegetation changes coincides with findings in some other studies (e.g. Améztegui et al. 2010; Lasanta-Martínez et al. 2005).

Two types of increases are visible in the naturally vegetated area. There are 1) small patches of relatively strong and medium increases of vegetation and 2) a relatively low but overall increase of vegetation in the naturally vegetated area. The small patches of relatively strong and medium increases might be attributed to artificial causes and secondary succession after abandonment. The low increase might be the result of densification of the present vegetation due to climate change. Améztegui et al. (2010) studied the encroachment and densification of forest in the Catalan Pyrenees with the use of aerial photographs taken between 1956 and 2006. They found an increase of the surface coverage of pine and an densification of the cover. Just as this study they found that the spatial pattern of change matched the land-use changes in the Pyrenees.

6.2 Changes in river discharge as a consequence of succession

The change of discharge due to secondary succession was estimated with the use of a hydrologic model called PyCatch. The linear regression model of LAI versus time was used to estimate LAI and vegetation height in the Arnás catchment for the hydrological years 1950, 1980, 2005, 2040. This vegetation input was used to estimate changes in river discharge at the catchment outlet while keeping climatic input constant. The results of this study show that vegetation change in the Arnás catchment between 1984 and 2013 can considerably alter the streamflow at the outlet of the catchment. The decrease of discharge due to an increase in vegetation was 66% between the years 1950 and 2005. By the year 2040 the discharge of 1950 is expected to be reduced with 87%. The decrease of discharge was highest in summer and autumn, with the maximum decrease as high as 99% between the years 1950 and 2005. The decrease of river discharge due to vegetation change is expected to be wide spread throughout the Upper Aragón basin and possibly the rest of the Spanish Pyrenees, based on the changes in vegetation found in this study. Caution should be used with the interpretation of the changes of discharge caused by secondary succession. The remote sensing study cannot explicitly differentiate between changes due to succession or climate, because climate change can also indirectly result in changes of the vegetation in an area.

The modelled change of river discharge due to succession is caused by changes of vegetation LAI and height which influence the interception and evapotranspiration components of the PyCatch model. An increase of LAI causes the maximum interception storage in the canopy to increase, limiting the amount of precipitation that directly reaches the surface. An increase of LAI causes the surface resistance to decrease and thereby increasing canopy transpiration and decreasing the amount of evaporation from the soil surface because of the shielding effect the vegetation has but in a lesser amount (Zhang and Walsh 2007). An increase of vegetation height causes the aerodynamic resistance to decrease, because the roughness length increases with an increase of vegetation height. If the surface resistance is low, a decrease of the aerodynamic resistance leads to an increase of evapotranspiration. But when the surface resistance is high, a decrease of aerodynamic resistance leads to a decrease of evapotranspiration (Moene and van Dam 2014).

The decrease of discharge can be compared to actual measurements of annual average discharge values in the Upper Aragón basin given in theoretical background in section 3.5.3.. The discharge at the stations of the Esca at Sigüés, the Veral river at Biniés and the Aragón river at Jaca show a decrease of approximately 40% between the years 1950 and 2005. Although the homogeneity of the series cannot be guaranteed, the modelled decrease of discharge in this study clearly overestimates the actual decrease. Beguería et al. (2003) also found a lower decrease of discharge. They estimated that streamflow was reduced 30% between 1945 and 1995 due to changes in land-use. The relatively high decrease, as found by this study compared to others, can be caused by differences in catchment characteristics between the modelled Arnás catchment and the catchments of Esca-Sigüés, Veral-Biniés and Aragón-Jaca. The Arnás catchment consists for a large part of abandoned cultivated areas, where vegetation changes are suspected to be relatively large. The other catchments of Esca-Sigüés, Veral-Biniés and Aragón-Jaca, all contain high areas with sparse vegetation and areas which are currently still cultivated where vegetation cover did not change considerably over time. Other explanations of the difference between the modelled decrease of discharge in this study and other studies can be due to assumptions or errors which are made in the model or the parameters. Or it can indicate other factors which counteract a decrease of discharge that are not incorporated in the model.

