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2003 - *Interdisciplinary approaches in small catchment hydrology : Monitoring and research*, 9th ERB Conference (Demänovská dolina, 2002), L. HOLKO et P. MIKLANED édit., TDH in Hydrology, n° 67, UNESCO, p. 79-84.

The Impact of Interception Losses on the Water Balance in Forested Mountain Ranges

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Abstract: Although it is commonly admitted that forest reduces annual runoff, the amount of the reduction may vary considerably as a function of the soil and climatic conditions. Forest enhances evaporation through two main processes: 1) Deeper root systems use the water stored in soil more efficiently during the summer period. As a result, more water is retained in the soil during the following autumn before the resumption of winter discharge, and annual runoff is reduced. 2) Loss by interception is greater in forested areas than for other types of vegetation cover during the winter months, mainly because of more efficient use of advective energy.
Studies in small catchments on Mount Lozère (South of France) have shown that during the winter period, "actual" evapotranspiration (calculated by the water balance method) is higher than "potential" evapotranspiration (estimated using a standard equation). These differences are due to interception losses. During the study period, one small spruce-forested catchment was cut and replanted, while another grassland/heath catchment was left undisturbed. Interception losses for the two basins were compared. The study period (1982-1995) covered the pre-cut (1982-1987), cutting (1987-1989) and postcut/regrowth (1990-1995) periods. Results show that cutting the forest did reduce interception losses. However, the hydrological behaviour of the cut catchment changed back to its pre-cut behaviour relatively quickly and clearly before the new plants had developed enough to be considered as forest cover.

Keys-words: Forest hydrology; interception; forest evaporation.

1.INTRODUCTION

The hydrological impact of forest is one of the most controversial issues when it comes to studying the consequences of human activities on water resources (Calder, 1979, 1985; Morton, 1984, 1985). As early as 1982 – and the study is still a reference – Bosch and Hewlett concluded their study "A review of catchment experiments to determine the effect of vegetation changes on water yield and evaporation" by emphasizing the complex nature of the results. Only one thing was certain: "No experiment in deliberately reducing cover caused reductions in yield, nor have any deliberate increases in cover caused increases in yield". Obviously, then, if the forest has an impact on annual runoff, it is to reduce it. The reduction is all the greater when conditions include a large water deficit, abundant water reserves, and also frequent but light rainfall (Cosandey and Robinson, 2000).

Two mechanisms account for the reduction:

- One, the forest affords a larger surface for interception during rainfall and enough roughness to favour high air turbulence and, therefore, more efficient use of advective energy and a higher rate of evaporation. On the other hand, the evaporation can limit plant transpiration, and it is difficult to evaluate the increase in overall evapotranspiration that results from the direct evaporation of intercepted water. It is not possible to know the value for the increase from direct measurements of the intercepted water that does not reach the soil, since a partial compensation can occur with a decrease in plant transpiration (the available energy is used more quickly in order to evaporate the water that is more easily available on the surfaces of leaves or branches).
- Two, because the forest is more deeply rooted, it has a greater potential soil moisture reserve (which secures its water supply when evaporation exceeds rainfall). A greater reserve allows more evaporation during the summer months, and therefore lower flows in autumn that start later in the season due to the larger amount of water taken up by the soil.

If a classic sequence of rain events for an hydrologic year in temperate climate is considered (Cosandey and Robinson, 2000), the forest delays the resumption of flows at the start of the rainy season, because the soil moisture reserves have been depleted by the trees during the dry season. Of course, the delay is accompanied by a drop in runoff. The forest also reduces winter flows directly, due to the direct evaporation of part of the precipitation that is intercepted by the canopy and does not reach the soil. Such higher winter evaporation depends a lot on the type of vegetation, of course, and a heath with broom growing on it is probably much more efficient than a broad leaved forest.

Evaporation during the summer period (when evaporation demand exceeds rainfall) is dependent on the available water (precipitation plus the soil water storage). Interception has no impact on precipitation, none on soil water storage, and so it does not change the values for evapotranspiration during the summer. The resulting interception losses, therefore, have an effect on flows only during the winter period and can be estimated only within that framework.

