Goldberg, V. & Ch. Bernhofer (2007): Water balance of forested catchments. In: Lozán, J. L., H. Grassl, P. Hupfer, L.Menzel & C.-D. Schönwiese. Global Change: Enough water for all? Wissenschaftliche Auswertungen, Hamburg. Online: www.klima-warnsignale.uni-hamburg.de

1.9 Water balance of forested catchments

VALERI GOLDBERG & CHRISTIAN BERNHOFER

SUMMARY: *More than 26% of the land surface are covered by forests. Today these forests are threatened by human activities like increasing usage of wood, agricultural use and air pollution. The water budget of forested catchments differs markedly from bare soils or grasslands by significantly higher interception losses due to higher leaf area per surface area. This filtering function of forests leads generally to a lower quantity but better quality of usable water as well as to a more equally distributed runoff thus minimising erosion. In the last decades the contamination of vegetation and soils by high deposition led to a higher concentration of nitrogen in runoff, especially near strong emissions. Altogether the positive effects of forested watersheds on water supply dominate, so that the conservation of large and dense forests is necessary to cope with global water problems in the future.*

Forest is one of the most important surface types globally covering about one quarter of the land surface. This fraction corresponds to an area of about 38.7 millions km² which is circa 8 % of the entire Earth surface (earthtrends.wri.org). Forest areas are shared into tropical forests (42%), boreal forests (33%) and temperate forests (25%), and they are the land use type with the strongest reduction in area in the human history. While large areas in Russia and Canada as well as in the Amazon and Congo Basin are still covered with primary stands the forested areas in Central and Western Europe are exclusively managed by forestry.

Recently 35% of the formerly 66 millions km² of forest areas were destroyed, and 43% were converted in secondary forests (BRYANT et al. 1997). In this context forest fires as natural phenomena play an important role to control the forest fraction of the boreal zone. The change of global forest cover in the future depends on the climatic and socio-economic development (*Table 1.9-1*).

In modern industrial societies forests are sources of wood for paper, pulp, building, furniture, and energy. In developing countries wood is primary used for cooking and building. In the last decades protection and social functions of forests become more important. Forest areas act as recreation areas and as sources of cold and fresh air for urban areas. In high mountains forests additionally protect the terrain against erosion, landslides and avalanches.

Table 1.9-1: Trend of global forest cover (millions ha) in the 21th Century based on IPCC scenarios B1 (globalisation with sustainable and balanced development) and A1 (globalisation with material-oriented development) (www.ipcc.ch).

Region	*1990*	*2050 B1*	*2100 B1*	*2050 A1*	*2100 A1*
OECD	1,115	1,351	1,451	1,263	1,262
East Europa /Russia	1,146	1,350	1,480	1,238	1,200
Asia (without Russia)	488	302	671	244	515
Africa/LatinAmerica/ Middle East	1,528	1,548	1,940	1,429	1,722
World	*4,277*	*4,551*	*5,543*	*4,173*	*4,700*

Forests often cover catchments of drinking water, and hence, they play an important role for water management. E.g., large cities like Los Angeles, Beijing, Vienna and Munich cover the main part of water demand from forested watersheds.

The water budget in a forest

The characteristics of forest water budget permit to change the quantity of usable water with relatively small changes in forest management. *Fig. 1.9-1* shows the most important components of the water budget in a forested catchment. The complete balance is written by:

$$PF = I + T + E + RBO + fGW + S - RBI - fKa - IK$$

with undisturbed precipitation **PF**, interception **I**, transpiration **T**, evaporation **E**, lateral outflow near surface **RBO**, deep percolation **fGW** , soil water storage **S**, lateral inflow near surface **RBI** , fog interception, rime **fKa**, capillary rise from **IK**.

The area runoff **RB0** mostly depends on the partition between area precipitation **PF**, transpiration **T** (physiologically controlled water transport from the plant to the atmosphere), evaporation **E** from the soil surface and interception **I** (evaporation from the wet plant surface controlled by the atmosphere).

Forests lose in general a distinctly higher part of incoming precipitation than agricultural areas (*Table 1.9-2*). This fact is mainly caused by the higher interception of forest – the ability to store precipitated water on the plant surface temporarily (DIN 4049, part 1 und 101).