From 1950 to 2040, the absolute and in terms of percentage largest discharge change occurred in autumn. The high changes in autumn can be attributed to the depletion of the water reserves during summer and the difference in reaction between a cultivated and forested catchment. In the case of a forested catchment, after summer the interception storage is running low, the soil water content is low and the water consumption by vegetation is high. The rainfall events in autumn mostly fill up the empty storages, a considerable part of the rainfall gets intercepted by the forest and the still relatively high temperatures in autumn cause water to be lost into the atmosphere by evapotranspiration. Storages are quicker replenished after a dry period when a large part of the catchment is cultivated, causing saturated overflow to happen more easily and streamflow to be higher. This can also explain why, with continued vegetation growth, the month of highest discharge change shifted from October between the hydrological years 1950 and 1980, to November between 1980 and 2005, and finally to December between 2005 and 2040. The difference is especially remarkable due to the relatively large amount of precipitation in early autumn. These findings correspond with what was found by Serrano-Muela et al. (2008) who compared the discharge pattern from the forested San Salvador catchment with the formerly cultivated Arnás catchment. The absolute change of discharge in our study was smallest in winter, which can be attributed to low temperatures in this season and relatively full storages after the high amount of rainfall in autumn. Low incoming shortwave radiation, makes it that not much energy is available for evapotranspiration, causing minimal changes between a cultivated and forested catchment. In spring the discharge experienced absolutely a moderate decrease, but in terms of percentage the lowest decrease especially the months March and April. March and April are also the months with the highest discharge left by the year 2040. This can probably be attributed to full storages, which causes a forested catchment to behave more similar to a cultivated catchment. This observation again corresponds with the findings of Serrano-Muela et al. (2008). The absolute decrease of discharge from 1950 to 2040 was low, but is still relatively high in terms of percentage decrease. Absolute discharge is low in summer because of depleted storages, high temperatures and low precipitation. Percentage wise the decrease in summer is large because the rain that falls is easily intercepted by the vegetation and evaporated back into the atmosphere.

Changes in the inflow of Yesa reservoir have affected the water storage regime (López-Moreno et al. 2004), changes had to be made to ensure a sufficient storage in the summer season when water is used for irrigation. The most important seasons for filling the reservoir are now Autumn and Spring (López-Moreno et al. 2004). Since the highest decrease of discharge occurred in autumn, changes in vegetation will affect storage. Although the discharge did not change much in spring, also this decrease might affect storage of water. The reservoir is filled to its maximum as late as possible before the dry summer, because a safety margin needs to be kept against floods (López-Moreno et al. 2004). A decrease of discharge in autumn and spring might make it necessary to revise the management plan of the reservoir by keeping more water retained earlier in the year.

A drawback of this study is that the effect of the total vegetation change is modelled and no distinction was made between secondary succession after abandonment and other changes, e.g. artificial reforestation, gradual changes due to climate. An attempt at locating the formerly cultivated fields can be done with the regression parameters and by making several assumptions. The regression slope will most likely be moderate, low slopes indicate no change at all and high slopes often indicate a more recent or artificial change. The LAI zero of the formerly cultivated fields will be 1950 or somewhat earlier, because the linear model most likely underestimates the actual year. Another factor which can be taken into account is the r-squared value. A visual analysis of high r-squared values reveals that these are often located in areas where something was artificially altered, a road which was built or an area which was reforested. Succession is a gradual process which is not expected to have severe outliers. Assessment of the areas with a moderate regression slope, an LAI zero between 1930 and 1950 and an r-squared larger than 0.3, revealed no clear pattern in the upper Aragón basin other than a concentration of possible abandoned areas between the 700 and 1400 meter. It is hard to determine the former agricultural fields with this method because of several reasons. Not all the fields are abandoned at the same time and the speed with which the secondary succession takes place is not equal for all the fields. Areas which were abandoned after 1950 and areas which are suffering from erosion after abandonment might not be marked as abandoned field locations.

6.3 Effect of climate change on streamflow compared to secondary succession

The influence of climate change on the streamflow was compared to the effect of succession, to assess their relative influence. This was done with the use of a scenario where the temperature and precipitation input was changed, but the vegetation input was kept the same. From the results of this study it can be concluded that the effect of climate change on river discharge is less than that of secondary succession on river discharge. An increase of temperature, especially in the summer months, together with a decrease of precipitation caused the streamflow to diminish with 28% between the years 2005 and 2040 instead of the 60% decrease in the succession scenario. The absolute difference between the two scenarios was highest in the months which had a relatively high river discharge (December and March) and lowest in the summer season.

