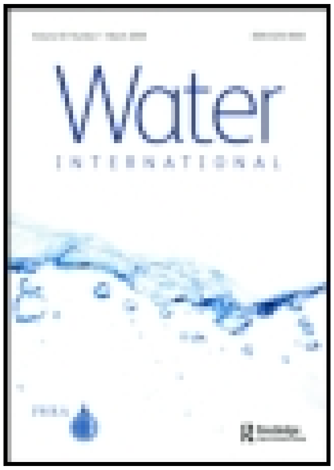

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Catchment Management under Environmental Change: Impact of Land Cover Change on Water Resources

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Catchment Management under Environmental Change: Impact of Land Cover Change on Water Resources

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***Abstract**: Since the second third of the 20th century, it has been clearly established in the hydrological science that an increase of the forest cover in a catchment determines a decrease in water resources from this catchment. Nevertheless, the application of this paradigm for catchment management has been delayed. In Spain, extensive mountain areas that were farmed or grazed in the past have been abandoned during the last 50 years and undergone spontaneous or induced afforestation, mainly by pine trees. The historical flow records of several Spanish rivers during the last 50 years show significant decreases that average an annual reduction of about 0.4 percent of mean annual flow, whereas in the Ebro River the annual decrease was as high as 0.63 percent of mean annual flow. About one-third of these decreases were not explained by increases in water consumption by irrigation or by climate variability, but should be attributed to an increase in evaporation from the headwaters. These results confirm that the assessment of future water resources must take into account the past and expected changes in land cover in the catchment headwaters and that land use and cover planning should be integrated in the management of catchment water resources, especially in scarce water environments.*

***Keywords**: Land use change, Land cover change, Historical flow records, Water resources, Headwaters.*

Introduction

The traditional perception that forests increase water resources has been seriously questioned by the results of scientific forest hydrology since the early 20th century (e.g. Calder, 2002). A large number of catchment experiments conducted all over the world clearly demonstrated that the deforestation of a catchment implies an increase of water yield from it and, conversely, the establishment of a forest cover implies a decrease of water yield (Hibbert, 1967; Bosch and Hewlett, 1982; Sahin and Hall, 1996). The application of this paradigm to the water management practice, although necessary for sustainable management in water stressed regions, has been largely delayed because of difficulties inherent to the change of any scientific paradigm, the limited experience on the hydrological consequences of land cover changes in large territories, and the disconnection between policy and science (Falkenmark et al., 2000; Calder, 2002).

In Spain, large areas formerly used for marginal agriculture and grazing have been abandoned during the second half of the 20th Century, especially in mountain areas (Lasanta, 1990). On the other hand, several of the main rivers show significant decreasing trends of annual flow that must be attributed to the combined role of the increasing water consumption for irrigation, the decreasing trend of precipitation, and the increasing evaporation in the headwaters because of the growth of forest cover (Gallart and Llorens, 2002a; Beguería et al., 2003). A recent assessment of a sample of headwater tributaries to the Ebro river promoted by the catchment Authority (Confederación Hidrográfica del Ebro), lead to the establishment of a relationship between increase in forest cover and decrease of flow for the period 1970 to 1990 (Gallart and Llorens, 2002b).

The purpose of this paper is to summarize the state of the art on the relationships between land cover change and water yield from catchments and to analyze how this knowledge might be used for a sustainable water management in Spain.

Hydrological Consequences of Land Cover Changes

Early Studies

The public perception of the hydrological role of vegetation was based on the experience that forested regions are commonly wetter than deforested ones, leading to the beliefs that the forest 'made' or increased rainfall, fed aquifers, and increased water resources (for more details see Guillerme, 1980; McCulloch and Robinson, 1993; Llorens and Gallart, 1996).

