Iñaki Antiguedad editorearen argazkia

Ur-baliabideen kudeaketa: iturburuetako landarediak baldintzatzen du akuiferoen birkargatze-maila

Klima-larrialdiaren testuinguruan, datozen hamarkadetan lehentasunezkoa izango da lurpeko akuiferoen ur-erreserbak ondo kudeatzea. Azken ikerketek erakutsi dute akuiferoen inguruan dauden iturburuetako landarediak akuiferoen birkarga baldintzatu dezakeela: abeltzaintza-larreek eta baso helduek, ur gutxi kontsumitzen dutenez, akuiferoen birkarga errazten dute; baso-landaketa berriek, ordea, ur-kontsumo handia dutenez, eragotzi. Baso-kudeaketan paradigma-aldaketa ekar dezake honek.

Klima-aldaketaren proiekzioek aurreikusten dute iberiar penintsulan asko murriztuko dela ibaietako ur-emaria udan, lehorte gogorrek eta goi-mendietako elurra goizegi urtzeak eraginda. % 10-30 bitartean murriztuko dira ur-baliabideak mendearen erdialderako. Ondorioz, estrategikoa izango da lurpeko akuiferoak ahal den guztia birkargatzeko neurriak hartzea.

Ikertzaileek ikusi dute sistema hidrologikoak eta lurzorua estaltzen duen landaredia zuzenean lotuta daudela: deforestazioak eta baso-berritzeek inpaktu zuzena dute lurpeko akuiferoen birkarga-prozesuan. Larreak eta 100 urtetik gorako baso helduak dituzten iturburuek errazago birkargatzen dituzte akuiferoak, zuhaitz gazteez estalita daudenen aldean.

«Baso-masa handitze hutsak akuiferoen birkarga zaildu dezake, eta abeltzaintza larreek, aldiz, lagundu»

Izan ere, zuhaitzek, ebapotranspirazio-prozesuan, lurzoruko ura jasotzen dute sustraietatik eta ur-lurrun moduan askatzen dute, hostoetatik. Prozesu horrek lurzoruko hezetasuna kentzen du, eta akuiferoak birkargatzeko gaitasunean eragiten du. Zuhaitzek larreek baino ur gehiago kentzen diote lurzoruari, batez ere gazteaz direnean eta hazkuntza betean daudenean. Baso lehorrek ere ur asko kontsumitzen dute. Lainoa harrapatzen duten baso hezeek, ordea, akuiferoen birkarga eraginkorra lortzen dutela ikusi da. Lanaren egileek ikusi dute lurzoruaren estaldura aldatze hutsarekin erregimen hidrikoa sasoikoa izatetik iraunkorra izatera pasatu daitekeela, edo alderantziz.

Duela gutxi arte, herrialde askok jarraitutako baso-kudeaketak baso-masa handitzea hobesten zuen kasu guztietan, lurzoruaren higaduratik eta uholdeetatik babesteko estrategia eraginkorrena delako. Hidrologikoki sentikorrak diren arroetan, ordea, lehentasunezkoa izan daiteke akuiferoak birkargatzea erraztuko duen landaredia hobestea.

Mendiko artzaintza desagertzearen ondorioak

Mendi-eremu hezeak ganaduarentzako larre gisa erabili izan dira tradizioz, baina, gaur egun, abeltzaintza galtzen ari da eremu askotan. Ikerketek erakusten dute artzaintza-larreak galdutako eremuetan akuiferoen birkarga murriztu egin dela. Eragin bera du goi-mendietan zuhaitzak basoaren muga naturaletik gora landatzeak eta izurriteak ugaritzeak. Gune horietan guztietan artzaintzarako larreak berreskuratzeak maila freatikoa handitzea ekartzen duela ikusi da nazioartean.

Honek guztiak paradigma-aldaketa bat ekar dezake basoen eta baliabide hidrikoen kudeaketan. Ikertzaileek uste dute tokian tokiko lehentasunezko zerbitzu ekosistemikoei begira hartu behar direla erabakiak: eremu batzuetan, lurzorua higaduraren aurka babesteak izango du lehentasuna, eta, beste batzuetan, ur-akuiferoak betetzeak. Hidrologikoki sentikorrak diren arroetan, larreak berreskuratzea eta baso zaharrak babestea izango da lehentasuna.

InpAkta 00 (2023) 6-17
https://doi.org/10.1387/InpAkta.24999

Vulnerability of water resources to changes in land cover and climate

Francesc Gallart*
Instituto de Diagnóstico Ambiental y Estudios del Agua (IDAEA), CSIC

ABSTRACT: In various hydrographic basins in Iberia, reductions in annual flows attributed to the increase in forest cover have been observed in the last 50-60 years, as much or more important than the changes attributed to variations in precipitation and temperature. Several studies in diverse climates show that groundwater recharge is generally lower under forest cover than under grass or agricultural cover.
The predictions of the climate models coincide in more marked increases in temperature and decreases in precipitation in summer than in winter in most part of Iberia, inducing not only a decrease of water resources but also an increase in water stress of the vegetation and a reduction in dry season flows.
It will be necessary to implement land cover strategies adaptive to climate change scenarios to care for water resources, such as reversing the reforestation of mountain pastures and improving the management of timberlands to reduce their water stress and consumption.