When a forest is cut, the estimation of evaporation before and after the cut should make it possible to estimate the differences between a forested catchment and an unforested one, and therefore the impact of interception losses on runoff.

2.EXPERIMENTAL SET-UP

Three small catchments on granite in the Mount Lozère Experimental Research Basin (ERB) have been monitored since 1981. These are the spruce-forested Latte (0.195 km^2), the beech-forested Sapine (0.54 km^2), and the grazed-grassland Cloutasses (0.81 km^2). The slopes there are moderately steep - approximately 12° (Latte), 18° (Sapine), and 10° (Cloutasses). The Latte catchment (Fig. 1) was the most closely observed catchment, as 80% of its surface was clear-cut of its spruce forest from 1987 to 1989.

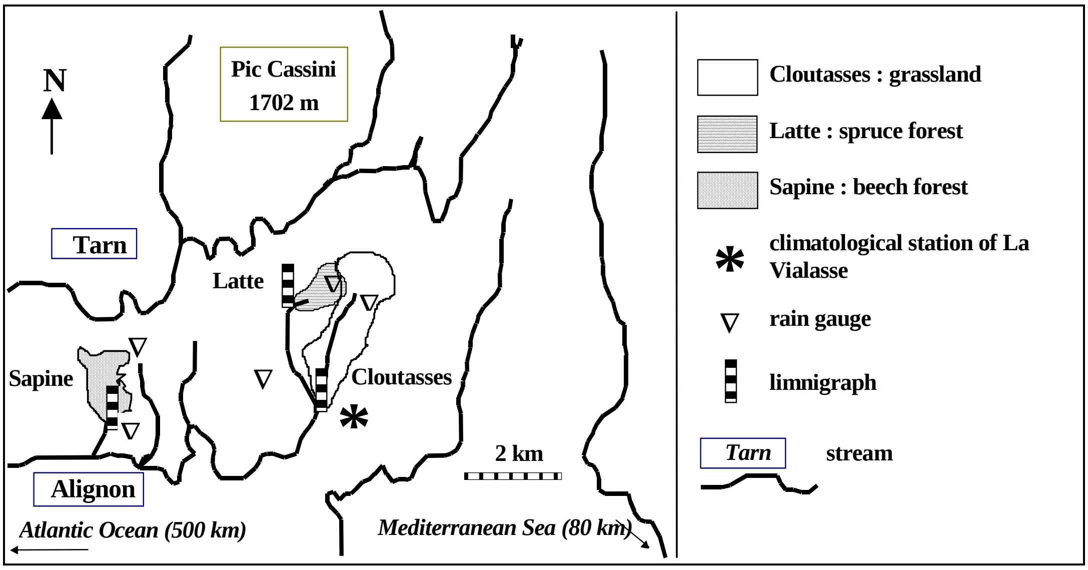

Figure 1 - Experimental pattern.

At between 1100 and 1500 metres in elevation, the Mount Lozère ERB has a mediterranean climate with mountain characteristics. The mean temperature at 1300 m is of 6.9 °C. Mean annual precipitation is about 2000 mm, and ranges between 1100 and 3500 mm. Rainfall can be very violent, especially in autumn during "cévenols" events; for example on the Latte catchment, maximum intensities for 30 minutes reached 179 mm h^{-1} on August 28 1999 and 131 mm h^{-1} on September 22 1993. On the average, the soils and superficial deposits are from 60 cm (Sapine) to 70 cm (Latte and Cloutasses) thick. Filtration rates for the soils as determined in simulated rain conditions range from 78 to more than 123 mm h^{-1} under undisturbed vegetation and for well-protected soils (Cosandey *et al.*, 1990).

3.METHODOLOGY

Estimation of "interceptions losses" (increase in global evapotranspiration resulting from interception) can be done only from water balance. Direct measurement of interception allows knowing the part of the rain that never reaches the soil. But the energy used for evaporated this intercepted water is not able for transpiration or other evaporation, and the global evaporation is not accrues by the total value of measured interception.