In the beginning of the 20th century, the rising concern on water resources and forest conservation, as well as protection against flooding, led to the first scientific experiments on the hydrological role of vegetation in the Emmental region in Switzerland (Engler, 1919), the Wagon Wheel Gap in Colorado, USA (Bates and Henry, 1928), and at the Stocks reservoir in the United Kingdom (Law, 1956). The results of these experiments showed that forested catchments produced lower water yield than grassed ones and opened a debate.

The first argument against the new evidence was that forest evaporation could not be higher than the "potential evapotranspiration" from well watered grass, controlled by climate. Subsequently, it was recognized that the exchange of water vapor between the vegetation and the atmosphere was controlled by plant physiology (stomata closure) and that the exchange of energy and mass between the land surface (vegetation cover) and the atmosphere was also controlled by its aerodynamic roughness (Monteith, 1965). This led to change the concept of "potential evapotranspiration" into "reference evapotranspiration" stressing the fact that the energy for evapotranspiration depends on the characteristics of vegetation (or crops) (Doorenbos and Pruit, 1976).

Another major argument was the poor representation and the significant border effects of the experimental catchments because of their limited size. Nevertheless, the best known hydrological impact of land cover change over a large area confirms the results from catchment experiments: the massive deforestation for agricultural development in Australia has led to the raising of the water tables and the salinization of water and soils, with huge environmental and economic costs (MDBMC, 1999). Furthermore, the data from large catchments are consistent with data from small catchments (Sahin and Hall, 1996; Zhang et al., 2001).

Other arguments about the beneficial role of forest for increasing precipitation, reducing flooding and erosion, and improving water quality are discussed later.

The Evidence and its Interpretation

The recapitulation of results from 39 paired catchments by Hibbert (1967) and from 55 additional catchments by Bosch and Hewlett (1982) represented respectively the establishment and the confirmation of the new paradigm:

- Reduction in forest cover increases water yield.
- Establishment of forest cover on sparsely vegetated land decreases water yield.

Subsequent works tried to validate or nuance this paradigm for different climatic conditions, forest management practices or seasonal trends (e.g. Burch et al., 1987; Rambal, 1987; Keppeler and Ziemer, 1990; Humbert and Najjar, 1992) or to verify the long-term validity of preliminary works (Kirby et al., 1992; Beschta et al., 2000).

The reason for the differences between grass and forest evaporation largely vary depending on climate. In wet areas, evaporation is limited by the energy available for vaporization, whereas in dry areas, evaporation is limited by the availability of water (Calder, 1998).

In wet conditions, both the lower albedo and the higher aerodynamic roughness of forests surfaces increase the energy available for evaporation. The increased roughness is especially relevant for evaporation of intercepted water, when the canopy is wet and advected energy is much greater than radiative one, consequently, the rate of evaporation of intercepted water may be much higher than the "potential evapotranspiration" (Rutter, 1967; Stewart, 1977). Calder (1976) showed than over a *Picea abies* forest in Plynlimon, annual losses through interception were about twice those due to transpiration.

In dry conditions, bushes and trees have deeper roots that allow them to get more water available for transpiration than shallow-rooted grasses. Canadell et al. (1996) showed that average maximum depth of rooting was 7 m for trees against just 2.6 m for herbaceous plants. Deep rooted shrubs in semiarid areas may transpire at rates independent on seasonal rainfall amounts (Domingo et al., 2001).

In intermediate or seasonal climates, forest interception may continue to play an important role in spite of the relatively high precipitation intensities (Llorens et al., 1997) and deep roots allow trees to transpire when shallow soils are already dry (Moreno et al., 1996).

Other Hydrological Consequences of Land Cover Change

The traditional wisdom on the hydrological benefits of forests, in addition to the increase in runoff formerly discussed, includes also the increase in rainfall, increase in aquifer recharge, reduction of floods, reduction of erosion, and improvement in water quality.