1. Recent evolution of water resources in Iberian basins

During the last decades, various works have been published that show clear decreases in water contributions in the headwaters of several hydrographic basins during the last 50 years, such as the Ebro (García-Ruiz *et al.*, 2001; Gallart & Llorens 2003 and 2004, Beguería *et al.*, 2003, López-Moreno *et al.*, 2011; Buendía *et al.*, 2016a and 2016b), the northern slope of the Duero (Morán-Tejeda *et al.*, 2012; Pisabarro *et al.*, 2019), the south-western tributaries of the Duero (Ceballos-Barbancho *et al.*, 2008), the Llobregat and the Ter (Gallart *et al.*, 2011). In all these studies except in Ceballos-Barbancho *et al.* (2008), it is evident that the decrease in contributions is not justified by climatic reasons, but must be attributed totally or partially to the increase in evapotranspiration caused by the extension of forest cover in these headwaters, since they have not

* **Corresponding author / Harremanetan jartzeko:** Francesc Gallart. Instituto de Diagnóstico Ambiental y Estudios del Agua (IDAEA), CSIC. Jordi Girona 18 (08034 Barcelona). e-mail: francesc.gallart@idaea.csic.es. **Contributed by** Iñaki Antigüedad **editoreak egindako ekarpena**.
How to cite / Nola aipatu: Gallart, Francesc. «Vulnerability of water resources to changes in land cover and climate», *InpAkta* 00 (2023) 6-17 (https://doi.org/10.1387/InpAkta.24999)

experienced any increase of water consumption for irrigation.

Lopez-Moreno *et al.* (2010) also showed that during this period there is a decrease in the frequency and size of floods in the Pyrenean headwaters that is not justified by changes in precipitation but rather must be attributed to the increase in forest cover. They also found an increase in low flows, especially in winter and spring; this increase should be attributed mainly to a premature melting of the snow due to an increase in temperature (0.3° C per decade according to López-Moreno *et al.*, 2011).

It is important to note that both in the headwaters of the Ebro (Gallart & Llorens 2004) and Llobregat and Ter (Gallart *et al.*, 2011), the relationship found between the increase in forest cover and the decrease in contributions is very close to the that can be predicted as a result of the increase in forest cover according to the results obtained in experimental basins throughout the world, synthesized in the equation of Zhang *et al.* (2001). Table 1 summarizes the changes observed in these basins. The gross variation of the water contributions refers to the variation observed in the gauging and the net variation refers to the residual variation of the contributions once the effect of climatic variability has been taken into account, as well as the increase in consumptive uses (irrigation) in the case of the Ebro basin.

These results show that the predictions on the availability of water resources for the future cannot be estimated only from the results of the climate models, but must also take into account the changes suffered by the vegetation cover, which, in turn, they depend on the evolution of the climate, the vegetative cycles and the management of the territory. By way of comparison, the estimated reductions over a period of 50 years due to the increase in forest cover with respect to the average annual flows are from 10 to 17% for the Ebro (Gallart & Llorens 2003), 25% for the Cardener (tributary of the Llobregat) and 12% for the upper Ter (Gallart *et al.*, 2011). Currently there are adequate models available for forecasting water inputs at the operational basin scale (resource management) in the face of changes in cover and climate (Delgado *et al.*, 2010; Zhang *et al.*, 2001; Buendía *et al.*, 2016b; Yang *et al.*, 2021; Karki *et al.*, 2023).

Table 1
Changes in water supply volumes and forest cover in some watersheds.
Net variation refers to the residual when climate variability has been cancelled.
The periods of study are diverse. Based on Gallart & Llorens (2003) and Gallart *et al.* (2011)

Basin	Water volumes			Forest cover Annual variation (% of basin area)
	Annual mean hm³	Gross annual variation (%)	Net annual variation (%)	
Ebro	12900	−0.63	−0.20	0.22
Cardener	99	−0.82	−0.50	0.61
Alto Llobregat	210	−1.10	−0.66	0.39
Alto Ter	493	−0.25	−0.26	0.36

2. Effects of afforestation and deforestation on groundwater recharge

In addition to the observations mentioned in operational catchments, experimental results obtained in various environments show that soils tend to be wetter in grassy clearings than under tree cover (Gallart *et al.*, 1997, Gray *et al.*, 2002, Cubera & Moreno 2007, García-Estríngana *et al.*, 2013), which implies higher aquifer recharge rates in the absence of forest cover (Joffre & Rambal 1993, Hatton & George 2000, Ladekarl *et al.*, 2005, Green *et al.*, 2006, Kim & Jackson, 2012).

A marked rise of the water table is a general rule in several large territories elsewhere, where shrub-forest covers have been cleared for grazing or dry-farming (Walker *et al.*, 1999; Scanlon *et al.*, 2005; Leblanc *et al.*, 2008). This is only in some particular cases, such as the localized recharge of karstic systems in semi-arid environments, where change in forest cover may be of little importance (Bazan *et al.*, 2013).