The method is based on the water balance equation calculated during the "excess water period", when rainfall exceeds atmospheric water demand (what is called “hydrologic winter”, usually – but not always – from October to April).

It is known that during the hydrologic winter (defined by R>Pe), the equation may be expressed as:

$$R = D + Ae + \Delta R,$$

Where:
R = measured rainfall
D = measured runoff
Ae = actual evapotranspiration
Pe: potential evaporation (calculated with Turc formula; Turc, 1961):
$\Delta R = \Delta Ru + \Delta Rh$
with ΔRu soil moisture storage (function of soil characteristics and depth of root development)
and ΔRh groundwater storage (deduced from beginning and end-of-period base flow and the recession curve)
In the following study, the thin soils prevent the vegetation from developing a very deep root system, so there is very little difference in the soil moisture storage. This difference has been estimated at 20 mm (100 mm for the forest and 80 mm for heath/grassland). These reserves probably were somewhat depleted when the forest was cut, at least during the two year following the cut. Because these values are a bit arbitrary, they do constitute a source of uncertainty in the following developments. If the estimated interception losses into consideration, however, the magnitude of the uncertainty is negligible.

From this basic equation, you obtain for the duration of the hydrologic winter:

$$Ae = R - D - \Delta R$$

This calculation of Ae is done for the two basins. The problem, well known, is that the value of Ae is the residual term of the calculation, which includes errors in rainfall and runoff storage measurements. For this reason, not the values themselves, but only *the ratio between the values* are taking in account, according to the "comparative basins method". This method allows to reduce error concerning rainfall (which are quite the same for the two basins, and have no consequence on the difference of Ae estimation) and error concerning runoff, due to calibration curves, which remain the same for each basin respectively.
Of course, the forest cut didn’t change only evaporation (from the angle of evaporation of intercepted water). It also affected plant transpiration, although we are operating here on the hypothesis that plant transpiration can be ignored during the months of winter dormancy, especially given the low temperatures involved.

4.RESULTS

Differences in Ae, attributed to differences in interception losses were estimated over a period of twelve years for two catchments, (the heath/grassland Cloutasses, and the initially forested Latte, five years before the cur; seven years after the cut during the summer of 1987). The results are shown in the following table (Table 1).

Two preliminary remarks:

1) Values of Actual evapotranspiration are higher than values of Potential evapotranspiration from Turc formula (from local data). Turc formula is not the best for Pe estimation. But there is not data for Penman equation and theses Pe values are taken in account only for the limits of winter season. Even if Turc formula drives to lower values, it seems that interception losses are effective even on the grazed heath/grassland catchment. The presence of broom plants and clumps of trees can probably explains this.

2) The wide range of values is difficult to explain, even if they are clearly in relation with Etp values. It is clear that measurement error both on rainfall and runoff play a role; but as seen above consequences are minor on the differences.
In order to determine the impact of the forest cut on interception losses, we can take a look at the evolution in the ratio between Ae in the two basins before and after the cut.

Figure 2 shows that after the cut, the ratio between evaporation in the two basins, with was positive before the cut became negative after.

Table 1 - Actual evaporation in the two basins for the whole period (see annexe 1 for details):

hydrologic winter	Ae Cloutasses	Ae Latte	Ae Lat - Ae Clout	Ae Lat / Ae Clout
82/83	555	671	-116	1.21
83/84	349	456	-107	1.31
84/85	463	572	-109	1.24
85/86	121	198	-77	1.64
86/87	348	499	-151	1.43
87/88	504	394	110	0.78
88/89	300	283	17	0.94
89/90	538	498	40	0.93
90/91	226	198	28	0.88
91/92	447	444	3	0.99
92/93	457	475	18	1.04
93/94	328	347	-19	1.06
94/95	488	470	18	0.96
95/96	347	276	71	0.80

