# Effects of Altitude on Ecohydrological Processes

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**Abstract**

In several locations of the Osterzgebirge mountain area in south-eastern Saxony, at different altitudes but exhibiting the same soil conditions and similar plant communities, we measured abiotic environmental factors such as radiation, temperature, humidity, wind velocity, precipitation, and soil moisture, as well as the rates of such · controlled ecohydrological processes as interception, transpiration, runoff formation, and percolation. There are some differences between the gradients of meteorological variables in this area and those in some other regions, e.g., in high mountain areas in the tropics or sub-tropics. Therefore, the general synoptic and climatic situation of the investigated area has been taken into consideration. The results obtained by experiments and modelling provide an insight into the complex and temporally varying ecohydrological processes; as being dependent on the altitude of the investigated location. One important result is that the greater the altitude the smaller the evapotranspiration, the greater the percolation, and the greater the soil moisture available for plants.

## Introduction

Abiotic environmental factors, such as radiation, temperature, humidity, precipitation, wind, and soil, influence not only the development of a plant community but also the processes of the hydrological cycle. They depend on the synoptic situation of the area, soil conditions, and local climate. The latter is, in mountainous regions, chiefly dependent on altitude. Consequently, under otherwise equivalent climatic and soil conditions, the interrelationship between vegetation cover and hydrological processes in mountain areas is greatly influenced by the altitude.

But the dependence of ecohydrological processes on elevation in a high mountain area in the tropics or sub-tropics is fundamentally different from what it is in a high mountain region of the middle latitudes or in sub-alpine mountains within these zones (Blüthgen and Weischet 1980). The trade winds or monsoon prevalent over long periods of time and the small differences between the seasons in the low latitudes produce other conditions than those strongly changing air streams caused by cyclones and anticyclones in the middle latitudes. Thus, if the elevation gradient of the atmospheric forces driving the ecohydrological processes and represented by the gradients of meteorological elements is to be understood, the integration of the investigated region into the macro- and meso-scale climatic situation has to be considered first of all.

## Investigated Area and Locations

Investigations have been carried out in the low mountain range of south-eastern Saxony. Starting from an altitude of approximately 100masl, in the valley of the river Elbe, the terrain rises over a distance of 40km to the ridge of the eastern Erzgebirge mountains at nearly 1,000masl. Within this area we have intensively investigated ecohydrological processes at stations at lower altitudes (Ökomeßfeld/ Wildacker (ÖM) - 375masl) and upper altitudes (Oberbärenburg (OBB) - 735masl; Zinnwald (ZI) - 877masl). In those locations, the geology (porphyry) and the periglacially formed soil profile (podsol brown earth, rich in skeleton, sandy loam) are the same. Thus the gradients of the meteorological variables cause the variations in the ecohydrological processes and the average water balance.

From the skeleton fraction and grain size distribution of the fine soil, the hydrological properties of the latter may be determined. Small storage capacity and high hydraulic conductivity characterise the sites as well drained and of excellent infiltration capacity. Lateral runoff components (overland flow, interflow) do not occur in such soil. The vertical exchange of moisture (infiltration and percolation during precipitation events and removal by evapotranspiration) controls the site water balance. In both locations, spruce forests (*Picea abies* (L.) Karst.) thrive. But there are differences in the ages of the stands and in the degree of anthropogenically caused damage to the trees. In Ökomeßfeld, we find a 122 year-old forest; in Oberbärenburg only a 40 year-old one. The latter is more damaged (needle loss, yellowing) due to decades of $SO_2$ pollution from the brown coal open-cast mining in the Bohemian basin.

## Climate and Gradients of the Meteorological Variables

Among the abiotic environmental factors, the meteorological ones are of particularly great influence on ecohydrological processes. Our goal of estimating rates of ecohydrological processes in a mountainous area requires knowledge of the meteorological variables dependent on altitude (Running et al. 1987).

The relief influences the climatic situation in three ways: i) hypsometric change of the meteorological elements (radiation, temperature, steam, wind velocity, precipitation), ii) windward and lee effects arising from the interaction between mountains and air currents, and iii) curvature of isotherm and isobare surfaces above high mountain areas.

The third influence can be neglected for the research area in Saxony because of the area's small morphological gradients and the relatively low elevation compared to high mountains.

