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Hydrological implications of afforestation of abandoned lands: water balance simulation of a small Mediterranean mountainous basin

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ABSTRACT

The intense human activity suffered by Mediterranean mountainous areas till 50 years ago induced important geoecological modifications that played a significant hydrological and geomorphological role during agricultural land use and still have relevant consequences after land abandonment. Reforestation of these areas is perceived to suppose in the next future a serious water management problem, but more research is needed to quantify the magnitude of the hydrological implications of this change.

This paper presents a simulation model made to analyze the role that vegetation cover changes can play on water resources. This simulation model compares the actual hydrological behaviour of a small mountainous catchment covered by grassland with its behaviour modeled considering that the whole area is covered by a *Pinus sylvestris* stand.

Simulation results during a sensitivity analysis, with forest water consumption parameters taken from literature, show that differences in vegetation cover can modify all the water balance components but effect especially both quickflow and baseflow. The differences depend much more on the parameters used for the simulation of interception than on those used for stomatal control of transpiration.

INTRODUCTION

The abandonment of marginal agricultural fields since early this century appears as one of the main geoecological modifications in mountainous Mediterranean areas. Moreover the actual agricultural policies of the European Community and the Mediterranean countries encourage agricultural land abandonment in low productivity areas, like mountain ones. This would lead to the abandonment in the next future of 15 million hectares of cultivated fields in the European Community countries (Miller, 1992).

The main geoecological adjustment that has or will be produced in these abandoned fields is related to afforestation, either spontaneous or promoted by the landscape management policies. Although the afforestation has been promoted as a good land conservation practice, mainly in degraded areas, it can result in important problems on water conservation. A greater loss of water to the atmosphere in forested areas caused a diminution of water discharge (Calder, 1993). Bosch & Hewlett (1982) summarized some studies over the world that showed that the greater water consumption by forests is sufficiently significant to stop the afforestation of headwater areas policy.

Taking into account the present importance of land use change in mountainous areas, and also considering recent predictions of climate change, more research is needed to quantify the magnitude of the hydrological implications of reforestation. The aim of this paper is to present a basin water balance simulation model that illustrates the potentially different hydrological behaviour between two possible types of vegetation covering abandoned fields: the grassland or a spontaneous reforested *Pinus sylvestris* stand, in a Mediterranean mountain area with mean annual rainfall of 850mm.

THE CAL PARISA BASIN: AN EXAMPLE OF HYDROLOGICAL RESPONSE IN MEDITERRANEAN MOUNTAINOUS ABANDONED AREAS

The small Cal Parisa basin (36 Ha), located in the Eastern Pyrenees (Spain) was selected as a representative of agricultural abandoned fields in Mediterranean mountainous areas. This basin has been monitored since 1988 to analyze the role of land abandonment in water and land conservation (Llorens & Gallart, 1992). The main geoecological implications of old agricultural land use are the modifications in vegetation cover, topography and drainage net.

The old *Quercus pubescens* forest was removed and a system of terraces was constructed. Due to the hydrological modifications induced by topographical changes, especially the outcrop of phreatic water in the inner part of terraces, a net of man-made ditches was constructed modifying significantly the total drainage length (Llorens et al., 1992).

As a consequence of these geoecological modifications, the hydrological behaviour of the basin should exhibit:

a) A greater water storage capacity due to increased soil thickness produced by the terraced system.

b) An important modification of water circulation due to the remodelling of topography. This hydrological change is characterised by the formation of frequently saturated areas in the inner parts of terraces, and subsequently by the role of the man-made ditches.

Data obtained from the catchment monitoring show that in this conditions its hydrological behaviour is characterized by (Llorens, 1991):

a) A hydrological response strongly regulated by the basin antecedent water reserve.
b) A runoff generation by saturation mechanisms.

c) A quick stormflow response after basin saturation.
A comparison of this hydrological functioning with the behaviour predicted for a natural catchment, with the same general topographic structure, was performed (Gallart et al., in press) using the fundamentals of the semidistributed hydrological model TOPMODEL (Beven & Kirby, 1979). This analysis confirmed that terraces clearly modify the pattern of saturated areas, and suggested that the water balance of the basin would be consequently modified towards a higher saturation storm runoff at the expense of lower baseflow and evapotranspiration.