Numerous studies carried out in experimental basins show that low or low flows increase by the same or greater percentage than flood flows when forest cover is eliminated, leading in some cases to a change in the water regime, which goes from seasonal to permanent, or vice versa in the case of afforestation (Hornbeck *et al.*, 1993, Scott *et al.*, 2000, Sikka *et al.*, 2003, Silberstein *et al.*, 2003, Brown *et al.*, 2005). In some experimental or larger basins, the effects of cover changes on low flows are negligible, which has been attributed to a more important effect of geological characteristics than of cover on low flows: if the aquifers are of small volume, they can be completely filled during the wet season whatever the cover, so that low-water flows are not affected by their changes (Robinson *et al.*, 2003, Calder 2005).

3. Expectable changes in hydrological systems over the coming decades

Climate change projections have a high degree of uncertainty, due to the various emission scenarios and the characteristics of the different models. In addition, precipitation, which is the main input to hydrological systems, is not yet reliably simulated by current climate models. Despite these uncertainties, there is a broad consensus among the various models that the increase in temperature and, secondly, the decrease in precipitation will cause a significant reduction, between 10 and 30% of water resources in the Iberian Peninsula for the middle of this century compared to the period of the late 20th century (Arnell *et al.*, 2003, Milly *et al.*, 2005). Later assessments of the IPCC do not significantly modify these projections but show medium confidence in the increase in recently observed and projected droughts (IPCC 2022).

From a seasonal point of view, the predictions show a remarkable agreement that the increases in temperature and decreases in precipitation will be much more pronounced in summer than in winter by the end of this century (Christensen *et al.*, 2007). To simplify the problem, the two main limiting factors of evapotranspiration can be considered: energy (where there is no shortage of water) and water (where there is no shortage of energy); in environments where evapotranspiration is limited by energy, such as high mountains, an increase in temperature in summer can represent a direct increase in evapotranspiration and a decrease in water inputs. Conversely, in environments where evapotranspiration is limited by the availability of water, an increase in temperature in summer may not have an appreciable effect on actual evapotranspiration and water flows. Therefore, it can be expected that the increase in aridity will have greater effects on the water stress of terrestrial plant communities than on the generation of water resources.

However, it can be foreseen that both the increase in the severity of the summer drought and the premature melting of the snow cover in high mountains due to the increase in temperatures, will cause a decrease in dry season flows (García-Ruiz *et al.*, 2011). At the same time, it is foreseeable that there will be a notable increase in the frequency and magnitude of extreme droughts, such that droughts that had a recurrence period of 100 years at the end of the 20th century may have recurrence periods between 70 and less than 10 years in the middle of this century (Lehner *et al.*, 2005). The modifications of floods are less clear in the predictions for the Mediterranean area; although it is generally considered that extreme events will play an increasing role as a result of enhanced atmospheric circulation, an increase in flooding related to climate warming has not been observed (Kundzewicz *et al.*, 2007; IPCC2022).

On the other hand, changes in climate forcing will not occur on a stationary vegetation cover, but rather it will undergo modifications that will affect the hydrological consequences of changes in precipitation and temperature. Some of the causes of these modifications of the vegetal cover are the expansion and growth of forest masses on areas of crops or abandoned pastures (Poyatos *et al.*, 2003), the afforestation of high mountain areas close to the altitudinal limit of the forest favored by the climate warming (Peñuelas *et al.*, 2007), the decline of species maladapted to changing climatic conditions due to direct causes (Keenan *et al.*, 2011) or due to proliferation of pests (Rouault *et al.*, 2006), and the forest management actions that will be carried out.

4. Water resources and adaptive forest management in the present context

Until the end of the 20th century, forest management carried out in many countries, including Spain, was based on the hypothesis that increasing the mass and forest cover in a hydrographic basin was the best option to protect soils against erosion and regulate the hydrological response. That is to say, to reduce floods and improve the regularity of resources, by favoring the recharge of aquifers and increasing low flows (MAGRAMA 2002). At present, there is sufficient evidence to affirm that forest cover can provide good protection against erosion and small and moderate floods, but at the expense of greater evapotranspiration, which usually leads to appreciable decreases in total water inputs, the aquifer recharge and low water flows. Only forests that capture significant volumes of fog or primeval forests (more than 100 years old) seem to deviate from this general rule (see next section). This paradigm shift has already been collected in documents in the field of forest management, such as the FAO (2006) and the European Forest Institute (2011).

Due to the changing climatic conditions and the paradigm shift, the design of hydrologically sensible forest restoration actions in hydrographic basins and the very definition of forest hydrological ecosystem services are currently at a crossroads and pose serious scientific and technical challenges. The protection against soil erosion and the protection of water resources through afforestation are no longer equivalent, but in most cases they are antagonistic. In certain areas, soil protection will be the preferred criteria for actions, while in others it will be runoff generation or aquifer recharge. The selection of tree species with diverse water needs (Zabaleta *et al.*, 2018), the design of actions such as cutting cycles, thinning or control of the undergrowth, as well as forecasts on the progression, growth and viability of forest masses in different locations of the basins under changing climatic conditions are some of these challenges.