The stored rain water reaches afterwards the soil surface as throughfall and steam flow, or it is evaporated from the plant surface to the atmosphere. The part which does not reach the surface due to interception is called interception loss.

In Central European forests the water loss caused by interception range between 10 and 50% of the undisturbed precipitation. This is a significant quantity for water management especially in combination with land use

valeri.goldberg@tu-dresden.de

changes. Usually interception is determined as residual of standard and stand precipitation. To get a representative value of stand precipitation randomly distributed rain gauges or interception troughs are used. *Fig. 1.9-2* shows an example for relation between stand and outdoor precipitation in the summer period of 1998 at the experimental site Tharandter Wald (110 years old spruce stand).

The interception depends on numerous meteorological (total amount, duration and intensity of precipitation, wind, temperature, humidity, precipitation type and temperature) and plant-specific controlling factors (type, age, stand density and structure, height, leaf area index, roughness, size, number, configuration, elasticity and water deficit of leaf and needles, forming of branches, boughs and steams). E.g., the interception of coniferous and deciduous forests differs markedly (*Table 1.9-3*).

In contrast, the transpiration is controlled by type and number of stomata per leaf area as well as by physiologically based opening of stomata. This transpiration control is often described by the canopy resistance. In forests the minimal canopy resistance is determined by leaf anatomy and, without interception it is typically much higher than for crops. This is a hint for an evolutionary adaptation of trees to avoid high transpiration losses caused by higher wind in the tree crowns. Therefore, forests normally transpire less than agricultural areas.

Since the mid of the 1990s the evapotranspiration (and the carbon dioxide flux) is measured continuously at several forest sites in Europe, North America and Japan using micrometeorological methods (FLUXNET).

E.g., in Germany there are parallel measurements of spruce evapotranspiration in the forest Tharandter Wald using both micrometeorological methods at a tower and hydrological methods in a forested catchment. The results show an amazing agreement of these two different methods (*Fig. 1.9-3*). Two thirds of precipitation are evaporated. One third of evapotranspiration is caused by the interception, almost two thirds by transpiration. This is typical for the mid-latitudes and regions with a mean and continuous water supply. In tropical and subtropical regions with distinguished dry and rainy seasons forests also are crucially responsible for the stability of soils because of their high evapotranspiration and water storage capacity. In these regions trees with their deep roots are often the only one vegetation which can spend food for humans and animals after long dry periods.

Anthropogenic influence on the water balance of forested and non-forested catchments

The anthropogenic influence on the water budget of forested catchments becomes apparent by

- forest management (thinning, clear cutting, new growing, soil management)
- deposition of trace gases and aerosols (forest damages, soil acidification, etc. but also fertilisation)

The effect of forest management on the water balance can be investigated by clear cutting and so-called »twin« experiments.

In the first method an experimental catchment is clear-cut and if necessary treated with herbicides. Afterwards the change of runoff is observed for several years dependent on growing up of new trees (*Fig. 1.9-4*). In the second case a forested catchment is treated and compared with measurements of an undisturbed catchment in the same area.

Tab. 1.9-2: Comparison of forest evapotranspiration with values of other land uses (BAUMGARTNER 1979).

Land use	***Evapotranspiration/ Precipitation (%)***
Fallow	30
Cereal	40
Crop	45
Pasture	65
Forest	70
Open water	75
Wet soil	95

Tab. 1.9-3: Interception (% of precipation) of spruce and beech forest in Sauerland region (DVWK-Merkblätter 238/1996).

	Spruce	***Beech***
Winter	20 %	4 %
Summer	31 %	11 %
Year	26 %	8 %

Table 1.9-4: Water balance components of the forested catchment Wernersbach (4,6 km², Tharandter Wald, 25 km south-west from Dresden, measurements since 1968).