SIMULATION OF CAL PARISA BASIN HYDROLOGICAL BEHAVIOUR: THE SIMBAL MODEL

The SIMBAL model was built as a tool to better understand the hydrological behaviour of Cal Parisa grassed basin (Llorens & Gallart, 1990). The initial structure of the model considering only grassland cover, is:

- Model input: Daily measured rainfall (P).
- Initial variable: Initial soil water deficit (S_i).

- Evapotranspiration submodel:

- Potential evapotranspiration (E_t) is provided by a stochastic generator based on the annual distribution of Penman's potential evapotranspiration (Penman, 1948) measured in the basin (during 1989-90).

-The calculation of simulated actual evapotranspiration (E_a) is done considering that:

a) Simulated actual evapotranspiration is equal to the potential one for basin water deficit lower than 100 mm.

b) For basin water deficit higher than 100 mm, simulated actual evapotranspiration diminishes as a function of the basin water deficit (Hillel, 1971).

- Runoff and soil water deficit submodel:

- Baseflow runoff (R_b) depends on a negative exponential function of catchment water deficit based on the baseflow equation of TOPMODEL (Beven & Kirkby, 1979). After calculation of evapotranspiration and baseflow then basin water deficit is updated by losses.

- Quickflow runoff (R_q) is calculated using a simplified partial saturation model (one parameter). Basin water deficit is updated after the calculation of quickflow runoff to acount for infiltration.

- Outputs of the model: simulated actual evapotranspiration and runoff at daily scale.
The model was built using data measured from 1989 to 1990, and validated for the quickflow runoff with measured data from 1990 to 1992.

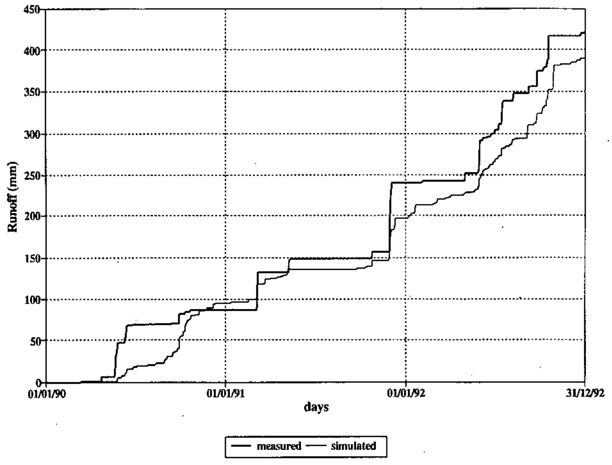

Figure 1. validation of simulated Quickflow Runoff using Cal Parisa measured data for the period 1990-1992

Figure 1 shows a cumulative graph comparing measured and simulated quickflow runoff (R_q) for the years 1990-92. The total difference between measured and simulated runoff is less than 8% for this validation period. The specific differences observed between measured and simulated runoff are attributed to the limitations of the single store model, made to simulate daily water balance. This is due to the occurrence of high and quick discharges produced by great rainfall events (up to 140 mm/event or up to 50 mm/day).

SIMULATION OF HYDROLOGICAL DIFFERENCES BETWEEN FORESTED AND NON FORESTED AREAS

Physical hydrological differences between grassland and forest

The hydrological differences between forest and grassland are deemed to be primarily due to two factors: the water losses by transpiration and by interception. Secondary changes induced by forest in soil hydrological behaviour (water retention, infiltration...) are not considered by the model.

