Water

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2012

document version
Publisher's PDF, also known as Version of record

citation for published version (APA)
Moors, E. J. (2012). *Water*. [PhD-Thesis – Research external, graduation internal, Vrije Universiteit Amsterdam]. Al Terra Scientific Contibutions 41.

Chapter 9

Epilogue

9.1 Main conclusions

An example of the possible value of improved knowledge on the water use of forests may be obtained from the spring drought in the Netherlands of 2011.

The Dutch National Weather Service (KNMI) reports the continuous sum of potential excess of precipitation, which is precipitation minus potential evaporation as based on Makkink (1959) corrected for land cover type. This potential excess precipitation is a good measure to compare between different years. It is, however, of limited use when evaluating the actual effect of the depletion of water resources.

For the dry spring over the period 1 April to 9 May 2011, KNMI reported for the forested area of the Veluwe a potential excess precipitation of -80 to -100 mm. However, the measurements at the pine stand of the Loobos site on the Veluwe showed over the same period an actual excess precipitation of -35 mm. An absolute difference of 45 to 65 mm is considerable and it makes the use of the potential excess precipitation in reporting drought situations questionable.

Reporting actual excess precipitation would provide a much better insight on the actual status of the water resources. Although the status of the water resources can be simulated by using numerical models (see e.g. Section 7.5.4) and/or estimated from remote sensing images, it is recommended to use for verification direct measurements (see Section 4.3.2). At present the measurements of actual evaporation are not incorporated in operational reports. The Loobos site is at present the only long-term continuously run forest station in the Netherlands and could be used for such purposes.

The results of the present doctoral thesis may contribute to improve operational water management issues related to forest hydrology as it discusses the water use of a number of different forest types in the Netherlands. The leading question was: “What is the difference in water use of different tree species in The Netherlands?”. This question has been divided into three underlying research questions. In the following paragraphs the main findings will be briefly discussed.

"*What are the main processes controlling the magnitude of the different components of the water balance of forested areas in the Netherlands?*". The main components of the soil water balance over a certain period of time are precipitation, evaporation, soil water change and the resulting discharge. Evaporation is arguably its most important component as it controls land-atmosphere feedbacks through the land surface energy budget. The processes controlling the evaporation rate are different for both dry and wet conditions. During dry conditions the processes controlling the availability of soil water and the flow of this water to the leaf surface of trees and undergrowth are most important (see Chapter 7). During wet conditions the processes controlling the amount of water stored at the leaf surface and the vertical location of the vapour sources will determine the evaporation rate (see Chapter 8).

"*What are the controlling parameters of these processes and are they related to tree species?*". In comparison to other vegetated surfaces, forests have a relatively large surface roughness providing a low aerodynamic resistance r_a, which makes the magnitude of stomatal conductance g_s the determinant of the evaporation rate under dry conditions.

In Chapter 7 it has been shown that not only g_s of the trees, but also g_s of the undergrowth plays an important role in determining the evaporation rate under dry conditions. Fig. 7.3 and Table 7.5 show the resulting conductance functions and parameter values based on the equations of Section 2.5.3 for the 5 forest stands of this study. The low sensitivity to soil water deficit θ_D shows that the forest stands of this study are not very sensitive to the range of changes in soil water encountered during this study. The sensitivity of these forests to more severe droughts cannot be concluded from the present data sets. The relatively good performance for moderate soil water stress conditions by the model introduced to represent the feedback of θ_D on g_s under more extreme dry situations (see Fig. 7.10 and Fig. 7.11), shows the potential of such a parametrization taking into account drought conditions. Especially situations of extreme drought leading to cessation of root water uptake from the groundwater reservoir.

During and just after showers have ceased, the main parameters governing the quantity of water evaporated are those parameters that determine the water holding capacities of the vegetation as well as the rate of evaporation. In Chapter 8 attempts have been made to improve the estimates of interception evaporation E_i and canopy water storage C, being two of the most important parameters that simulate interception loss. It has been shown that it may take up to 13 hours before transpiration is returned to its normal level (see Fig. 8.4).

During such a drying period the rate of interception evaporation E_i is largely depending on the roughness length for heat z_{0H} as well as for momentum z_{0M}.

Measurements show that under wet conditions, both the roughness length for heat z_{0H} and for momentum z_{0M} are subject to changes. Applying site and tree specific values for the ratio of roughness length for heat z_{0H} and for momentum z_{0M} in combination with C per unit canopy cover, will improve the general applicability of the interception models. The in Chapter 8 presented ratio's of z_{0H} and z_{0M} (see Table 8.1) and C values (see Fig. 8.8 and 8.7) may well be used for similar forests under approximately the comparable conditions.

To enable parametrization of the differences between sites, more experimental data however will be needed before the present results can be generally applied to regions with different climatic conditions.

The relatively large contributions of the undergrowth at the *pine* and the *poplar* forest during large parts of the year showed the importance of this component of total forest water use (see e.g. Fig. 7.12).

"*Will this knowledge be of added value to predict effects of different tree species on the water balance?*". Parametrizations as are found in this study that allow to quantify the effect of most common forest types on the water balance in the Netherlands. These capabilities have among others being demonstrated by the modelled interception evaporation E_i for the Oak forest at the Edesebos site (see run1 in Fig. 8.10).

9.2 Deriving actual evaporation for forests in the Netherlands

At present hydrological practitioners mainly use numerical models based on the input of a reference evaporation rate. Direct measurements of forest evaporation by the eddy-correlation technique, such as has been used in the present study (see Chapter 4), are often not part of general hydrological practice. For a more complete overview of different methods to measure actual evaporation see e.g. Moors (2008). Each of these methods has their own advantages and disadvantages. Issues to be considered are the temporal and spatial scale of the measurements, operational requirements and the associated uncertainty.