In order to understand the special features of the meteorological gradients in the investigated region, we have to consider its integration into the macro-scale synoptic situation (Peschke 1992). The zonal axis of Saxony lies 51° north. Thus, there is great seasonal differentiation as to the sun's altitude and the duration of its radiation. For example, the altitude of the midday sun at winter solstice amounts to only 15.4°, and the length of daylight is about eight hours. The analogous values at summer solstice are 62.4° and 16.6h respectively. As a consequence, there are great thermal differences between the seasons: spring, summer, autumn, and winter.

The atmospheric circulation above Saxony is dominated by the westerlies of the middle latitudes. In front of frequently eastward-moving cyclones, warm air from the subtropical regions stream northwards, while along their back side, cold air from sub-polar regions moves southwards. This results in frequent and abrupt weather changes. Cloudiness and precipitation are non-seasonally distributed and reach their peaks in winter and in summer. Owing to increasing convection and higher humidity, the summer peak exceeds the winter one. Given the nearness to the ocean, we have a maritime influence predominating during the warm season. Due to the Gulf Stream, Saxony has a thermal preference compared to other locations of equal latitude. Average monthly temperatures of 0°C in the valley of the river Elbe and -5°C at the highest elevations are indicative of the winter minima. The highest average summer temperatures are 18°C and 11°C, respectively. Not only the differences of temperature between warm fronts and cold fronts but also wind velocities increase during the winter because of greater differences of temperature and air pressure between northern and southern Europe.

Characteristic, frequently occurring, general weather patterns delay not only the warming in spring but also autumn cooling. The general weather patterns featuring westerlies predominate in winter and summer (45 - 50% of all days). During autumn and spring they are less frequent. Thus, the winter and summer seasons are more maritime, with a lot of precipitation; the winter season is milder and the summer cooler. If there is high pressure above northern Europe and low pressure in the Mediterranean region, easterly wind situations occur, particularly during May (27% of all days). In winter they account for 20 per cent and in July for 10 per cent of all weather. Among the meridional forms of general weather patterns, northerlies transport arctic polar air directly to Central Europe. They occur increasingly during the period from April to June (25% of all days) and delay the warming during spring.

This synoptic situation, unknown to other climatic regions, and the lower elevation of the investigated low mountain range, modifies the gradients of the meteorological elements in their absolute value and seasonal variability. They can be very different between years, seasons, months, decades, and pentads. In this paper we cannot deal with this temporal variability in detail. We merely refer to it in some connections to explain certain trends.

The main driving power of all meteorological, hydrological, and ecological processes is solar radiation. Its intensity and the ratio of direct solar radiation to global radiation increase with altitude in high mountains. At this point, we encounter the contrary conditions in our research area. Among all climatic stations in Saxony, the station Zinnwald-Georgenfeld on the ridge presents the lowest values of sunshine duration. The average annual totals are reduced by 80-90 per cent. This fact is also valid for single months, except for the summer months from June to August. That is a consequence of the barrier effect of the mountains on the air currents. Northwesterlies flow perpendicular to the eastern Eerzgebirge mountain range. The cool and humid air masses from the Atlantic region cause a relatively steep drop in the condensation level. Therefore they produce humid, cool, overcast, and often foggy weather. Classic foehn effects occur only with southerly winds and are very seldom. Inverse thermal stratifications can be observed predominantly during a few days in winter. They reverse the normal situation and produce radiative and warm weather in the higher altitudes and cooler and foggy weather in the valleys of low regions. Because these inversions have only short-term effects, they are not decisive for the annual averages.

For some stations in Saxony. Figure 1 shows a decrease of the mean temperature with increasing altitude. A gradient of almost 0.6°C per 100m is representative in the region. During the winter it is lower, and, in inversion weather situations, the reverse. From these facts (barrier effect, decrease of temperature) there results an average increase of precipitation by about 50mm/100m (lower part of Fig. 1). The special microclimatic conditions of the area around each station, differences in season, and certain weather patterns can lead to considerable deviations from the mean gradient. From a comparison of the climatic diagrams of the stations of Ökomeßfeld/Wildacker and Zinnwald (Fig. 2) it is clear that the seasonal variability of the mean monthly precipitation is greater in the high-altitude locations, due to more convective precipitation during the summer season.