Changes in climate influence the river discharge in several ways. A rise in temperature significantly increases potential evapotranspiration. Higher temperatures cause the saturated vapour pressure to increase and thereby may increase the vapour pressure deficit. This leads to an increase in evapotranspiration, which causes less runoff. A decrease of precipitation leads to a decrease of river discharge since less water reaches the surface and maximum storage capacity is less easily reached. Since the rainfall intensity decreases, less runoff is produced as infiltration-excess overland flow. A decrease of rainfall volume causes maximum storages to be less easily reached, and thereby also produces less runoff in the form of saturation-excess overland flow. However, the real life situation might be somewhat more complicated than that, because more factors than precipitation and temperature alone influence the potential evapotranspiration.

The relatively higher importance of land use changes compared to climate on runoff was also confirmed by López-Moreno et al. (2014). However, Buendia et al. (2015) found the opposite to be true. They studied trends in runoff due to climate and afforestation in the Pyrenees, 150 kilometres east of the study area used in this thesis. They found that approximately up to 40% of the decrease in runoff could be attributed to land use changes, but most of the change could be attributed to climate change. This difference is most likely the result of differences that exist between our study area and theirs. The study area used by Buendia et al. (2015) consist for approximately 50% of natural grasslands and contains high altitudes, with snow accumulation influencing streamflow. Also the vegetation changes are different from the changes found in our study area. This indicates that the relative influence of succession and climate change on streamflow can differ locally. As also stated by Buendia et al. (2015), climate change nor changes in vegetation should be neglected since it could lead to an underestimation of streamflow changes. There are two other reasons why both should always be kept in mind when studying their individual effect on streamflow. First, a relation between vegetation changes and climate change might exist. An increase in temperature, especially in a dry summer season, combined with a decrease in precipitation hampers vegetation growth and therefor succession. Secondly, the relative effect of secondary succession and climate change on streamflow is expected to change in the future. Land-use changes are expected to decrease, because succession eventually reaches an equilibrium, while climate change is expected to increase in the second half of the 21st century (Ribalaygua et al. 2013).

In the climate scenario used in this study only the amount of precipitation is changed, not the timing and duration of the precipitation events. Also snow accumulation and melt is not taken into account. This makes it hard to use the results of this study on the total Upper Aragón basin, especially in terms of changes in the seasonal discharge pattern. The results of this study do not show a shift of high flows, the month with annually the highest flow remains March with the climate change scenario used in this study. A shift would be expected for locations where snow accumulates. The rise of temperature causes the zero degrees isotherm to shift to higher locations, which results in a shift of high flows to earlier in the year.

6.4 Limitations of the research methods

6.4.1 Limitations of the satellite remote sensing

The used methods in this study have proven to give a useful insight into secondary succession and its influence on the hydrology of an area. However, the used methods are not without their limitations, which should be taken into account. The remote sensing part of the study gives an impression of the temporal and spatial change of vegetation in the Upper Aragón basin. However, it has its limitations, uncertainties and assumptions which should be discussed in order to highlight their impact on the results.

Some limitations come from the use of Landsat satellite data. The first image of the study area is from 1984, while several studies noted that the abandonment and following succession already started somewhere around de 1950s (e.g. Pueyo and Beguería 2007). There is also a gap of 9 years in the data between 1991 and 2000, which is relatively large for a database which in total compasses a period of 29 years. These limitations make it difficult to determine which type of model should be used for describing the vegetation change over time. In the relatively small timeframe the relation between LAI over time seems to be linear, but the actual shape is expected to be different. As noted in the method section, the change of LAI is expected to be high in early stages of succession and is expected to diminish over time, eventually reaching an equilibrium. The use of a nonlinear model with an upper horizontal asymptote might describe the real world process better. While the linear model and its parameters are easier to interpret and requires less calculation time, its use for studying succession has its limitations. Extrapolation of the data becomes especially prone to errors. The calculated year in which the LAI becomes zero is likely to be underestimated and the LAI after 2013 overestimated.

