17.6 APPLICATION OF METEOROLOGICAL MONITORING IN WATER BUDGET MODELING

Water budget modeling represents an ideal example for an integrated analysis of meteorological data in connection with soil and stand information. Water budget models are commonly used either to determine elements of the water balance equation and the accompanying fluxes of nutrient elements or to estimate plant available water and drought stress of trees (e.g., Bredemeier et al., 1998; Czajkowski et al., 2009; Gundersen et al., 2009; Wegehenkel and Jochheim, 2003). Within the ICP Forests, the following water budget models were successfully applied: ArcEgmo (Becker et al., 2002), ZALF-BiomeBGC (Thornton, 1998; White et al., 2000, modified by Jochheim et al., 2007), LWF-Brook90 (Federer and Lash, 1978, modified by Hammel and Kennel, 2001), Coupmodel (Jansson and Karlberg, 2004), Theseus (Wegehenkel, 2000), SIMPEL (Hörmann, 1997; Hörmann et al., 2007), and Watbal (Starr, 1999). All models are driven by meteorological input data (temperature, humidity, precipitation, solar radiation, wind speed). Important input data for the calculation of transpiration and interception loss are stand-specific leaf area, the evaporating surface of the trees, and stomatal conductance. In the soil, the water uptake depends on fine root distribution and is restricted to maximal rooting depth. Drainage is mostly calculated from water retention characteristics and hydraulic conductivity of the soil applying the Richards equation (Richards, 1931) or, simpler, assuming a maximum water content of the soil matrix which implies a drainage flux when total infiltration exceeds this limit. Changes in soil water content (ΔSWC) are calculated by the water balance equation (Equation 17.2):

$$\Delta \mathrm{SWC} = P + \mathrm{CR} - I - E - T - R - D \tag{17.2}$$

where
P = precipitation; CR = capillary rise of soil water from deeper layers; I = interception; R = surface runoff; E = evaporation; T = transpiration; D = vertical drainage flow below rooting zone.

Apart from the selection of a model, strategies for the parameterization in the case of missing data and for model validation need to be established in order to provide reliable results. An application of different water budget models by different users to the same data sets of forest monitoring plots revealed that a considerable amount of variability in the modeled fluxes remained, based on different methods of gap filling even when the same calibration data were used (Figure 17.1).

Missing or typically not measured model variables include, for example, the length of the growing season (see Chapter 9), the surface resistance of the soil, stomatal conductance, or the root length distribution. If soil water retention curves are not available, a pedotransfer function has to be chosen to derive the relationship between soil water content and matric potential for each horizon.

The validation process should include a plausibility check of the driving meteorological inputs, of soil and stand variables, and of the measured data used for validation, which should include at least bulk precipitation, throughfall, and soil water content. After running the model, the following validation steps are recommended:

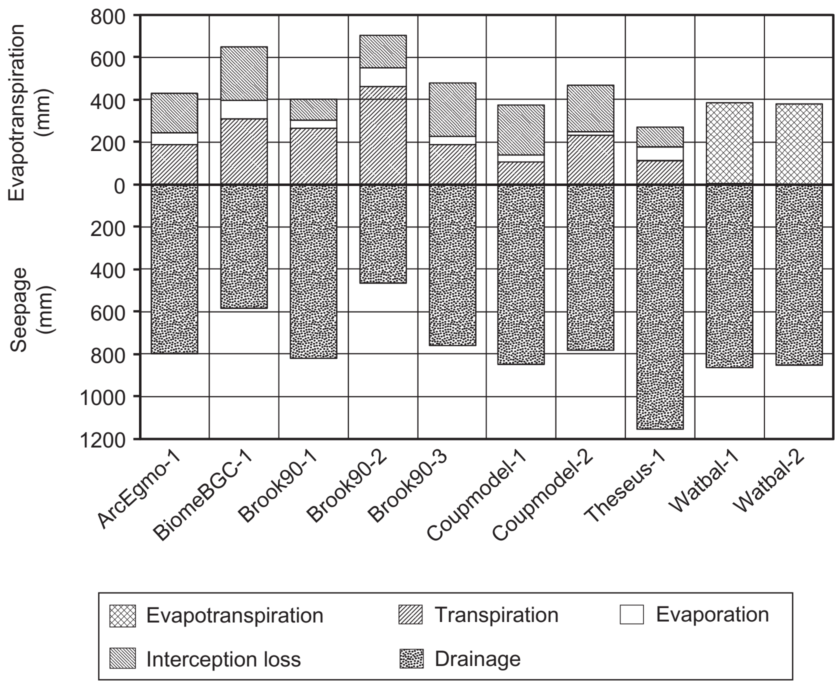

FIGURE 17.1 Comparison of the results from different water budget models applied to European forest monitoring plots by up to three users. Example: Solling—Germany; European beech, average data from 2004 to 2008. *Modified after Wagner and Weis (2011).*

1. Plausibility-check of long-term water budgets and comparison of the results to values from the literature.
2. Validation of measured and modeled throughfall.
3. Adjustment of soil water retention characteristics. Porosity, field capacity, and permanent wilting point applied in the model should match the respective values of soil water content measurements.
4. Validation of measured and modeled soil water content and/or matric potential both for all measurement depths and throughout the soil profile. A consistent validation is usually only possible if measurements from both, wet and dry time periods, are available.
5. Validation of measured and modeled transpiration rates. This can be accomplished using xylem sap flow measurements (if available), eddy correlation methods, or calculated daily differences in the soil water content during drought periods. If using soil water content, validation has to be carried out for the whole soil profile as well as for all available measurement depths.
6. Validation of measured and modeled soil water flux rates. This is only possible if measured flux rates from catchment hydrographs or confined large-scale lysimeters are available.