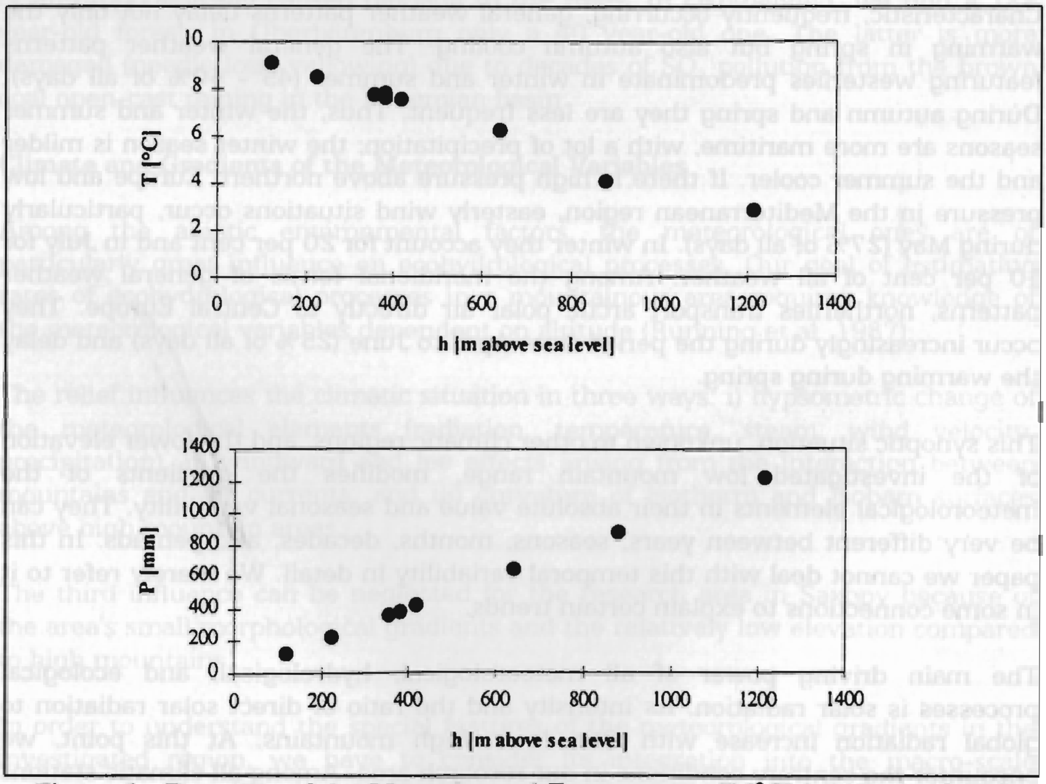


**Figure 1: Decrease of the Mean Annual Temperature T [°C] (upper part) and Increase of the Mean Annual Total Precipitation P [mm] (lower part) with Increasing Altitude, h, for Some Stations in Saxony**