The forest management of each perimeter will depend on the priority ecosystem services, which may be the generation of water resources in any of them. By way of example, the installation of dense forest covers should be avoided in areas where the main water resources are generated in the basins. The headwaters in high and medium humid mountain areas have traditionally been used as pastures for livestock, but currently they tend to experience the expansion of the forest due to the abandonment of livestock activities and global warming, which is producing a decrease of the generation of water resources. The recharge areas of large aquifers are also areas that should be kept free of dense forest cover, provided that this is compatible with other priority ecosystem services.

Forest thinning (density reduction) is a current forest management option that decreases competition for water and light between trees and may increase aquifer recharge and stream flows. In water stressed areas, thinning increases the water availability for the remaining trees but may not decrease the areal water consumption (Gracia *et al.*, 1999). In wetter environments, thinning can increase water yield and groundwater recharge but must be repeated every 3 to 9 years in order to maintain these effects (Del Campo *et al.*, 2022).

Finally, as is often the case in various semi-arid areas, the excessive spread of phreatophyte stands should be avoided to conserve groundwater resources and low water flows (Doody *et al.*, 2011).

5. Complementary information

5.1. Role of vegetation cover changes in water balances

If only the limiting factors to evapotranspiration are considered, the differences between tree and short vegetation covers can be simplified (Calder 1998b).

When the limiting factor is energy, a tree canopy typically has a lower albedo (captures more radiative energy) and much higher aerodynamic roughness (exchanges energy and matter with a much thicker atmospheric layer) than an herbaceous canopy. During rainy events, trees have a greater aerial biomass, so they can intercept a greater volume of water and, for the above reasons, they have a greater capacity to evaporate the intercepted water. When the limiting factor is water, trees often have significantly deeper root systems than herbaceous plants, so they have access to a greater volume of water. As a result, trees have a greater capacity to evapotranspire water than herbaceous covers under a wide range of conditions, which explains the coincidence of results obtained in various parts of the world (see for example Brown *et al.*, 2005, Zhang *et al.*, 2011).

If a forest cover implies a greater real evapotranspiration than a herbaceous cover, it will cause a higher atmospheric humidity and therefore a greater return of this humidity in the form of precipitation (see an explanation of the mechanisms in Millán *et al.*, 2005). What usually happens in reality is that this greater precipitation becomes effective outside the scope of the same basin, on a very large or continental basin scale. There are several observed and simulated examples of continental-scale precipitation variation as a result of changes in vegetation cover (Calder 1998a, 2005; Sant'Anna Comar *et al.*, 2023).

There are few exceptions to the general pattern that forest cover causes decreased watershed inputs compared to herbaceous cover. In some areas with recurring mist, trees can capture part of this mist and convert it into "hidden precipitation", which can represent significant water input in areas with little conventional rainfall (Bruijnzeel *et al.*, 2005). It has also been observed that when primeval forests are felled or burned, runoff shows an initial increase, but drops sharply with respect to the original value as young forest develops. It has therefore been suggested that the water consumption of some forests gradually decreases with their age, until reaching stable rates not much higher than those of a herbaceous cover, when they reach an age of 100-150 years (Kuczera 1987, Vertessy *et al.*, 2001).

5.2. *Current perspectives on the management of water resources in river basins*

The traditional management of water resources in a basin is based on estimating the contributions of water available in rivers and aquifers, using gauging data or simulations carried out with a hydrological model, and assigning flows to the various intended uses (MARM 2008). The big problem with this approach from the point of view of sustainability, especially in a context of global change, is that it assumes that the hydrological cycle begins in (and can only be managed from) the river or the reservoir. The evidence that the uses and vegetation covers of the headwaters of the basins have a relevant role in the water contributions of the rivers has shown the need to carry out an integral management of the water balance of the basins, taking into account all the consumptions (natural and artificial) in particular when water resources in the basin are limited.

The Republic of South Africa has played a pioneering role in the development of this comprehensive approach when it became apparent that the establishment of commercial forestry in the headwaters of the watersheds diminished the water inputs necessary for subsistence crops in the lower parts. This led to the enactment of the "National Water Act" (Republic of South Africa, 1998), in which commercial forest plantation is considered "Stream Flow Reduction Activity" and is required to financially compensate to the authority of the basin for the withdrawal of flows that they cause. In the words of Calder (2005), this law represented a departure from the colonial rules and regulations of humid European countries, which favoured the interests of a dominant group with privileged access to land and water.

Other market-based instruments have been elsewhere introduced, based on the payment of off-site beneficiaries (water users) for the water provision services provided through the Payment for Ecosystem Services scheme (PES),(European Forest Institute (2011). This may allow the establishment of water -producing land uses that are not economically sustainable, such as extensive livestock farming.

To facilitate integrated land and water management, in 1993 the concept of "green water" was introduced at an FAO seminar (1995) to express and quantify the water consumed by terrestrial ecosystems, including meadows and dryland crops , reserving the term "blue water" for liquid runoff or groundwater. It is estimated that, globally, two thirds of precipitation water is used in the production of biomass of terrestrial ecosystems (green water) while only one third is blue water; 60-70% of the world's food production is produced thanks to "green water" that is not taken into account in traditional water balances.