- Water loss by transpiration:

In soil water deficit conditions transpiration of forested areas is certainly

lower than grassland one. Forest transpiration could represent 20-50% less than the grassland one (Wallace & Oliver, 1990), although forest has more evaporative potential because:

a) Its energetic budget is greater:

Forest albedo (about 7 to 8%) is lower than the grassland one (about 20 to 30%) due both to the dark colour of forest surface and to the radiation trap effect caused by forest structure (Oke, 1987).

The loss of long wave radiation over forest is lower than over grassland. Forests consist of rough surfaces generating greater eddies over them, which allow more sensible heat transfer and lower the surface temperature.

b) Its potential to transfer water vapour to the atmosphere is greater:

Atmospheric conditions over forest are more turbulent than over grassland, because forest is a rougher surface that has lower aerodynamic resistance, or atmospheric control of water vapour transfer (ra), (Monteith, 1965). For example for a wind speed about 3 ms-1, grassland aerodynamic resistance is about 50 sm-1 and conifers one is only about 3.5 sm-1 (Wallace & Oliver, 1990).

The difference in transpiration rate between forest and grassland for the same atmospheric conditions is controlled by the surface resistance, or vegetation physiological control (r_s), which is 3 times greater in forest than in grassland. Considering the one leaf model of Monteith (1965) grassland surface resistance is about 50 sm^{-1} (Wallace & Oliver, 1990) and *Pinus sylvestris* one is about 150 sm^{-1} (Gash & Stewart, 1977). Because resistances (atmospheric and surface ones) act in series, surface resistance that depends directly on soil water stress (Rutter, 1975) is the main limiting factor for transpiration and provides the difference in transpiration rate between grassland and forest.

- Water loss by interception:

When vegetation canopy is totally wet, surface resistance (r_s) is zero. In these conditions there are two phenomena causing greater losses to the atmosphere over forest than over grassland:

A forest is capable to intercept a greater volume of rainfall because of its structure. A descriptive parameter of vegetation structure is the LAI (Leaf Area Index) that shows the relationship between leaf and soil surfaces. Typical values of measured LAI are about 2-3 $m^2\ m^{-2}$ for different kinds of crops and range from 2 to 5 $m^2\ m^{-2}$ for *pinus sylvestris* (Breda, 1993).

The aerodynamic resistance (r_a) over forest is about 15 times lower than over grassland, in wet conditions fo-

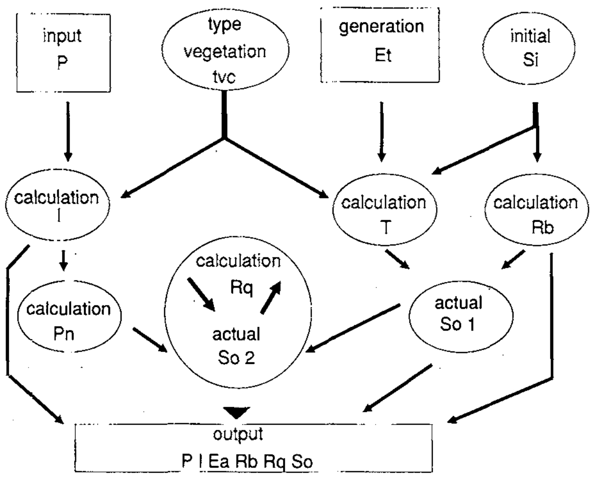

Figure 2. Flux diagram of the SIMBAL model. P= Precipitation; Ea= Actual evapotranspiration; Et= potential Evapotranspiration; I= Interception; Pn= Net precipitation; Rb= Baseflow; Rq Quickflow; Si= Initial soil water deficit; T= Transpiration; tvc= Type of vegetation cover.