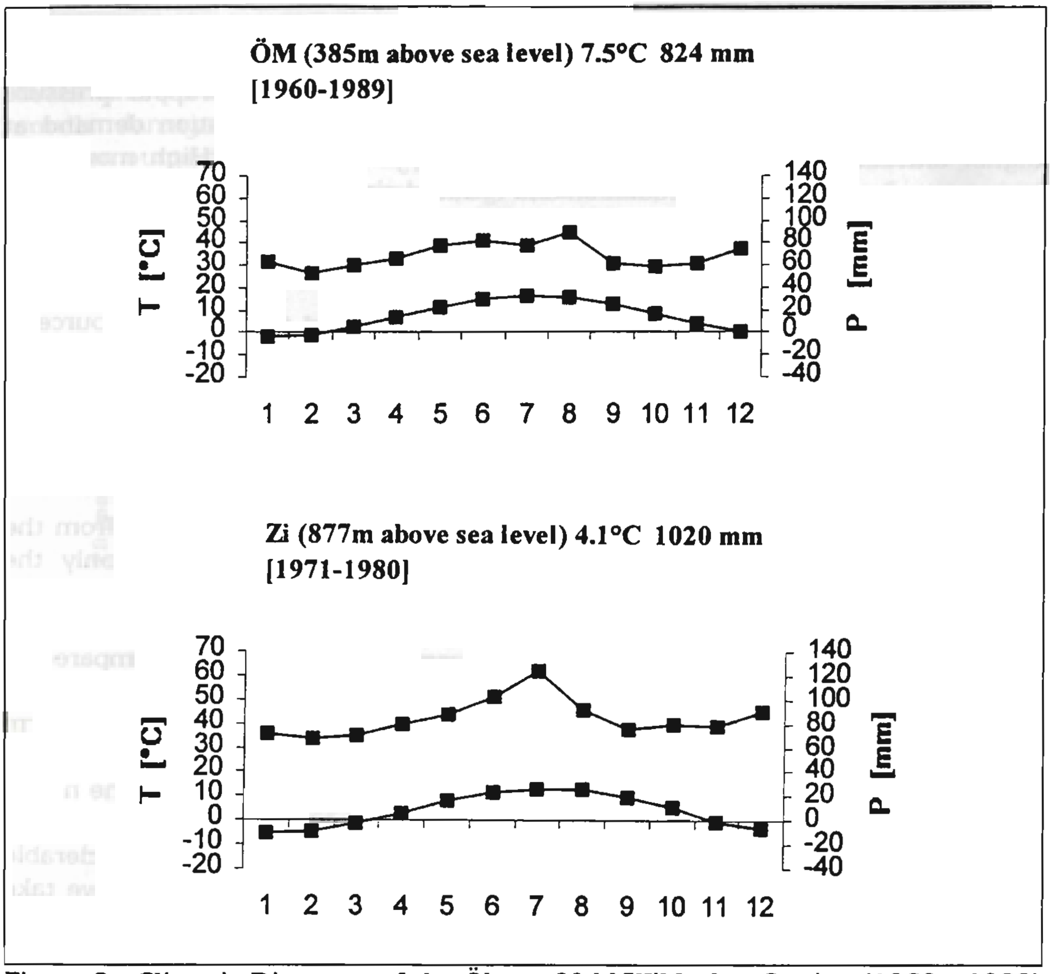


Figure 2: Climatic Diagrams of the Ökomeßfeld/Wildacker Station (1960 - 1989) (upper one) and of the Zinnwald - Georgenfeld Station (lower one)

At the stations of Ökomeßfeld and Oberbärenburg we carried out experimental ecohydrological investigations during the period from 1985-1994. From the results of Table 1 we can calculate mean gradients of $\Delta P/\Delta h$ = 57mm/100m and $\Delta T/\Delta h$ = 0.7°C/100m, which are very close to mean values of the whole region. In addition, the great variability can be seen: the gradients fluctuate between 11mm/100m in 1994 and 110mm/100m in 1988, between 0.58°C/100m in 1986 and 0.92°C/100m in 1989.

**Table 1: Mean Annual Precipitation [P] and Mean Annual Temperature [T] at the Stations of Ökomeßfeld/Wildacker (ÖM) and Oberbärenburg (OBB)**

| | P [mm] | | T [°C] | |
|---|---|---|---|---|
| | ÖM | OBB | ÖM | OBB |
| 1985 | 744 | 895 | 6.7 | 4.4 |
| 1986 | 932 | 1,129 | 7.3 | 5.2 |
| 1987 | 933 | 1,249 | 6.6 | 4.3 |
| 1988 | 852 | 1,248 | 8.3 | 5.6 |
| 1989 | 667 | 937 | 9.1 | 5.8 |
| 1990 | 614 | 832 | 9.1 | 6.5 |
| 1991 | 650 | 848 | 8.1 | 5.2 |
| 1992 | 791 | 959 | 8.8 | 6.6 |
| 1993 | 821 | 936 | 7.7 | 5.3 |
| 1994 | 891 | 929 | 9.0 | 6.3 |

The interrelations discussed up to now lead consequently to a further remarkable distinction of the investigated low mountain range in comparison to high mountains. Because of the decreasing energy and decreasing vapour pressure deficit with increasing altitude, the atmospheric evapotranspiration demand at higher altitudes is reduced in contrast to the high mountains. High mountains have a greater share of solar radiation and reduced air pressure.

### Comparison of Water Balance at Different Altitudes

Precipitation is not only an input to the water balance but also the only source of water available to plants. Let us turn our attention to plants. The amount of precipitation, P, forming soil moisture, Θ, is

$$\Theta = P - IE - R - E \qquad (1)$$

(IE - evaporation of intercepted water, R - percolation, E - evaporation from the ground cover). From this amount of soil moisture, plants can use only the difference between the field capacity and wilting point.