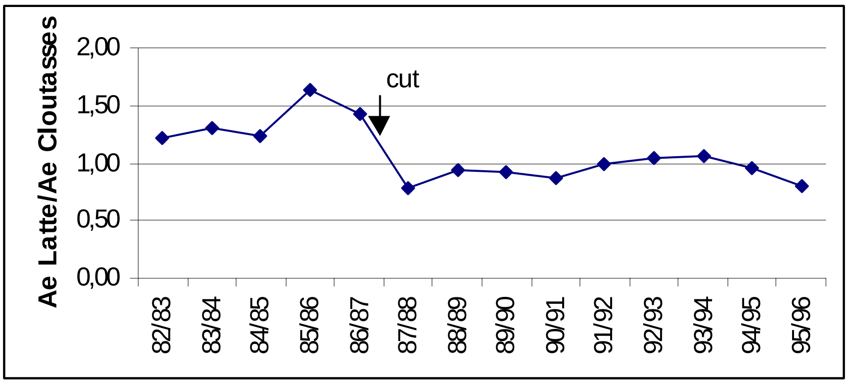

Figure 2 - Ratio between Actual evapotranspiration values for the Latte and the Cloutasses Basins.

5.DISCUSSION

Before the cut, the interception losses were higher in the spruce-forested Latte catchment than on the Cloutasses catchment. There was a large decrease in interception losses during the winter that followed the cut, explained by the reduction in evaporating surface area: more than a third of the trees were cut and, although debris from the cut was strewn over the ground, there was no plant colonisation to cover the deforested areas. In these conditions, it is not surprising that interception losses were lower than on the heath/grassland catchment.

The situation rapidly changed, however. By the following summer, an abundant herbaceous (great willow herb) and shrub (raspberry bush) vegetation had developed; nowhere was bare ground to be found. By the second post-cut winter, the deforested catchment's behaviour was similar to that of the heath/grassland catchment, even though cutting operations had resumed in an area where tree growth was less successful; it remained similar even though some very small trees were planted (very slow growth in the difficult climatic conditions, so their impact was still very limited).

6.CONCLUSION

This study was based on a certain number of hypotheses and rough calculations. In particular, it is clear that using water balances involves the risk of accumulating errors in data measurements (principally rainfall and discharge). Comparing neighbouring catchments is a way to reduce this type of risk, however, especially since it makes it easier to take any possible impact of climate variability into account.

Beyond such uncertainty, we felt that it was of interest to give further thought to the hydrologic processes that bring about lower flows under forest cover. Once a higher level of evaporation during the winter period was identified on the forested catchment, and it was ascertained that it could be due only to the involvement of loss by interception, it became easier to understand why the overall increase in runoff that was observed after the cut concerned only minor floods. During the "cévenols" rainfall events, the amount of rain and the depth of runoff can be enormous – and the effects of interception losses become totally unnoticeable. The same cannot be said of a relatively light rainfall event. In that case, the depth of runoff measures only a few millimetres, and can therefore be heavily influenced in terms of relative value by a reduction in the effective rainfall due to interception of part of the rain by the plant cover.

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Annexe 1 - Data for Ae calculation

Latte Basin				
hydrol. winter	D (mm)	R (mm)	**ΔR**	Ae
82/83	1500	2269	98	671
83/84	874	1490	160	456
84/85	1455	2150	123	572
85/86	840	1310	272	198
86/87	1273	1890	118	499
87/88	1959	2608	255	394
88/89	624	1065	158	283
89/90	752	1384	134	498
90/91	950	1280	132	198
91/92	805	1380	131	444
92/93	1185	1798	138	475
93/94	1690	2216	179	347
94/95	1369	2012	173	470
95/96	2797	3227	157	273

Cloutasses Basin				
hydrol. winter	D (mm)	R (mm)	**ΔR**	Ae
82/83	1513	2184	116	555
83/84	1018	1490	123	349
84/85	1452	2052	137	463
85/86	1049	1310	140	121
86/87	1221	1738	169	348
87/88	1925	2608	179	504
88/89	620	1065	145	300
89/90	720	1384	126	538
90/91	934	1276	116	226
91/92	826	1392	119	447
92/93	1194	1769	118	457
93/94	1754	2216	134	328
94/95	1386	2012	138	488
95/96	2760	3227	120	347