A second drawback of the use of Landsat satellite data is that the collected satellite images are not all from the same satellite and sensor. Differences in platforms and sensors might have caused artificial differences in the NDVI. A total of four different satellites (Landsat 4, Landsat 5, Landsat 7 and Landsat 8) were used and three different sensors (TM, ETM+ and OLI). Seven of the twelve images were obtained with the TM sensor aboard the Landsat 5 satellite, three images were obtained with the Landsat 7 and its ETM+ sensor, one image with the TM sensor aboard Landsat 4 and one image with the OLI sensor of Landsat 8. One of the differences between these sensors are the band designations. Difference in the band designations of the red band and the near infrared band, can result in differences in the NDVI. Especially the near infrared band of the OLI sensor differs from the near infrared band of the rest of the sensors. Other studies have shown that there is a high correlation between the NDVI of the TM, ETM+ and OLI sensor (Li, Jiang, and Feng 2013). There might be a slight difference between the three sensors, but they are comparable. Inter-calibration might improve results, but this should be checked.

The satellite images used are all taken around the same period in the year, between 20th of July and the 20th of august. This has the benefit that seasonal changes are mostly omitted from the analysis. However, one month difference in the acquired date or a change in the seasonal pattern throughout the measurement period might still effect the results of this study. However the extra data outweighs a smaller time span.

An uncertainty arises form the amount of change in vegetation, which seems to be quite large and widespread from 1984 to 2013. Especially the described overall increase of NDVI in the area raises questions if there are not any other artificial factors influencing the change of NDVI over time. Despite the manual check, an atmospheric correction might improve the results of the amount of change. A further analysis of the effects and differences of this extra step is necessary because it also might cause the data to be less consistent.

The relation between NDVI and LAI is kept constant throughout the years, and between vegetation species. While this might not be valid, it seems acceptable as an approximation. However, this study could benefit from field data, to test the established relationship and assess if it is the previously mentioned assumptions are valid for this study. Also field measurements of LAI might give a more accurate relation between NDVI and LAI, because a maximum of 2.4 might be somewhat low but was chosen because it was the only measured LAI value around the study area.

6.4.2 Limitations of the hydrological modelling

Besides limitations in the remote sensing part, there are also some limitations to the modelling part. These limitations arise from: model simplifications to cover for lack of data, simplifications made because of a lack of understanding of the real world system and parameter uncertainties.

Not all the vegetation variables were modelled. Albedo and stomatal conductance were kept constant, while these actually change with ongoing succession. The albedo will increase in the early stages of succession, when the dark bare soil becomes covered with the first pioneer vegetation. However, after some time the albedo decreases in most cases, because the more complex structure of the vegetation traps radiation instead of reflecting it; especially when succession eventually leads to a coniferous forest as is the case in the Upper Aragón basin. Another vegetation parameter which was kept constant is the maximum stomatal conductance, which is a measure of the water exchange between plant and atmosphere. Maximum stomatal conductance can vary significantly between species, but overall woody species have a lower value compared to herbaceous species (Breuer et al. 2003). This would mean that during succession a decrease of maximum stomatal conductance could be expected. A lower stomatal conductance generally decreases transpiration, which counteracts water losses to the atmosphere. But since the stomatal conductance value varies greatly, not only between species but also during the day, a constant value might not be a bad approximation (Breuer et al. 2003).

Soil parameters were also kept constant in the hydrological model. Soil and plant can act as a feedback mechanism making their interaction complex. Continued succession generally increases the quality of the soil. Soil thickness, maximum infiltration capacity and organic matter content increase (Lesschen et al. 2008). However, when the area is topographically unfavourable, e.g. sunny steep slopes, erosion may cause impoverishment of the soil. This can subsequently limit the regrowth of vegetation. Lesschen et al. (2008) found that recovery of soil properties can happen, but is slow. However a relatively low cover of vegetation, may already significantly reduce soil erosion and enhance further regrowth.

Snow was not incorporated in the model, while some of the precipitation has likely fallen as snow. The average daily temperature was below zero for 40 days over the period of 1 October 2005 till 30 September 2006. Precipitation fell in twelve of those days, but the snowpack is not likely to have stayed long. Temperatures reach below zero during the night, but rise above zero during the day. Precipitation that falls in the form of rainfall during the day also speeds up the melting. Incorporation of a snow module in the PyCatch model is therefore not necessary for the Arnás catchment. However, it plays a role in the distribution of streamflow over the year when the whole Upper Aragón basin is concerned. The pack may be influenced by the shielding effect trees have on incoming solar radiation, but this is likely to have little effect on the stream flow compared to other factors.

An assumption of the modelling section was that all the vegetation changes observed with the satellite images in the Arnás catchment were the consequence of secondary succession. These changes are however also partly caused by other factors as changes in climate, reforestation or other land management. This may affect the discharge negatively or positively, but as mentioned before, it is very difficult to distinguish between causes of change.