Increase in precipitation

The recent evidence that human activity can change the climate of the globe and the rising concern with land degradation have led to the renovation of the old argument that forest increases precipitation. The new version of this perception considers that the increased evapotranspiration by forest cover is counteracted at the regional scale by and increase in precipitation. This assertion has never been experimentally validated, a difficult task due to the uncertainty and scale issues of precipitation measurements (McCulloch and Robinson, 1993). Indeed, as forest increases evaporation, it may reasonably increase precipitation somewhere and therefore increase water resources in a nearby region (Calder, 1998; Savenije, 1995), but not in the same afforested catchment, where the increase in precipitation may be only a part of the increase in evaporation. Modeling experiments of the hydrological response to large scale land use changes using Global Climate Models coupled to Soil-Vegetation-Atmosphere Transfer models, suggest that precipitation increase due to forest evaporation would be only significant for the wider continental-sized forests of the world (Amazonia), but not for smaller continents surrounded by oceans (Southeast Asia) (Rowntree, 1988; Henderson-Sellers et al., 1995).

Increase in infiltration

It is usually recognized that forest soils have higher infiltration capacity than pasture or crop soils, mainly due to the role of macropores produced by decaying roots. The increased infiltration under forest is usually claimed to favor deep infiltration and aquifer recharge. Indeed, forest soils usually have higher infiltration capacity than pasture or crop soils, but, due to rainfall interception, these soils are usually drier than in clearings under grass cover (Gallart et al., 1997). Moreover, as discussed before, tree roots may evaporate water from the deep soil profiles or weathered rock. The claim for the hydrological role of increased infiltration in forests sometimes arise from a misunderstanding with the use of precipitation-runoff models: most hydrological models are provided with simple evapotranspiration submodels that do not consider either aerodynamic or physiologic differences between vegetation and do not include explicitly the process of rainfall interception; therefore, when they are calibrated with discharge data, soil parameters must take values of higher infiltrability in forests to explain the lower discharge. There are several experimental examples that demonstrate the breakdown of water table after afforestation (Calder, 2002), whereas the best example of the converse may be found in Australia, where the extensive deforestation led to the generalized rise of water tables (MDBMC, 1999).

Reduction of floods

Forest has been also claimed to reduce flooding. Indeed, the decrease in water yield from forested catchments is actually linked to lower peak flows during events. Nevertheless, a long-term study in Oregon (Beschta et al., 2000) showed than the higher is the magnitude of the event, the lower is the reducing effect of forest. A study in the Pyrenees (Gallart and Clotet, 1987) showed that the differences in peak flows from small catchments with different land covers were high for small storms but imperceptible for larger events. The role of forest in reducing floods is three-fold: (i) the drier antecedent conditions of soils before the event; (ii) the higher infiltration in soils due to the macro-porosity; and (iii) the interception losses. During prolonged heavy rainfall, soils are close to saturation, infiltration is counteracted by return flow (Gallart and Clotet, 1988), and the evaporation of intercepted water may not play a relevant role.

Reduction of erosion and pollution

Finally, forest is claimed to reduce soil erosion and to preserve water quality. Indeed, both the soil protection against rain splash by the canopy and the litter, and the decreased runoff mean a reduction of erosion. Furthermore, waters from forest streams have commonly lower nitrate concentrations than waters from pastures, as forests may absorb high rates of nitrogen deposition (Avila et al., 2002). Nevertheless, it has been shown that pre-planting ground treatment before forestation (Ortigosa, 1990) or forest harvesting works may cause severe soil erosion. Some of the erosion effects attributed to deforestation are actually more so the result of soil compaction and opening of logging roads than the hydrological effect of the lacking biomass (McCulloch and Robinson, 1993). On the other hand, it is now widely accepted that because of the trapping effect of the canopy for aerosols and particles, forest increases the deposition of atmospheric pollutants and may increase the risk for water acidification (Christophersen and Neal, 1990). Fortunately, in Mediterranean environments, alkaline dust coming from local soils and African deserts may neutralize acidic pollutants (Avila, 1996; Avila et al., 1998).