17.6.1 A Long-Term Study for Two ICP Forests Plots in the Solling Mountain Range

The analyzed plots in the Solling mountain range (51.763°N, 9.577°E) comprise a 165-year-old beech (*Fagus sylvatica* L.) plot and a 130-year-old spruce stand (*Picea abies* L.) and provide soil moisture measurements since 1968. Due to the exceptionally long time series, the plots have gained importance for model development within the ICP Forests. LWF-Brook90 (Hammel and Kennel, 2001) was used for elongation and gap filling of these time series based on local climate measurements.

Modeling results show that soil water availability in the summer months (June–August) decreased significantly by 13% (beech) and 7% (spruce) over the 50 years from 1960 to 2009 (Figure 17.2). Significance of this trend was tested with the Mann–Kendall test and yielded an error probability below 1%. Despite this significant decrease of soil water availability, two very wet summers occurred during the past decade. The five driest summers occurred during the past 20 years of the investigation period. Soil water availability was highest in summer of 1981 and lowest in summer 2003.

In contrast to this decrease, soil water content in the winter months (December of previous year, January, and February) increased by 2% on the spruce and by 4% on the beech plot. The development was significant on the 10% level. The three driest winters were modeled for 1963, 1970, and 1977, while the three moistest winters with regard to soil water content occurred in 1995, 2000, and 2004.

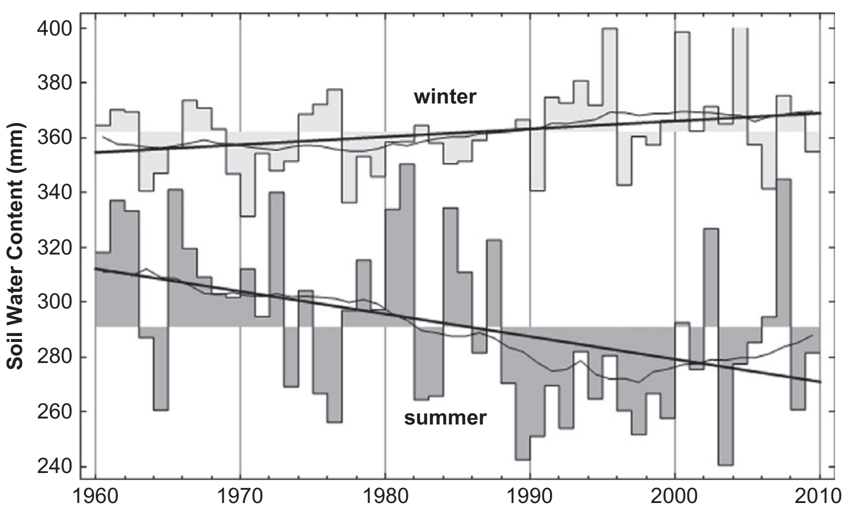

FIGURE 17.2 Diverging long-term trends of soil water content in winter (above, $p < 10\%$) and summer (below, $p < 1\%$) on the Level II plot Solling (beech). Absolute values are indicated as deviations from the respective 50-year-means for the months December till February and June till August.

Climate projections for the Solling area (Solomon et al., 2007) suggest increasing precipitation for the winter months and decreasing precipitation in summer. The actual data seem to confirm these projections and show that changes in climate do affect forest soil water availability.

17.6.1.1 Effects on Tree Growth

The influence of soil water content strongly depends on phenology, that is, the seasonal physiological activity of trees: while high soil water content in winter causes anoxia and subsequent dieback of roots, the same water content in spring enables strong growth and formation of vessels. A lack of soil water in this phase is usually more critical than in summer or autumn, since it affects tree growth over the whole year. Extremely dry soil conditions over longer periods in summer or autumn lead, however, to destruction of larger vessels and may affect growth in several following years. The analysis of soil water effects must, therefore, be based on the time course of soil water content over each year and the specific characteristics it exhibited in comparison to other years.

Tree growth rings of 20 co-dominant beech trees at the Solling site were evaluated and compared to modelled soil water content. The severest growth reductions during 50 years occurred after the most extreme and sudden changes in soil water content between preceding summer and actual summer, i.e., when extremely dry summers were followed by extremely moist winters and water content in spring decreased more sharply than usual (Figure 17.3).

On the other hand, highest increment was recorded when soil water content changed comparatively slowly and when the soil dried rather slowly in spring, staying moderately moist until end of June. Thus, over all years since

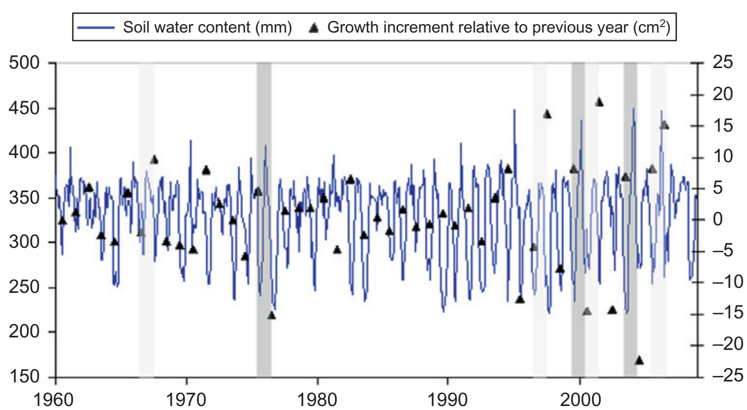

FIGURE 17.3 Dynamics of monthly soil water content (left axis) and annual basal area increment relative to the previous year (triangles, right axis) on the Level II plot Solling (beech). The years with severest growth reductions occurred after the 12 months of soil water content dynamics highlighted by dark gray shading and the years with highest growth increments followed the periods shaded in light gray. *Modified after Fleck et al. (2010).*