This approach allows the allocation of water resources to all uses of the basin, whether irrigated or not, making it possible to integrate water management with land management (Calder 2005, Falkenmark & Rockstorm 2004). Changes in use and vegetation cover, even if they are not irrigated, can thus be managed by the basin authority. This facilitates, for example, the establishment of economic compensation for ecosystem services related to changes in use or forest management actions, such as felling or thinning (reducing tree density).

Figure 1 shows a plot of the rainfall partition between green water and blue water for a range of precipitation; Figure 1B shows that in dry and sub-humid climates the change in vegetation cover represents a large relative change in water partitioning.

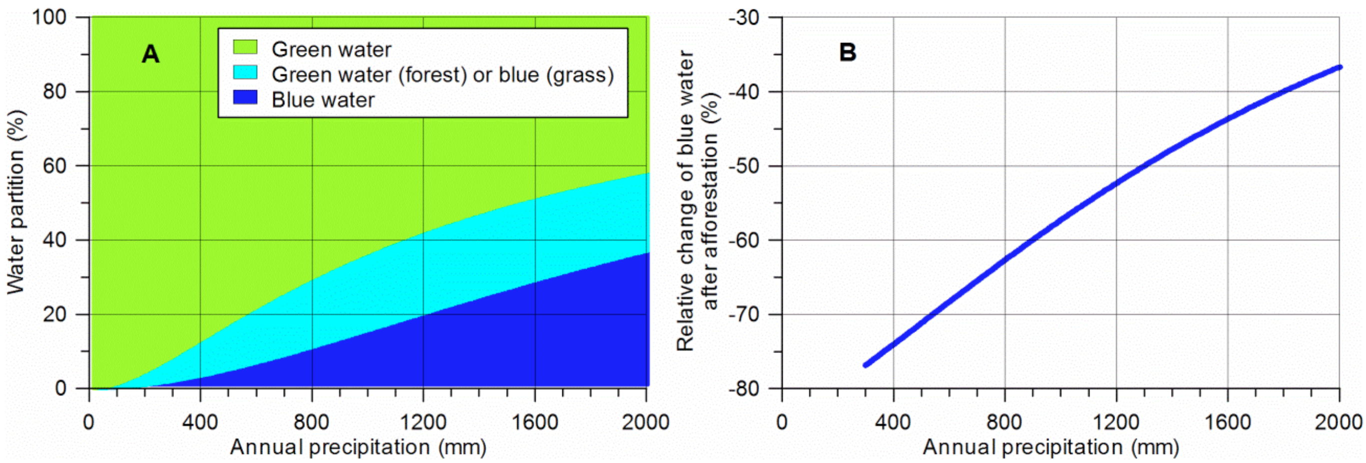

Figure 1: Diagram of the partition of rainwater in a range of precipitation between: i) green water, ii) green water if the vegetation cover is forest or blue water if it is herbaceous and iii) blue water in any case. B: Simulation of the relative change in runoff in the case of total afforestation of a basin with herbaceous cover. The original equation of Zhang *et al.* (2001) has been used, which assumes a subtropical climate with high evapotranspiration demand (1100 mm per year)

5.3. Hydrological models

The series of water flows observed at gauging stations are usually not suitable for hydrological planning. This is due to two causes: the observed flows are affected by the management of the resources (reservoirs, intakes and returns), and they are only available at the observation points and not at the points of interest for management. For these reasons, hydrological (or rainfall-runoff) models are used to generate flow series "in natural regime" from climatic records at points of interest in the basin.

The models used for this purpose in Spain are normally the Sacramento (Burnash 1995), which is calibrated using the gauging series of stations that are considered to be little influenced by uses, and the SIMPA (Ruiz-García 1999) which is parameterized with maps of terrain features. In both cases, the models are used to convert the precipitation and potential evapotranspiration series into input series, assuming that the characteristics of the basins do not vary over time. For this reason, the contributions simulated in this way should be properly called flows "in climatic regime" instead of "natural regime".

The comparison of the simulated contributions in climatic regime with the observed contributions is one of the methods that allow studying the hydrological role of the changes suffered in the headwaters, once discounting the changes in consumptive uses of water in the event that they have occurred. The use of the records and simulations carried out by the authorities responsible for management has the double advantage of being more convincing to these bodies and of facilitating the application of the results for management.

There are several hydrological models designed to study the hydrological role of vegetation cover changes. The simplest model is the equation of Zhang *et al.* (2001) that expresses the annual water balance in an area of uniform vegetation cover using a single empirical parameter (type of vegetation cover). Although for the development of this equation only basins in subtropical climates free of snowfall were used, it has given acceptable results when applied to basins with Pyrenean headwaters with a minor role of snow in total precipitation (Delgado *et al.*, 2010 , Gallart *et al.*, 2011). This equation can be easily implemented in a Geographic Information System to study the response of medium and large basins to various scenarios (Bradford *et al.*, 2001).

The daily scale model most used in practice is SWAT (Arnold & Fohrer 2005) which, although it has remarkably weak conceptual bases, is based on a structure of "hydrological response units" and has the great advantage of having an extensive community of users who exchange information and experiences. As default parameterisations of SWAT usually produce unrealistic predictions of the hydrological responses of forest covers, advanced parameterisations have been recently developed (Haas *et al.*, 2022; Karki *et al.*, 2023).