Land Cover Change and Water Resources in Spain

A preliminary estimation of the recent changes in land cover and their consequences on water resources in Spain has been made recently by Gallart and Llorens (2002a). This work demonstrated that during the last decades, the forested area increased in relatively dry areas and was more stable in wetter ones, while the increase in forest density was manifest throughout Spain. On the other hand, mean annual flow in several of the main rivers in Spain decreased between 37 and 59 percent of mean annual flow in the last 50 to 60 years (Table 1). Three main drivers have been identified to cause this marked decrease in flow: the decreasing tendency of rainfall inputs, the increase in water consumption for irrigation, and the increase in evaporation from headwaters due to the increase in forest cover (column 'residual' on Table 1). It is worth highlighting that the flow decrease attributed to the increase in forest cover ranges between 17 and 46 percent of the mean flow and that this decrease is moderate when compared with the cases reported elsewhere (Gallart and Llorens, 2002a).

A more detailed study on forest cover change and

Table 1. Breakdown of temporal decreases in flow for a sample of Spanish rivers

River and location	*Period (years)*	*Mean flow (hm^3 a^{-1})*	*Gross decrease (hm^3 a^{-1})*	*(%)*	*Consumption (hm^3 a^{-1})*	*(%)*	*Precipitation (hm^3 a^{-1})*	*(%)*	*Residual (hm^3 a^{-1})*	*(%)*
Duero at Carrascal	1921-95	4,440	1,770	39.8	658	14.8	338	7.6	774	17.4
Duero at Miranda	1934-96	9,190	5,450	59.3	1,080	11.8	1,630	17.7	2,740	29.8
Ebro at Palazuelos	1915-95	1,670	619	37.1	-	-	112	6.7	507	30.4
Ebro at Tortosa	1940-97	12,900	5,760	44.7	1,410	10.9	2140	16.6	2,220	17.2
Tajo at T-S transfer	1940-96	1,180	687	58.2	-	-	145	11.4	542	45.9

Residual means the decrease not explained by changes in precipitation or water abstraction. T-S transfer means Tajo - Segura water transfer inlet. For sources and methods see Gallart and Llorens (2002a).

temporal stability of stream discharge has been conducted for the Ebro catchment (Gallart and Llorens, 2002b). This catchment, with near 85,000 km^2 and an annual discharge of about 12,000 hm^3 is the most important river in Spain in terms of both discharge and water use. This study analyzed the main catchment as well as a sample of headwater tributaries scarcely affected by changes in water consumption, that afford about 50 percent of the total resources in the catchment. This analysis demonstrated a relevant increase in forest cover as well as decreasing trends of stream discharges more pronounced than those that may be expected from climate variability and water abstractions. A summary of these results is shown on Table 2. The flow decrease attributed to the increase in forest cover for the last 45 years is about 9 to 13 percent of mean flow. The comparison with the observations described elsewhere is discussed below.

These results show that changes in land cover in headwater areas in Spain must be taken into account in both the assessment and planning of water resources, as their consequences are similar to those of climatic trends and water consumption for irrigation.

Water Management of Catchments with Changing Land Use and Cover

The first step in catchment management is usually the estimation of available water resources, from measurements of discharge or precipitation, through precipitation-runoff modeling. Once a measured or simulated record of discharges is obtained, it is first tested for temporal stationarity. In the current practice, increasing or decreasing trends of discharge records are considered spurious if the null hypothesis (temporal stationarity) has a probability higher than 0.05 (this means that a risk of up to 0.95 of change in discharge is considered acceptable).

Nevertheless, the outcome of the former sections means that the hypothesis of a temporal stationarity of water resources cannot be used for management in a catchment where land cover changes are known or foreseen. Conversely, the analysis of temporal trends of discharge records in catchments subject to land cover change cannot be made under the null hypothesis of stationarity.