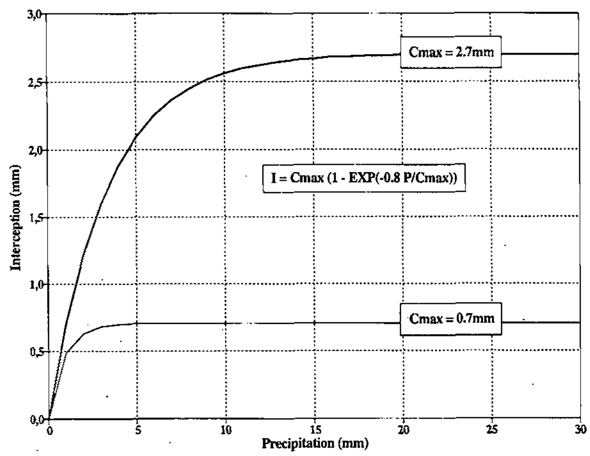

Figure 3. Relatioship between Precipitation and Interception used for the grassland and forest simulation. Maximum retention capacities are 2.7 mm for forest and 0.7 mm for grassland.

rest, and specially coniferous forest, are the best systems for water vapour transfer to the atmosphere.

Considering that for the same atmospheric conditions turbulent transfer is greater over forest than over grassland, the evaporation of intercepted water in grassland areas depends more on radiative energy supply than in forests. This difference is especially significant during or after rainfalls when the advective energy supply for evaporation is frequently greater than the radiative one (Oke, 1987; Rutter, 1975).

Simulation of the hydrological differences between grassland and forest

The simulation of these differences is performed by means of an interception submodel that simulates the loss of water intercepted by vegetation, and transpiration one that simulates the regulation of transpiration by stomatal control. (Fig. 2).

- The Interception submodel:

Daily interception (I) is simulated for rainy days using maximum retention capacity (C_{max}) and a negative exponential function (Fig. 3) depending on rainfall (Calder, 1990).

Maximum retention capacities in literature are about 0.7 mm for *Molinia caerulea* grass (Leyton et al., 1967), species representative of the basin grassland cover, and between 1.6 mm (Rutter, 1975) and 3.8 mm (Aussenac, 1968) for *Pinus sylvestris*. These maximum retention capacities were determined considering only continuous rainfalls with negligible evaporation. Using these parameters the model restricts evaporation of intercepted water to only evaporation between successive days.

Water volume intercepted by vegetation that exceeds maximum retention capacity is converted to a througfall-stemflow component and considered as a net precipitation (P_n). Difference in water volume between gross (P) and net (P_n) rainfall is evaporated differently in forest than in grassland areas:

a) Forest evaporates all the intercepted water. In these conditions the sum of daily transpiration plus interception can be greater than the Penman potential evapotranspiration calculated for grassland. This characteristic of the model allows the simulation of the evaporation by advection mechanism in forests that is underestimated by the classical Penman equation (Calder, 1990).

b) For evaporation of intercepted water in a grassed catchment, the model compares the volume of water intercepted with the meteorological evaporative demand (or the difference between actual and potential evapotranspiration). Then it evaporates a volume of intercepted water smaller or equal to this evaporative demand. This part of the model is based on the idea that in grassland areas intercepted water is evaporated depending mainly on radiative mechanisms that are suitably represented in the classical Penman equation (Calder, 1990)

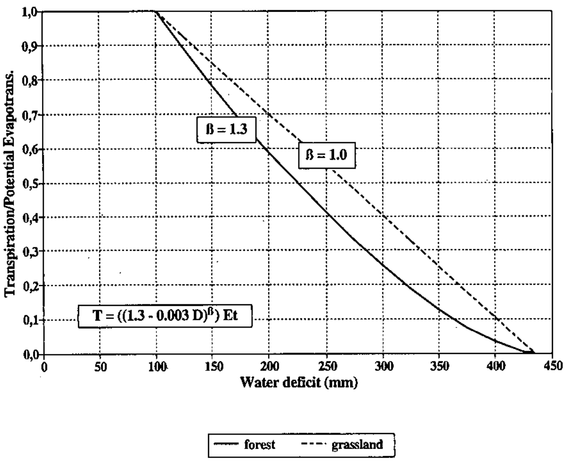

Figure 4. Relationship between water deficit of soil and the quotient transpiration versus potential Evapotranspiration used for the simulation of transpiration over grassland and forest

- The Transpiration submodel:

The decrease of transpiration in respect to the potential evapotranspiration acts, both in forest and in grassland, when basin water deficit is higher than 100 mm. This reduction of transpiration is as a function both of the basin water deficit and of the type of vegetation (Fig. 4).