Precipitation	**847 mm**	*Evapotranspiration*
Runoff	**240 mm**	**607 mm**
Characteristic runoff values (litre/second)		
Minimum runoff (absolute)	0.3 (17-08-1976)	
Minimum runoff (mean)	2.5	
Mean runoff	35	
Maximum runoff (mean)	1,228	
Maximum runof (absolute)	6,540 (23-7-1980) verified data 8,000–10,000 (13-8-2002) estimated date	

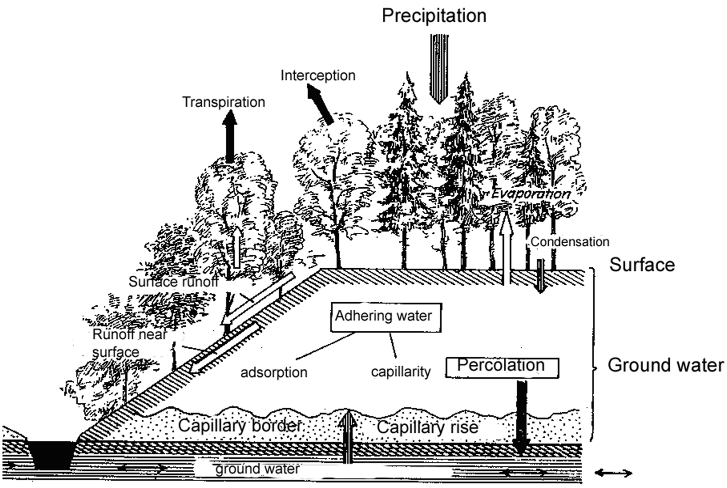

Fig. 1.9-1: Water budget of a forested catchment (according to REHFUESS 1990).

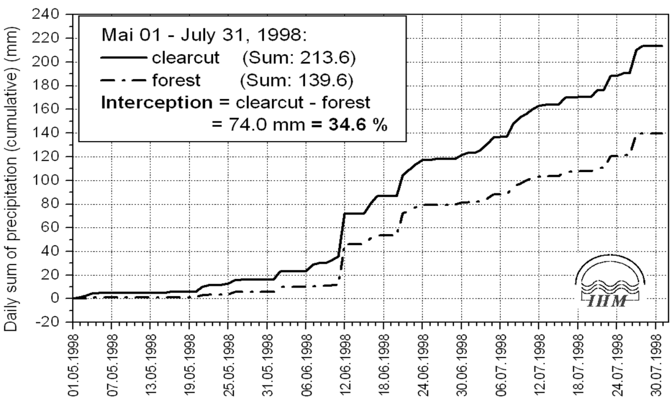

Fig. 1.9-2: Cumulative rainfall interception at an old spruce stand (Anchor Station Tharandter Wald / Wildacker).

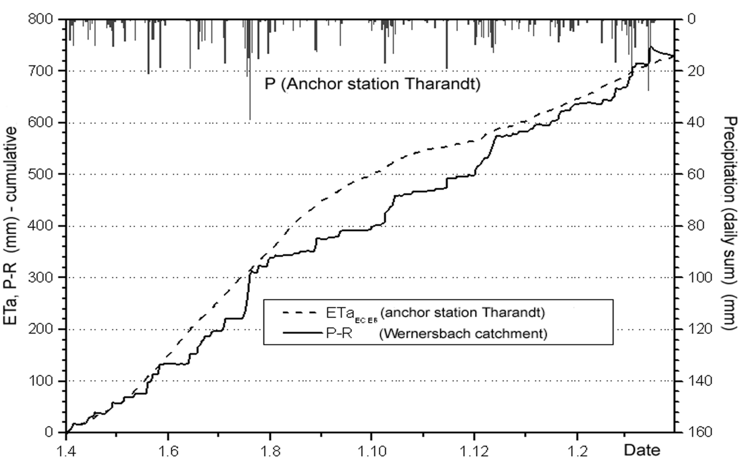

Fig. 1.9-3: Hydrological balance (cumulative daily sums of precipitation P – runoff R) of the catchment Wernersbach and the micrometeorological evapotranspiration at the Anchor Station Tharandt, period 1-4-1997–31-3-1998 (after FRÜHAUF et al. 1999).

The decrease of runoff in a forested catchment does not lead generally to an undersupply of water in the target area because forested land surfaces delay the area runoff and distribute them over longer periods. Forested catchments are also important for flood protection especially during local heavy rainfall events in the summertime (*Fig. 1.9-5*).

Beside field experiments water balance models were used to analyse the effect of potential land use changes in a forested catchment. In this context long time series of measured water balance components are necessary to calibrate and validate the models.