A special critical situation for trees arises if very little precipitation compared to the long-term mean values occurs. This happened in 1990. From Table 1, it follows that the total for 1990 amounts to about 80 per cent of the long-term average. However, the interannual distribution of precipitation (Fig. 3) shows that in May and July only about 23 per cent of the mean monthly sums fell. The nearly normal amounts in June were the result of a few heavy rainfalls. During and after them the water infiltrating into the soil rapidly percolated. Thus, a considerable soil moisture deficit accumulated during the period from May to July. If we take into consideration the higher potential evapotranspiration (Fig. 7) at the lower site, Ökomeßfeld, it follows that during the growing season drought stress can happen at lower altitudes, but rarely in higher regions.

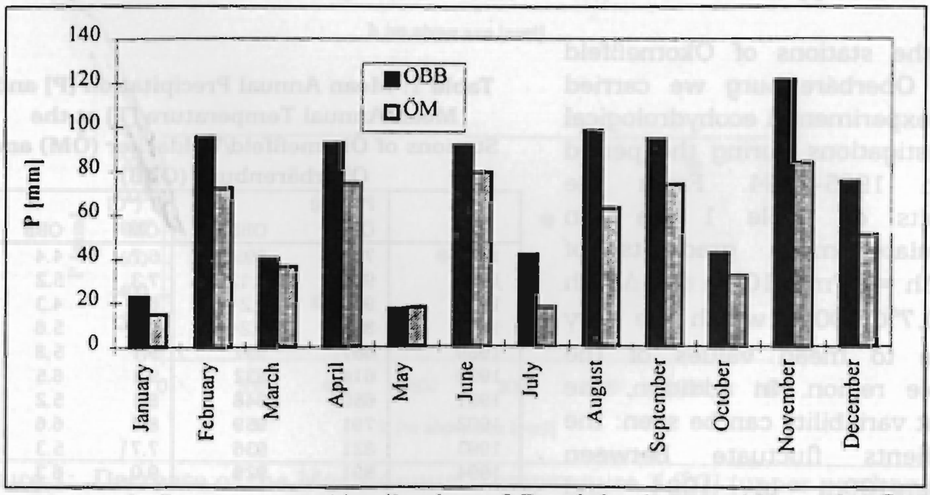


**Figure 3: Interannual Distribution of Precipitation (1990) at the Stations of Öberbärenburg and Ökomeßfeld/Wildacker**

We move on to a discussion of 'loss-term' evapotranspiration with interception. Figure 4 highlights the relationship between precipitation under trees within the forest and precipitation on uncovered ground. Due to the greater age and the smaller damage of the spruce stands in the lower range at ÖM, the leaf area index (LAI) amounts to $6.8m^2m^{-2}$ compared to $5m^2m^{-2}$ at OBB. Therefore, interception at the Ökomeßfeld station is greater (Fig. 4). Further, the percentage of interception is considerably increased for lower precipitation amounts and lower precipitation intensities.

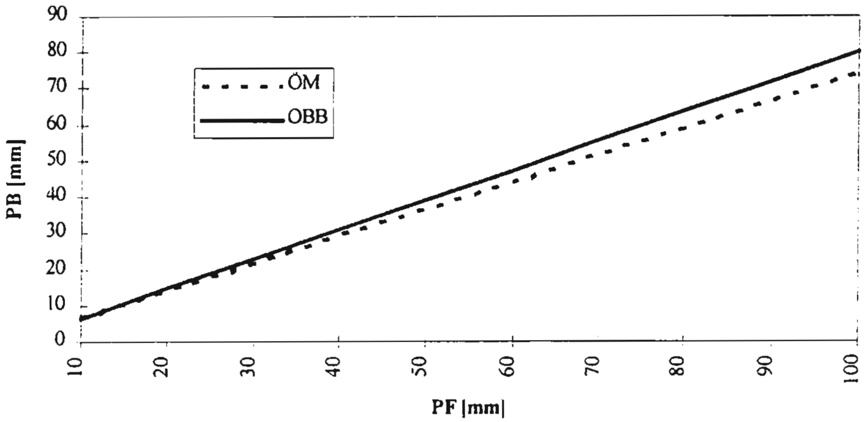


**Figure 4: Relationships between Precipitation under Trees (PB) within the Forest and Precipitation on Uncovered Ground (PF) to Estimate the Amount of Interception**

We determined the total evapotranspiration using several methods independently of each other (eddy-covariance measurement, calculation of potential evapotranspiration and soil moisture loss). We obtained the transpiration from plant-physiological measurements and simulation by models (Peschke et al. 1986, Gurtz et al. 1990, Münch 1994). Figure 5 gives an example of evapotranspiration and its components, estimated for the period August 1994 in the high-altitude range. The mean evapotranspiration amounts to 1 - 2 mm $d^{-1}$ and is, in dry periods, only represented by transpiration. In precipitation periods, a considerable part of the potential evapotranspiration is contributed by evaporation of the intercepted water on vegetation surfaces and on the ground.