This component of the model allows the simulation of a greater stomatal control by forest than by grassland in dry conditions. The equation presented in figure 4, and explicitly the ß coefficient (1.0 for grassland and 1.3 for forest) is used to simulate that transpiration of forest will be up to 50% lower that grassland one for the same atmospheric conditions (Wallace & Oliver, 1990).

Results of the simulation

To compare the simulated water balance for different vegetation cover in a sensitivity analysis exercise, the SIMBAL model was run using the 10 years daily precipitation data, since 1983 to 1992, collected by the Servicio Meteorológico Nacional (at the Vallcebre station near the basin). The initial conditions and parameters used in three executed runs are summarised in table 1.

The main results of the three model runs (table 1) considering the 10 years simulation are:

a) There are not important differences in simulated total water losses to the atmosphere (the sum of transpiration plus interception) between the two types of vegetation cover. Actual simulated evapotranspiration for each forest simulation are respectively 2 and 5% greater than grassland one (Fig. 5).- Mean forest simulated transpiration is about 87% of the grassland one.

- Simulated grassland interception is about 5.5% of the mean forest one (mean of forest1 and forest2).

b) There are not relevant differences in water deficit evolution between grassland and forest simulations (Fig. 6). Maximum annual differences are about 17 mm.

c) In spite of that there are very important differences in total runoff losses (the sum of quickflow plus baseflow) between the two types of vegetation cover.

This is due to that a little increase of water loss by evapotranspiration (transpiration plus interception) implies an important diminution in total runoff, because runoff is the smaller term of the basin water balance. Conside-

Table 1. Summary of parameters used in the three 10 years simulation runs of water balance.

Model runs	Period	Initial parameters		atmospheric losses parameters	
		Si (mm)	tcv	ß	C_{max} (mm)
Grassland	1983-92	100	grass	1.0	0.7
Forest 1	1983-92	100	forest	1.3	1.6
Forest 2	1983-92	100	forest	1.3	2.7

ß= Control of transpiration parameter; Cmax= Maximum retention capacity of intercepted water;
Si= Initial soil water deficit; tvc= Type of vegetation cover.

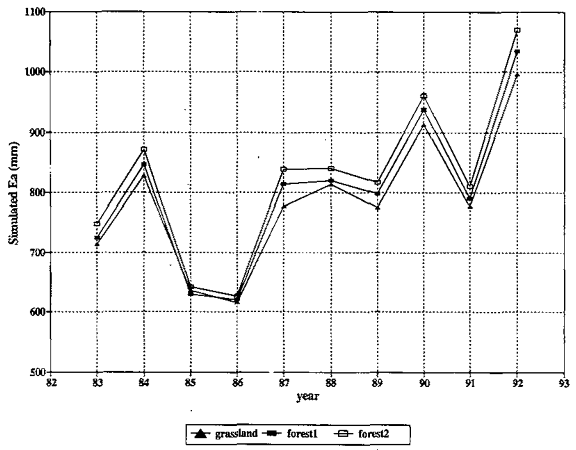

Figure 5. results of the 10 years simulation runs of water losses to the atmosphere. Simulated Actual Evapotransiration is the sum of Transpiration plus perception.