The HYLUC model (Calder *et al.*, 2003, Delgado *et al.*, 2010) is a daily scale sub-basin aggregate model specially designed for this problem, which has strong conceptual foundations. The distributed TETIS model has also been used at daily scale to analyse both the hydrological consequences of land cover change and climatic variations by comparing a sequence of different land-use maps with a constant land use scenario (Buendía *et al.*, 2016b).

Lastly, there are also other models, such as the monthly SIMPA model, which, although not designed for this purpose, admit the adaptation of its parameters to different vegetation covers to simulate changes (Ruiz-García 1999).

When using any type of model for this purpose, it is advisable to verify that the change in vegetation cover parameters essentially represents a change in the real evapotranspiration rates, and that the other changes in the simulated flows and stores are consistent with this change.

6. References

Arnell NW (2003) Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. *Hydrology and Earth System Sciences* 7: 619-641.

Arnold JG, Fohrer, N (2005) SWAT2000: current capabilities and research opportunities in applied watershed modelling. Hydrological Processes 19 (3): 563-572

Bazan RA, Wilcox BP, Munster C, Gary M 2013. Removing woody vegetation has little effect on conduit flow recharge. Ecohydrology, 6 (3): 435-443.

Beguería S, López-Moreno JI, Lorente A, Seeger M, García-Ruiz JM (2003) Assessing the effects of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. Ambio 32: 283-286.

Bellot J, Benet A, Sanchez JR, Chirino E (2001) Likely effects of land use changes on the runoff and aquifer recharge in a semiarid landscape using a hydrological model. Landscape and Urban Planning 55 (1): 41-53

Bellot J, Chirino E (2013) Hydrobal: An eco-hydrological modelling approach for assessing water balances in different vegetation types in semi-arid areas. Ecological Modelling 266: 30-41.

Bradford A, Zhang L, Hairsine P (2001) Implementation of a mean annual water balance model within a GIS framework and application to the Murray-Darling basin. Cooperative Research Centre for catchment Hydrology. Technical Report 01/8. Bruce, Australia. Available: http://www.nfp-facility.org/5865-06c5b4f-34ca7eb9155af198cbfdf42498.pdf. Accessed 27 January 2014.

Brown AE, Zhang L, McMahon TA, Western T, Vertessy RA (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310: 28-61.

Bruijnzeel LA, Eugster W, Burkard R (2005) Fog as a hydrologic input. En: Anderson M, McDonnell J, Anderson M, editores. Encyclopedia of Hydrological Sciences. John Wiley and Sons, Chichester, pp. 559-582

Buendia C, Batalla R J, Sabater S, Palau A, & Marcé R. (2016a). Runoff trends driven by climate and afforestation in a Pyrenean Basin. Land degradation & development, 27(3), 823-838.

Buendia C, Bussi G, Tuset J, Vericat D, Sabater S, Palau A, & Batalla R J (2016b). Effects of afforestation on runoff and sediment load in an upland Mediterranean catchment. Science of the Total Environment, 540, 144-157.

Burnash RJC (1995) The NWS River Forecast System - Catchment Modeling. En: Singh VP, editor. Computer Models of Watershed Hydrology. Water Resources Publications, Littleton, Colo. pp: 311-366.

Calder IR (1998a) Water-resource and land-use issues. SWIM Paper 3. Colombo, Sri Lanka: International Water Management Institute. Available: http://www.iwmi.cgiar.org/Publications/SWIM_Papers/PDFs/SWIM03.PDF. Accessed 27 January 2014

Calder IR (1998b) Water use by forests, limits and controls. Tree Physiology 18(8-9): 625-631.

Calder IR (2003) Assessing the water use of short vegetation and forests: development of the Hydrological Land Use Change (HYLUC) model. Water Resources Research 39 (11): 1318.

Calder IR (2005) Blue Revolution: Integrated Land and Water Resources Management. Earthscan, London, 353pp.

Ceballos-Barbancho A, Morán-Tejeda E, Luengo-Ugidos M Á, & Llorente-Pinto M. (2008). Water resources and environmental change in a Mediterranean environment: the south-west sector of the Duero river basin (Spain). Journal of Hydrology, 351(1-2), 126-138.

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional Climate Projections. En: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (editores.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clarke CJ, George RJ, Bell RW, Hatton TJ (2002) Dryland salinity in South-Western Australia: its origins, remedies and future research directions. Australian Journal of Soil Research 40: 93-113.

Cubera E, Moreno G (2007) Effect of land-use on soil water dynamic in dehesas of Central–Western Spain. Catena 71: 298-308.

Delgado J, Llorens P, Nord G, Calder IR, Gallart F (2010) Modelling the hydrological response of a Mediterranean medium-sized headwater basin subject to land cover change: The Cardener River basin (NE Spain). Journal of Hydrology, 383 (1-2): 125-134.

Doody TM, Nagler PL, Glenn EP, Moore GW, Morino K, Hultine KR, Benyon RG (2011) Potential for water salvage by removal of non-native woody vegetation from dryland river systems. Hydrological Processes 25 (26): 4117-4131.