Fig. 1.9-6 shows the change of runoff in the catchment Wernersbach - the long-time (since 1968) continuously probed experimental site of the Dresden University of Technology, Department of Meteorology (*Table 1.9-4*) - during the transformation of an old spruce stand (runoff MEFSL) into sapling (FLOW-Wbg_Jw0) and fallow (FLOW-Wbg_bare), respectively. *Fig. 1.9-7* illustrates the results of simulated groundwater flow fort the different land uses in the Wernersbach catchment regarding to the reference period 1968–1999 (box plots with mean, median and percentiles (1, 5, 25, 75 and 95%). The land uses coniferous forest and fallow are clearly distinguishable with the lowest and highest runoff in contrast to the others.

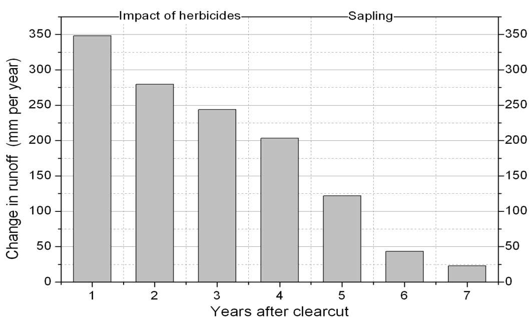

Fig. 1.9-4: Runoff change after a clearcut experiment in the Hubbard Brook catchment (NH, USA) (HORNBECK & FEDERER 1975, modified).

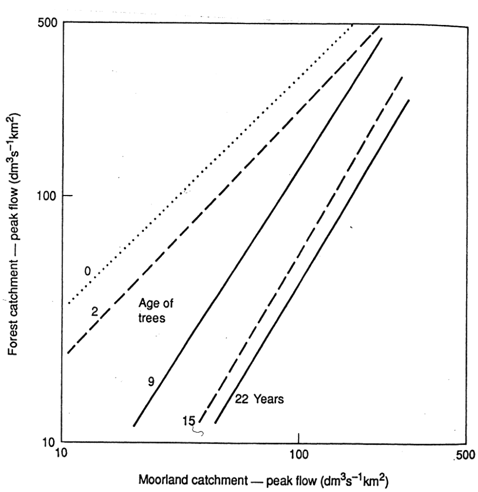

Fig. 1.9-5: Comparison of maximum runoff of a forested with a non-forested catchment (Southern Chiemsee Moor) dependent on stand age (after MAIDMENT 1993).

The forest damage caused by anthropogenic depositions (especially sulphur dioxide SO_2, Ozone O_3, and nitrogen dioxides NO_x) leads generally to an increase of runoff due to a decrease of interception (crown thinning, dying of single trees) and transpiration (disturbance of tree physiology). At the same time forests accumulate significantly more trace material than clear-cuts by their large effective surface.

Because of the high deposition loads for long years the buffer capacity of the mostly »poor« soils (considering the alkaline saturation) is very low (*Fig. 1.9-8* and *1.9-9*), and the contamination of area runoff with trace material (e.g. nitrate, aluminium) is significantly higher than for non-forested areas (NEBE et al. 1998). In the last years an improvement of water contamination in the forested areas of Europe could be found caused by decreasing deposition amounts. However, the time lag during the transport through the soil must be considered which lead in single cases to postponed effects of older depositions.

Final remarks

Forested land surfaces play, in addition to their traditional function as resource, a prominent role for supply of numerous urban areas with drinking water, for flood and avalanche protection as well as for recreation and as a sink of atmospheric carbon.

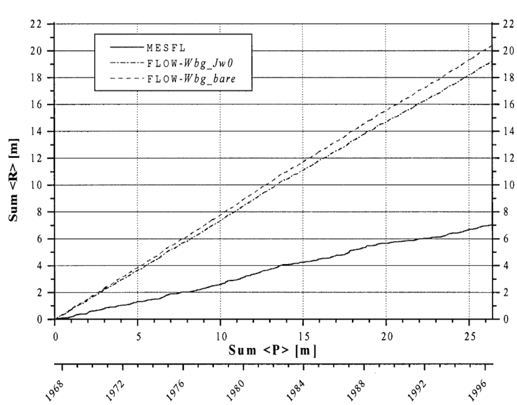

Fig. 1.9-6: Double sum (runoff R vs. precipitation P) of measured runoff (MESFL) and model run Wbg_Jw0 and Wbg_bare for the Wernersbach catchment. Simulations with the hydrological model BROOK90 after FEDERER (1995) (SEEGERT 1998).