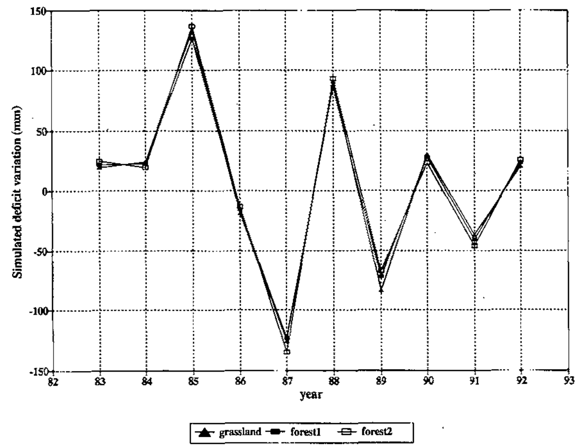

Figure 6. Results of the 1o years simulation runs of basin water deficit. The graphic presents the variations of catchment soil water deficit.

ring, as an example, the results of simulations of grassland and forest 2, the differences are: simulated actual evapotranspiration in forest2 is about 37.5 mm/year greater and runoff is about 35 mm/year smaller than in grassland. These similar figures represent an augmentation of 5% of evapotranspiration and a diminution of 32% of runoff.

Total runoff for each forest simulations are respectively 15 and 32% lower than grassland one (Fig. 7).

This difference is due mainly to the difference in the total simulated interception loss determined by the different maximum retention capacity parameters obtained for *Pinus sylvestris* from literature (Table 1).

Although simulated quickflow runoff is less affected by the change of vegetation cover than baseflow one, differences are not significant. Mean forest quickflow is about 78% of the grassland one and mean forest baseflow is about 74% of the grassland one.

d) The influence of vegetation on hydrological water balance is very sensitive to the used parameters, and specially to the interception maximum water retention capacity. A clear example of that is that difference between the two forest simulations depend directly on the maximum retention capacity figure used for the same type of tree species.

DISCUSSION AND CONCLUSIONS

As shown by the sensitivity analysis results, the variation of vegetation cover type can provoke important differences in total runoff due mainly to the increase of rainfall interception by the forest stand, even using an interception model that not allows evaporation of intercepted water during storms.

The simulation results using this conservative interception submodel predict a diminution of water yield due to afforestation of about 30%. This is about 10-20% lower than the figures presented by Bosch & Hewlett (1982) for some studies with similar mean annual precipitation.

Although in terms of total water losses to the atmosphere, part of interception loss by a forest will be balanced by a lower transpiration loss, a small modification of this water balance component implies an important variation of the runoff volume because it is the smaller component of the balance.

In order to design the most reasonable management of abandoned areas looking to the water conservation, it is necessary to better understand the hydrological mechanisms under different types of vegetation, by means of:

- The development of field experiments to obtain more accurate data of rainfall interception process. There are not sufficient experiments on conifers in the pluviometric range 600-1200 mm (Bosch & Hewlett, 1982) and especially under Mediterranean climatic conditions.

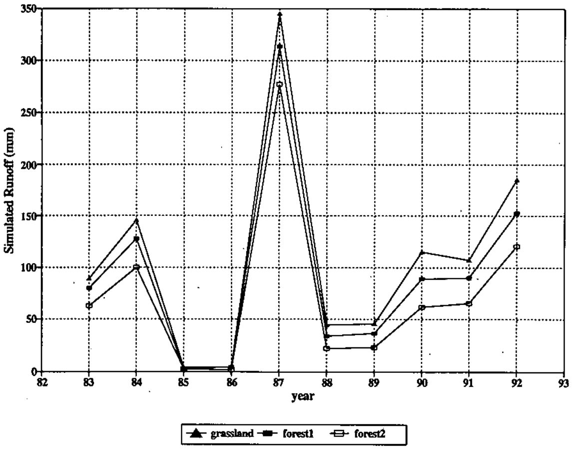

Figure 7. Results of the 1o years simulation runs of basin Runoff. Total Runoff is the sum of Quickflow plus Baseflow.

- The advancement of modelling runoff and actual evapotranspiration to lead as a final step to the construction of distributed models.

As described by Calder (1993), it would be possible to obtain a regulation of interception losses of a forest stand. Management strategies can consider, as an example, that forest can help water conservation in strong water deficit areas due to the better transpiration control by trees, whereas it could be a bad management practice in areas dominated by winds where trees are affected by higher evaporation of intercepted water.

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