European Forest Institute (2011) Agua para los bosques y la Sociedad en el Mediterráneo. Un difícil equilibrio. Birot, I, Gracia, C. Palahí M. (Editores). What Science can tell us. European Forest Institute. Available: http://www.efi.int/files/attachments/publications/efi_what_science_can_tell_us_1_2011_sp.pdf. Accessed 27 January 2014.

Falkenmark M, Rockstorm J (2004) Balancing Water for Humans and Nature. The New Approach in Ecohydrology. Earthscan, Sterling, VA. USA. Available: http://f3.tiera.ru/1/genesis/655-659/658000/a342d7a0a312513181fec0537faaadbe. Accessed 27 January 2014.

FAO (1995) Land and water integration and river basin management. Rome, Italy. Available: http://www.fao.org/docrep/v5400e/v5400e00.HTM Accessed 27 January 2014.

FAO 2006. The new generation of watershed management programmes and projects. Food And Agriculture Organization of the United Nations, Rome. Available: ftp://ftp.fao.org/docrep/fao/009/a0644e/a0644e.pdf. Accessed 27 January 2014.

Gallart F, Llorens P (2003) Catchment management under environmental change: Impact of land cover change on water resources. Water International 28 (3): 334-340

Gallart F, Llorens P (2004) Observations on land cover changes and water resources in the headwaters of the Ebro catchment, Iberian Peninsula. Physics and Chemistry of the Earth 29 (11-12): 769-773

Gallart F, Latron J, Llorens P, Rabadà D (1997) Hydrological functioning of Mediterranean mountain basins in Vallcebre, Catalonia: Some challenges for hydrological modelling. Hydrological Processes 11: 1263-1272

Gallart F, Delgado J, Beatson SJV, Posner H, Llorens P, Marcé R (2011) Analysing the effect of global change on the historical trends of water resources in the headwaters of the Llobregat and Ter river basins (Catalonia, Spain). Physics and Chemistry of the Earth, Parts A/B/C 16 (13): 655-661

Garcia-Estríngana P, Latron J, Llorens P, Gallart F (2013) Spatial and temporal dynamics of soil moisture in a Mediterranean mountain area (Vallcebre, NE Spain). Ecohydrology 6 (5): 741-753

Garcıa-Ruiz J ., Begueria S, López-Moreno J I, Lorente-Grima A & Seeger M. (2001). Los recursos hıdricos superficiales del Pirineo aragonés y su evolución reciente: Geoforma Ediciones, Logroño, 191, ISBN: 848777931X

García-Ruiz JM, López-Moreno JI, Vicente-Serrano SM, Lasanta-Martínez T, Beguería S (2011) Mediterranean water resources in a global change scenario. Earth Sciences Reviews 105: 121-139.

Gracia CA, Sabaté S, Martínez JM, Albeza E. (1999). Functional Responses to Thinning. In: Rodà, F., Retana, J., Gracia, C.A., Bellot, J. (eds) Ecology of Mediterranean Evergreen Oak Forests. Ecological Studies, vol 137. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-58618-7_23

Gray AN, Spies TA, Easter MJ (2002) Microclimatic and soil moisture responses to gap formation in coastal Douglas-fir forests. Canadian Journal of Forest Research 32: 332-43

Green JC, Reid I, Calder IR, Nisbet TR (2006) Four-year comparison of water contents beneath a grass ley and a deciduous oak wood overlying Triassic sandstone in lowland England. Journal of Hydrology 329(1-2): 16-25

Hatton T & George R. (2000). The Role of Afforestation in Managing Dryland Salinity. In: Plantations, Farm Forestry and Water. Proceedings of a national workshop, 20-21 July 2000, Melbourne. RIRDC Publication No. 01/20. ISSN 1440-6845. Kingston, ACT, 28-35.

Hornbeck JW, Adams MB, Corbett ES, Verry ES, Lynch JA (1993) Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology 150 (2/4): 323-344

IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

Joffre R, Rambal S (1993) How Tree Cover Influences the Water Balance of Mediterranean Rangelands. Ecology 74 (2): 570-582

Keenan T, Serra JM, Lloret F, Ninyerola M, Sabate S (2011) Predicting the future of forests in the Mediterranean under climate change, with niche- and process-based models: CO_2 matters! Global Change Biology 17: 565-579

Kim JH, & Jackson RB. (2012). A global analysis of groundwater recharge for vegetation, climate, and soils. Vadose Zone Journal, 11(1).

Kuczera G (1987) Prediction of water yield reductions following a bushfire in ash mixed species eucalypt forest. Journal of Hydrology 94: 215-236

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miller KA, Oki T, Sen,Z, Shiklomanov IA (2007) Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 173-210.