6.5 Recommendations for future research

Based on the limitations of this study presented in the previous paragraph and the results from this study, several recommendations for future research can be made. First of all, this research could benefit from ground truth, field data. It helps in getting more accurate predictions of LAI and in assessing the validity of the assumptions made. It can also help in distinguishing between various causes of vegetation change, e.g. for the identification of artificially revegetated areas. The use of for example aerial imagery with a higher spatial resolution, can also make identification of the cause of changes easier. However, no matter the cause, vegetation changes significantly influence hydrology.

Since the Landsat satellite imagery does not go back to the early stages of succession in this area, it might be interesting to study it in another area where abandonment is more recent. This can help getting a better idea of the actual shape of the curve of LAI versus time after a field was abandoned. It would also give a better impression of the use remote sensing for studying succession.

The combination of remote sensing and modelling seems a promising method to get a spatial and temporal idea of vegetation changes and its effect on hydrology. However, the effect of vegetation, soil and climate cannot be treated separately when looking at water availability. While the actual changes in discharge due to succession are overestimated, this study still gives an impression of the influence of vegetation changes on streamflow in a small catchment.

7 CONCLUSION

Revegetation after land abandonment is a common phenomenon in the Upper Aragón basin. Due to influences on the hydrologic cycle, it may cause streamflow to diminish. The current vegetation pattern in the Upper Aragón basin is the result of a combination of natural and anthropogenic factors. The central depression of the basin is marked with cultivated areas, but vegetation becomes increasingly dense up to an altitude of 1600 meters and in areas which have a shady aspect and a relatively steep slope.

An increase of vegetation cover could be observed between 1984 and 2013 in the Upper Aragón basin with Landsat satellite imagery. The leaf area index increased with an average of 0.018 per year in the naturally vegetated areas. The change was not limited to the formerly abandoned fields, as it was widespread throughout the whole basin. A densification of the existing vegetation and artificial changes as afforestation also affected the area. The highest change of vegetation was experienced in shady areas with a low elevation. Satellite imagery provides a useful tool to look at vegetation changes and the spatial pattern of them, especially when documentation of it is sparse. However the quantification of the changes is difficult, field research is recommended to improve the quantification of vegetation changes. It is also difficult to distinguish between various causes of vegetation changes. However, artificial changes are also likely to impact the hydrology of the area.

The effect of the vegetation changes on streamflow was tested in a small catchment inside the Upper Aragón basin, which is known to have experienced land abandonment. An increase of the leaf area and vegetation height after the agricultural abandonment around the 1950s, caused the streamflow to decrease with 66% between the years 1950 and 2005. Important factors causing this decrease are: an increase of interception, an increase of evapotranspiration and consequently a progressively delayed fill of groundwater storage. The highest changes are found in autumn, caused by a progressively delayed fill of the groundwater storage when vegetation increases. The negative trend in streamflow due to succession continues in the future, with only 13% of the 1950 annual discharge remaining by 2040. The amount of change by succession is overestimated when larger catchments are assessed, with high elevated areas, that experienced vegetation change to a lesser degree.

The effect of secondary succession on streamflow is higher than that of climate change. The projected decrease due to climate change between the years 2005 and 2040 was only half (0.20 hm^3, 54% less) of the streamflow decrease that might happen due to succession. However, the effect of climate change on streamflow should not be entirely disregarded, the relative importance of climate change and succession varies locally and might change in the future.

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APPENDICES

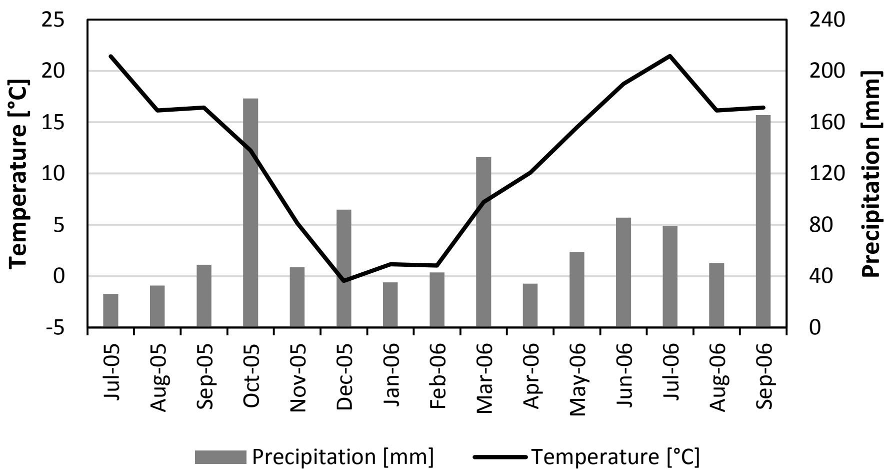
APPENDIX A: LANDSAT CALIBRATION COEFFICIENTS