If some change in land cover is known to have occurred in the catchment, the null hypothesis for analyzing the temporal stability of flow should be a trend with the opposite sign to the trend of forest cover, for a stationary climate forcing. In this case, instead of an acceptance/rejection approach, confidence intervals or probabilities for different temporal tendencies in discharge should be calculated. Nevertheless, the existence of a linear temporal trend in discharge does not mean that a regression line is a good model for estimating future resources, because this kind of model can not be extrapolated for more than a very short period. Instead of extrapolating the observed trends in discharge, first the future changes in land cover should be foreseen and, second, the hydrological consequences of these changes should be assessed (Calder et al., 1999).

A really integrated catchment management should take into account the consumption of water by all kinds of land use, including semi-natural vegetation, rangeland, forestry, and rain fed agriculture, together with water abstractions for irrigation, industry, or urban use, especially where water is a limiting resource or some land uses are suspect to

Table 2. Changes in forest land cover and stream flow at the main Ebro River and in a sample of headwater streams (SHS)

	Forest area increase (1970-1991)		*Gross annual flow decrease (1950-1995)*		*Residual annual flow decrease (1950-1995)*		*Runoff volume loss per rainfall volume over new forested area*
Catchment	km^2	*%*	*hm^3a^{-2}*	*%*	*hm^3a^{-2}*	*%*	*hm^3 / hm^3 ± 95% conf.**
Ebro	4,010	4.7	98	0.63	34	0.2	0.209 ± 0.140
SHS	1,771	10.4	72.9	0.86	23.6	0.29	0.183 ± 0.137

* Conf: confidence intervals obtained with the Student's t test
Residual means the decrease not explained by changes in precipitation or water abstraction. Data from Gallart and Llorens (2002b).

change in time due to other drivers (see an example in Kapp et al., 1995).

Predicting Hydrological Consequences of Land Cover Changes

Unfortunately, most hydrological models are not adequate for assessing the hydrological consequences of land cover change because, as discussed before, their evapotranspiration modules are too simplistic (e.g. Singh, 1995). On the other hand, physically-based models that might be adequate for this purpose need large sets of parameters that are usually not available at the scale needed. Some parametric models may mimic the role of vegetation through the use of parameters that lump the role of soil and vegetation (see an example in Ruiz-García, 1999). These models may be useful, provided they are properly validated against actual data.

An alternative to these models may be the analysis of the results obtained in catchment experiments conducted all over the world. The 94 case studies reviewed by Bosch and Hewlett (1982), were increased to 145 cases by Sahin and Hall (1996), and, finally, Zhang et al. (2001) gathered over 250 catchments. The results of these compilations are definite in the establishment of a negative relationship between forest cover and water yield, but show a wide range of variation in the quantitative relationship depending on the type of vegetation, the percentage of area subject to land cover change, and the annual precipitation in the case area.

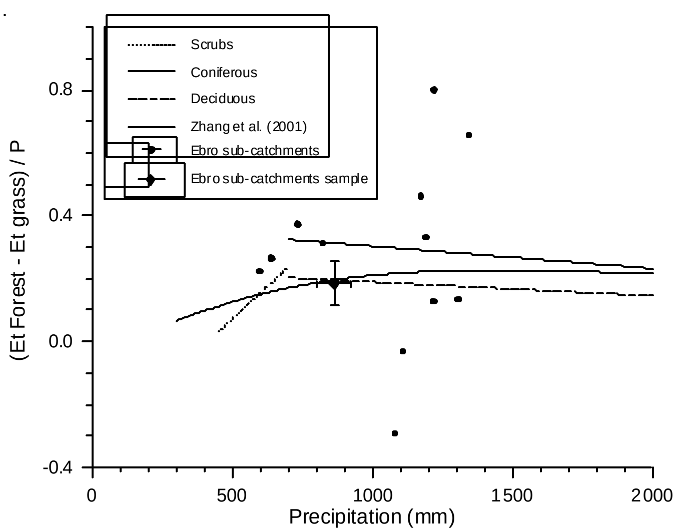

Figure 1. Relative differences between evapotranspiration from forest and grass covers for a range of annual precipitation.