Both sites are characterised by good infiltration and percolation conditions. Lateral runoff components are not found. It is particularly during the winter season that the greatest part of precipitation percolates (Fig. 6). Due to accumulation in the snow cover there is a temporal delay between precipitation and percolation.

Let us now consider the precipitation distribution in the various components of the water balance. Figure 7 gives the result for the five-year period from 1990-1994. The strong decrease of evapotranspiration and the significant increase of percolation at the higher altitude site is immediately noticed. Even if we hold

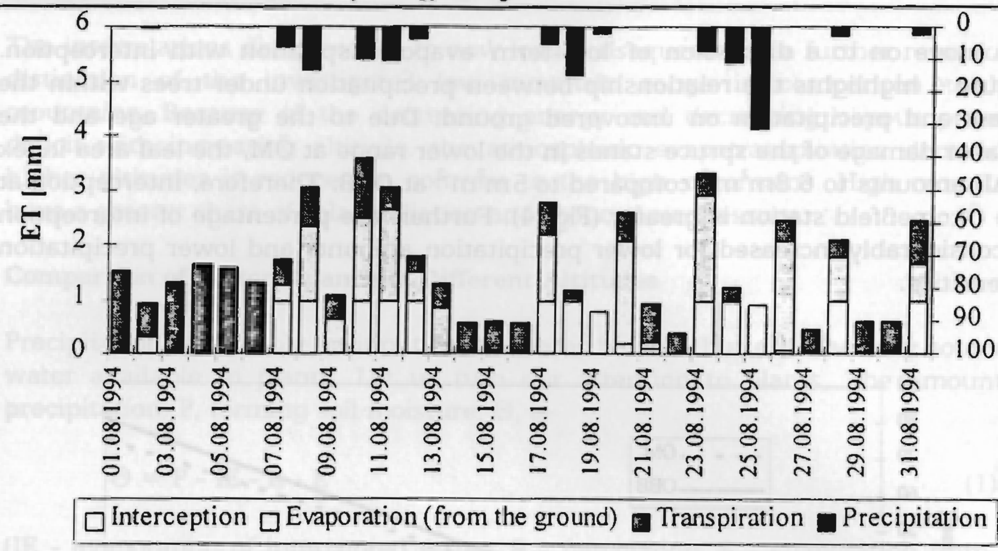


**Figure 5: Components of Evapotranspiration, ET, during the August 1994 Period in the High-altitude Range, Estimated by Simulation with a Mathematical Model**