Summary of the radiometric calibration coefficients for Landsat TM and ETM+ sensors. The numbers in grey are revised post-calibration dynamic ranges. The ranges were revised (grey values) for: L4 TM band 1 for data acquired between July 16, 1982 and August 23, 1986; And for L5 TM band 1 and 2 between March 1, 1984 (launch) and December 31, 1991. The ETM+ images are acquired with a low or high gain, depending on a pre-categorized surface type. Table is adopted from Chander et al. (2009).

Landsat sensor				
Band	Spectral Range	LMINλ	LMAXλ	ESUNλ
	μm	W/(m² sr μm)		W/(m² μm)
L4 TM				
1	0.452-0.518	-1.52	163	1983
		-1.52	171	
2	0.529-0.609	-2.84	336	1795
3	0.624-0.693	-1.17	254	1539
4	0.776-0.905	-1.51	221	1028
5	1.568-1.784	-0.37	31.4	219.8
7	2.097-2.347	-0.15	16.6	83.49
L5 TM				
1	0.452-0.518	-1.52	169	1983
		-1.52	193	
2	0.528-0.609	-2.84	333	1796
		-2.84	365	
3	0.626-0.693	-1.17	264	1536
4	0.776-0.904	-1.51	221	1031
5	1.567-1.784	-0.37	30.2	220
7	2.097-2.349	-0.15	16.5	83.44
L7 ETM+ Low Gain				
1	0.452–0.514	−6.2	293.7	1997
2	0.519–0.601	−6.4	300.9	1812
3	0.631–0.692	−5.0	234.4	1533
4	0.772–0.898	−5.1	241.1	1039
5	1.547–1.748	−1.0	47.57	230.8
7	2.065–2.346	−0.35	16.54	84.9
L7 ETM+ High Gain				
1	0.452–0.514	−6.2	191.6	1997
2	0.519–0.601	−6.4	196.5	1812
3	0.631–0.692	−5.0	152.9	1533
4	0.772–0.898	−5.1	157.4	1039
5	1.547–1.748	−1.0	31.06	230.8
7	2.065–2.346	−0.35	10.8	84.9

APPENDIX B: METEOROLOGICAL MODEL INPUT

Average monthly temperature and total precipitation in the Arnás catchment from July 2005 till September 2006. The data was used as an input in the PyCatch model.



APPENDIX C: DIGITAL APPENDIX

A digital appendix is available on request. It contains the items depicted in the following table:

Map	Filename	Description
1_Satellite imagery		
	LXSPPPRRRYYYYDDDGSIVV.tar.gz	12 Landsat images. Naming convention: L = Landsat X = Sensor S = Satellite PPP = WRS path RRR = WRS row YYYY = Year DDD = Julian day of year GSI = Ground station identifier VV = Archive version number
2_ArcGIS		
	LAI.mpk	Map package containing LAI maps obtained from the Landsat satellite imagery as described in the method section. Maps were used to perform the pixel based linear regression analysis. Map package files can be opened with ArcMap.
	Linear regression parameters.mpk	Map package containing linear regression parameters obtained from the LAI maps. Contains the data that can be seen in figure 11: a map of the regression slope, LAI zero and the r-squared in the Upper Aragón basin. Map package files can be opened with ArcMap.
	Upper Aragon.mpk	Map package containing a Digital elevation model of the Upper Aragón basin and the areas that are not naturally vegetated. Map package files can be opened with ArcMap.
3_Modelling data		
	LAI.txt	Text file containing script used for calculation of the LAI and vegetation height input parameters to use in the PyCatch model.
	regesInter.map	Contains a map of the regression intercept for the Arnás catchment, resampled to a 10 x 10 m pixel size.
	regesSlope.map	Contains a map of the regression slope for the Arnás catchment, resampled to a 10 x 10 m pixel size.