Ladekarl UL, Rasmussen KR, Christensen S, Jensen KH, Hansen B (2005) Groundwater recharge and evapotranspiration for two natural ecosystems covered with oak and heather. Journal of Hydrology, 300 (1-4): 76-99

Leblanc MJ, Favreau G, Massuel S, Tweed S, Loireau M, Cappelaere B (2008) Land clearance and hydrological change in the Sahel: SW Niger. Global and Planetary Change, 61(3-4): 135-150

Lehner B, Döll P, Alcamo, J, Henrichs H, Kaspar F (2005) Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated assessment. Climatic Change, 75: 273-299

López-Moreno JI, Beguería S, García-Ruiz JM (2010) Trends in high flows in the central Spanish Pyrenees: response to climatic factors or to land-use change?. Hydrological Sciences Journal, 51(6): 1039-1050

López-Moreno JI, Vicente-Serrano SM, Morán-Tejeda E, Zabalza J, Lorenzo-Lacruz J, García-Ruíz JM (2011) Impact of climate evolution and land-use changes on water yield in the Ebro basin. Hydrology and Earth System Sciences 15: 311-322

McCulloch JSG, Robinson M (1993) History of forest hydrology. Journal of Hydrology 150: 189-216

MAGRAMA, 2002. Plan Forestal Español. Available: http://www.magrama.gob.es/es/biodiversidad/temas/politica-forestal/pfe_tcm7-30496.pdf. Accessed: 27 January 2014.

MARM (2008) Orden ARM/2656/2008 de 10 de septiembre por la que se aprueba la instrucción de planificación hidrológica. Boletín Oficial del Estado 229:38472-38582.

Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature 438, 347-350

Morán-Tejeda E, Ceballos-Barbancho A, Llorente-Pinto JM, López-Moreno JI (2012) Land-cover changes and recent hydrological evolution in the Duero Basin (Spain). Regional Environmental Change 12:17-33

Peñuelas J, Ogaya R, Boada M, Jump AS (2007) Migration, invasion and decline: changes in recruitment and forest structure in a warming-linked shift of European beech forest in Catalonia (NE Spain). Ecography 30:829-837

Pisabarro A., Pellitero R, Serrano E & Lopez-Moreno JI (2019). Impacts of land abandonment and climate variability on runoff generation and sediment transport in the Pisuerga headwaters (Cantabrian Mountains, Spain). Geografiska Annaler: Series A, Physical Geography, 101(3), 211-224.

Poyatos R, Latron J, Llorens P, (2003) Land use and land cover change after agricultural abandonment. The case of a mediterranean mountain area (Catalan Pre-Pyrenees). Mountain Research and Development 23(4): 362-368

Republic of South Africa (1998) National Water Act. (Act No. 36 of 1998). Government Gazette 398 no. 19182.

Robinson M, Cognard-Plancq AL, Cosandey C, David J, Durand P, Fuhrer HW, Hall R, Hendriques MO, Marc V, McCarthy R, McDonnell M, Martin C, Nisbet T, O'Dea P, Rodgers M, Zollner A (2003) Studies of the impact of forests on peak flows and baseflows: a European perspective. Forest Ecology and Management, 186: 85-97.

Rouault G, Candau JN, Lieutier F, Nageleisen LM, Martin JC, Warzée N (2006) Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. Annals of Forest Sciences 63: 613-24.

Ruiz García JM (1999) Modelo distribuido para la evaluación de recursos hídricos. Monografías del CEDEX, 67. Ministerio de Fomento, Madrid.

Sant'Anna Commar LF, Medeiros Abrahao G & Heil Costa M. (2023). A possible deforestation-induced synoptic-scale circulation that delays the rainy season onset in Amazonia. Environmental Research Letters 18 044041

Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF (2005) Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Global Change Biology, 11(10): 1577-1593

Scott DF, Prinsloo FW, Moses G, Mehlomakulu M, Simmers ADA (2000) A re-analysis of the South African afforestation experimental data, Water Research Commission, WRC Report No. 810/1/00, South Africa.

Segura-Beltrán F, Sanchis-Ibor C (2013) Assessment of channel changes in a Mediterranean ephemeral stream since the early twentieth century. The Rambla de Cervera, eastern Spain. Geomorphology 201: 199-214

Sikka AK, Samra JS, Sharda VN, Samraj P, Lakshmanan V (2003) Low flow and high flow responses to converting natural grassland into bluegum (Eucalyptus globulus) in Nilgiris watersheds of South India. Journal of Hydrology 270: 12-26

Silberstein R, Adhitya A, Dabrowski C (2003) Changes in flood flows, saturated area and salinity associated with forest clearing for Agriculture. Technical Report 03/1. CRC Centre for Catchment Hydrology, Monash, Australia. Available: http://www.catchment.crc.org.au/pdfs/technical200301.pdf. Last accessed 27 October 2008

Vertessy RA, Watson RGR, O'Sullivan SK (2001) Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecology and Management 143: 13-26

Walker GR, Gilfedder M & Williams J. (1999). Effectiveness of current farming systems in the control of dryland salinity. CSIRO Land and Water. ISBN 0 643 06556 3

Yang Z, Hou F, Cheng J & Zhang Y. (2021). Modeling the Effect of Different Forest Types on Water Balance in the Three Gorges Reservoir Area in China, with CoupModel. Water, 13(5), 654.https://doi.org/10.3390/w13050654

Zabaleta A, Garmendia E, Mariel P, Tamayo I, & Antigüedad I. (2018). Land cover effects on hydrologic services under a precipitation gradient. Hydrology and Earth System Sciences, 22(10), 5227-5241.

Zhang L, Dawes WR, Walker GR (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research, 37: 701-708.