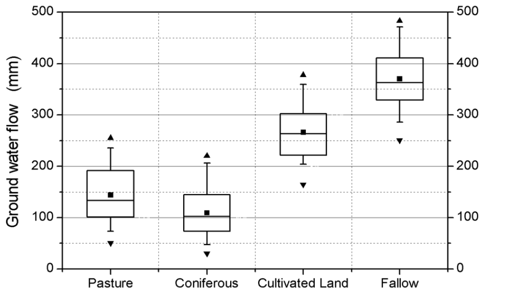

Fig. 1.9-7: Results of water balance simulations with the model BROOK90: Groundwater flow for different land use classes in the reference period 1968–1999 (BERNHOFER & GOLDBERG 2001)

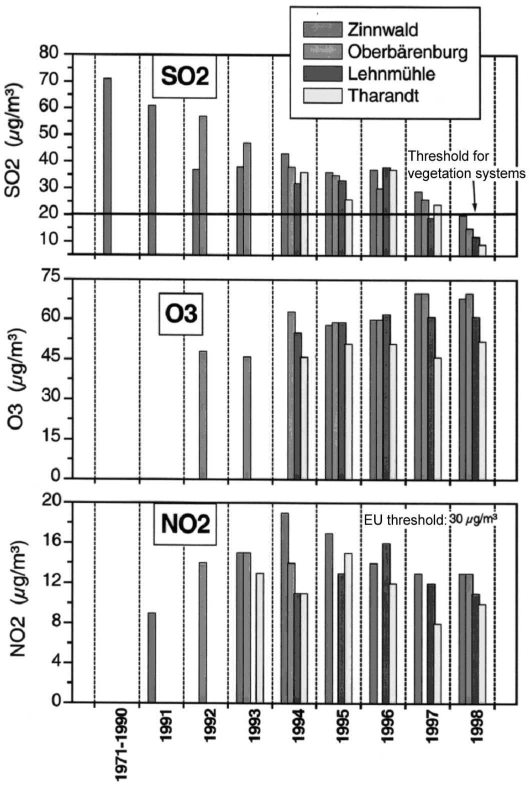

Fig. 1.9-8: Mean concentration of important trace gases in Eastern Ore Mountain (after ZIMMERMANN et al. 1998).

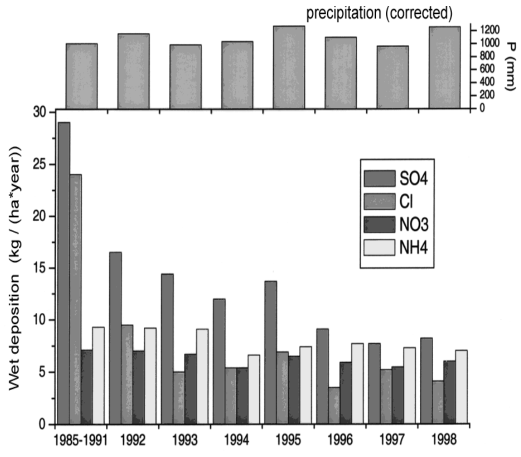

Fig. 1.9-9: Wet deposition at a forest site (spruce, Oberbärenburg) in Eastern Ore Mountain (after ZIMMERMANN et al. 1998).

At the same time forested areas suffer from an increasing population with a larger pressure of agricultural areas as well as from classic and modern deposition damages.

The reduced surface runoff leads on the one hand to a longer percolation in the depth and hence to an improvement of water quality. On the other hand the filter function of forests (biomass of soil and vegetation) regarding the air pollution yields increasing concentrations of accumulated cations and anions (e.g. nitrate and aluminium) which reduce the water quality. However, this effect is small compared to the high nitrogen load of agricultural land due to fertilising. The lower absolute runoff and groundwater flow of a forest demands a moderate reforestation and forest management in regions with problematic groundwater conditions (e.g. brown coal surface mining in the Lower Lusatia region). Otherwise forested areas have a higher potential for local recycling of evaporated water.

In general, positive effects of forested areas on water supply dominate, and the protection of large and as possible natural forests is one of the requirements to control regional and global water problems in the future.