The black curve represents the equation developed by Zhang et al. (2001); the black lines were fitted to the observations for scrub, coniferous and deciduous forests compiled by Bosch and Hewlett (1982); the black dots represent some of the tributaries to the Ebro River taken from a sample of headwater streams (Gallart and Llorens, 2002b); and the diamond dot with standard error bars represent the result obtained for the whole sample.

The last authors (Zhang et al., 2001) developed an empirical generalized formula for estimating the evapotranspiration from a catchment using only the annual mean precipitation and the relative forest cover. The main limitation for this equation is that catchments with significant precipitation in the form of snow were deleted from the data base used for fitting the parameters. This equation should therefore be subject to some test before being applied in areas with significant snow precipitation or moderate evapotranspiration demand.

Figure 1 shows the relative difference between evapotranspiration from forest and grass covers for a range of annual precipitation using the equation developed by Zhang et al. (2001), and the lines fitted to the observations for scrub, coniferous, and deciduous forests compiled by Bosch and Hewlett (1982). In the same figure, a sample of headwater streams tributaries to the Ebro river (Gallart and Llorens, 2002b), extrapolating their land cover change to 100 percent are represented (round dots). Only catchments with more than 10 percent of change in forest cover have been represented separately to avoid excessive extrapolation. The two points with the highest Y axis value are catchments with less than 15 percent of observed change in forest area, whereas the point with the more negative value represents a catchment with a mean altitude of 1263 m asl, where significant errors in precipitation may be expected. Finally, the diamond dot with standard error bars represent the result averaged for the whole sample of headwater streams, after weighing the area of the sub-catchments.

The sample of tributaries to the Ebro River represented on the Figure 1 consists of operational catchments with areas in the range between 50 and 1,500 km^2. The data used for the analysis of these catchments (Gallart and Llorens, 2002b) were the common data available at these scales: the precipitation network used had a density of one gauge per 3,000 km^2; the precipitation-runoff modeling was made at the one-year temporal step; and the data for the analysis of forest changes was obtained from national forest inventories. Although the scatter obtained for individual basins from these data is higher than those obtained from experimental basins, the spurious errors are compensated in the sample, giving average results similar to those obtained elsewhere.

Conclusion

The experiences carried out throughout the world clearly demonstrate that afforestation decreases water resources in the catchments. Besides the environmental benefits of forest land cover (protection of wildlife, carbon sequestration, protection of soils, and reduction of moderate floods), significantly higher water consumption by forest and the consequent loss in water resources must be taken into account in catchment planning.

The existing data show that forest land cover increased in Spain during the last decades and that through this period water resources in several large catchments declined more than the decrease that could be expected from both the climatic variability and the increase in water abstractions. In the examples analyzed, the relationships between increase in forest cover and decrease in water yield are similar to those experimentally obtained elsewhere.

Temporal stationarity of water resources cannot be used as a working hypothesis for water management in catchments subject to changes in land cover, for a stationary precipitation and climate forcing. Historical records of flow in catchments that undergo land cover changes must be analyzed assuming as null hypothesis a negative relationship between forest cover and water yield changes. Conversely, the estimation of future water resources must take into account not only the projection of climatic drifts but also the hydrological consequences of the predictable changes in catchment land cover. Scenarios of future water demand and availability must include scenarios of land cover in the headwaters with an assessment of their water needs.

In the cases where the lack of available data impedes the use of physically based models for the analysis of the hydrological consequences of land cover changes, the empirical relationships obtained from the numerous experiments conducted around the world may be used to obtain first estimates adequate for strategic planning. “A land use decision is also a water decision” (Falkenmark et al., 2000).

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