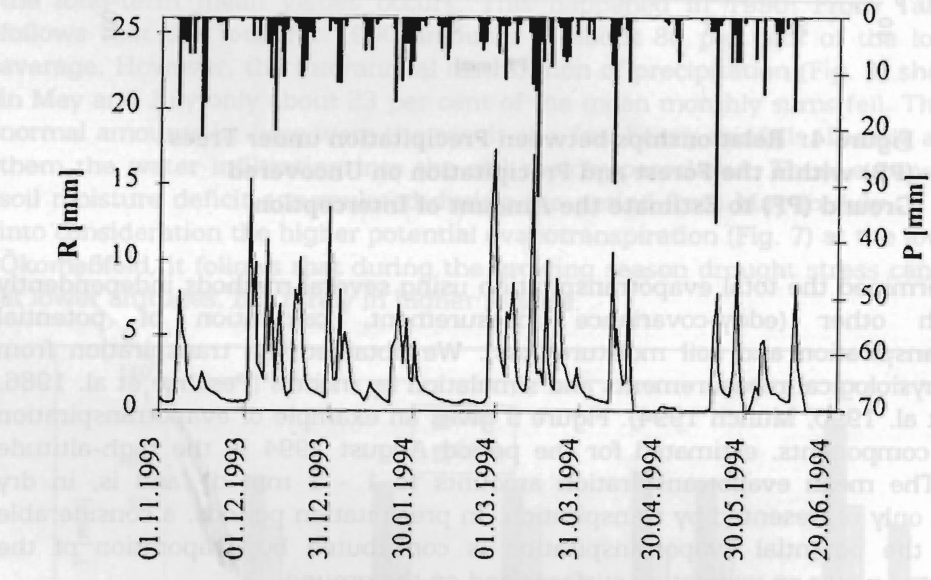


**Figure 6: Calculated Percolation, R, at the Oberbärenburg Site**

possible model errors responsible for the calculation of the small evapotranspiration in Oberbärenburg, the estimated trend remains in accordance with the discussion in Section 3 of this paper. This difference between the sites of lower and higher altitudes suggests a higher soil moisture content in the high-altitude range (Fig. 8). This means that even in relatively dry periods, significant drought stress will happen probably only in the low-altitude region.

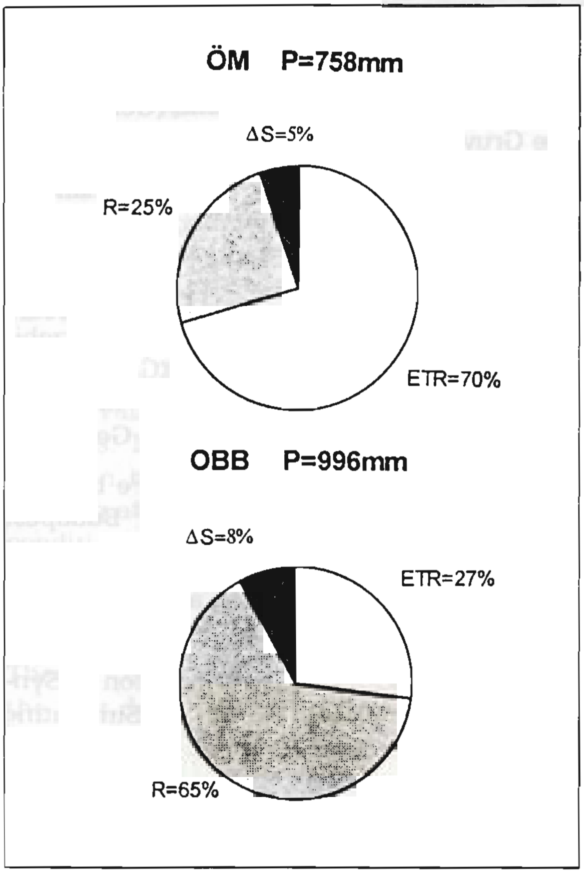


Figure 7: Components of the Water Balance in the Locations of Lower (left side) and Higher (right side) Altitude (ETR - evapotranspiration, R - percolation, $\Delta S$ - change of soil moisture storage)

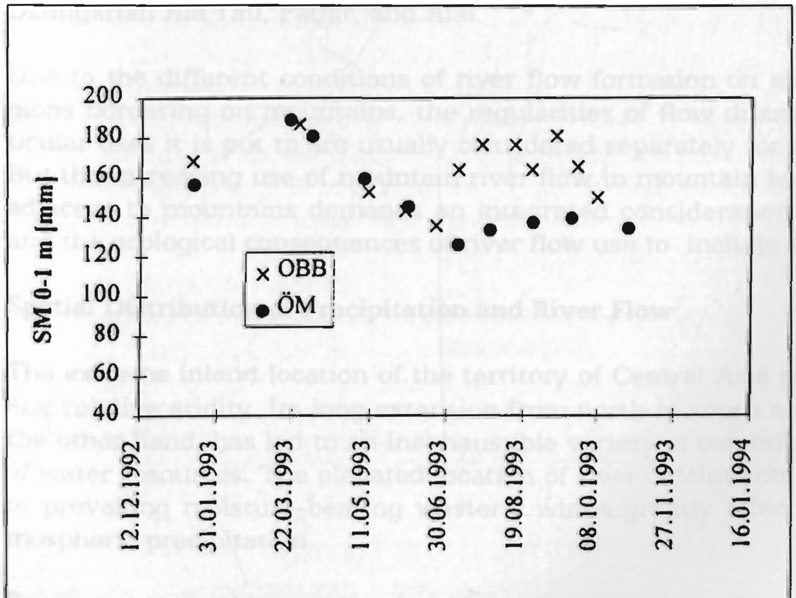


**Figure 8: Comparison of the Soil Moisture (SM) Content between the Stations at Lower and Higher Altitudes**

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