For the eddy-correlation technique as has been employed for this study on forest evaporation, it was shown that the uncertainty during dry conditions in summer at almost all sites was less than 5% (see Chapter 5). In winter the uncertainty was less than 15%. During wet conditions the uncertainty has been estimated as being less than 20%. Often longer time steps than the typical 30 minutes measurement time step of micro-meteorological measurements are required.

In Chapter 6 it has been shown that because of filling missing data the added uncertainty is less than 10%. A large part of the measurement error will depend on the experience of the user, i.e. doubling this error. Malfunctioning of equipment may cause a considerable additional error i.e. 5 - 100% (Allen et al., 2011).

To improve the estimates of actual evaporation by numerical models, the findings of Chapter 7 and Chapter 8 for the parametrizations of dry and wet evaporation can be used. In addition: the undergrowth contribution to evaporation can be made explicit, enabling improved evaporation estimates in all seasons of the year.

Further improvements can be achieved by taking seasonal differences into account among others by introducing parametrizations reflecting the differences in phenological phases.

Also capabilities to include human influences, for example the effect of deliberate or unintentional application of nutrients on the controls of trees on their transpiration rate, will help to improve evaporation estimates of unmeasured forest stands.

In the long run climate change may not only affect the evaporation rate by changing the magnitude of the physical drivers such as radiation, temperature, wind and precipitation, but also through changes in physiological characteristics of forest plant communities (see e.g. Kruijt et al., 2008; Milly and Dunne, 2011).

To implement improvements a five step approach is suggested:

1. Direct measurement of the actual evaporation rate at strategic sites is recommended for process understanding and verification purposes. Especially the real time use for verification is recommended during extreme conditions, such as droughts (see also Section 9.1).

2. Continuous use of crop factors will only be sustainable if the effects of elevated CO_2 and nutrient application will be taken into account and if updated crop coefficients will become available.

3. Replacing the crop factors by effective surface resistances will allow for the use of land surface models that take into account forest properties, such as albedo and L_{AI}. Such properties are almost constant with respect to changes in soil water content, but are important for the spatial differences of the energy balance.

4. A promising way forward to overcome the presently missing impact of elevated CO_2 and nutrient availability on the physiological processes, is an improved coupling between biogeochemical and hydrological models. This coupling will also pave the way to incorporate issues such as tree phenology, which is the main process dictating changes in seasonal patterns.

5. Finally the use of an atmospheric meso-scale model coupled to the land surface model will not only enable weather services to provide a forecast of the actual evaporation. Even more importantly this coupling will also ensure a consistent feedback of the atmosphere on the vapour pressure deficit. The latter being especially important if land surface models based on the vapour pressure gradient such as the Penman-Monteith model are to be used.

To improve in steps 1 to 5 the spatial variability (e.g. vegetation characteristics measured by Lidars) and the initial state of the models (e.g. soil water, Dolman and de Jeu, 2010), the use of remote sensing could greatly contribute.

Step 4 will allow support for the introduction of improved local feedbacks in climate models, which may help to investigate critical transitions in our climate (see e.g. Rietkerk et al., 2011). This knowledge will also support respectively step 3 and step 5, that will contribute to the implementation of more spatial explicit surface properties our land surface schemes.

The forecasts of the water use of forests of step 5 may be further extrapolated by for example taking into account the statistical depletion rate e.g. the historical draw-down characteristics of the groundwater table.

The approaches suggested above are primarily aimed to support proper water management and are for a part in line with the recommendations by Droogers (2009). Some of these approaches can also contribute to improve evaporation estimates of the land surface schemes being used in meteorological forecasting and climate modelling. For these land surface schemes improvements can be achieved by better representing the spatial heterogeneity in land surface schemes (see Jacobs et al., 2008; Shuttleworth, 2007).

9.3 Research perspectives

The *first* research challenge is related to the increased risk of droughts. Managing the available fresh water resources during situations of water scarcity requires reliable measurements and forecasts of water use. At present not much is known regarding how the water use of different forest types will change under more severe prolonged dry periods. Especially in areas with historically relatively high groundwater levels such as in The Netherlands, no data are available on how the water use of forest will change during dry periods with falling groundwater tables.

The *second* research challenge is related to the still often ignored contribution of the undergrowth to the forest evaporation. Considering the evaporation rate of the trees and the undergrowth separately will enable an improved understanding of the functioning of forest ecosystems. It will also improve our interpretation of the changing climatic and hydrological conditions affecting evaporation of trees and undergrowth differently.

To support such an approach, the rather limited number of plant functional types as are being used at the moment to describe forests, need to be replaced by plant functional types describing tree species in combination with undergrowth species. These plant functional types should not only allow to take leaf area index L_{AI} of the undergrowth into account, but also the different phenological phases of the trees and of the undergrowth. The latter will help to improve the simulation of the seasonal differences in the behaviour of the stomatal conductance g_s, which will provide better estimates of the total evaporation rate, i.e. also outside the growing season.

To enable research in these directions, additional data sets will be needed. These data sets should especially aim at representing the different phenological phases of the vegetation and should include:

- Evaporation data sets of undergrowth,
- Evaporation and soil water data sets for forests under water stress.

The release of water vapour and the intake of carbon dioxide by trees are both for an important part controlled by the opening and closing of the stomata. Because of this stomatal control, there is a strong link between the evaporation rate and the rate of the carbon dioxide uptake by forests. Therefore, most issues that are valid for the evaporation rate as mentioned above also hold for the photosynthesis rate.

It is still unclear what is driving inter annual variability in net ecosystem exchange of carbon. Extreme events such as droughts are clearly important, but the quantification of the impact is still a major challenge.

Measurements at the pine forest of the Loobos side showed that the undergrowth contribution to the total carbon uptake by photosynthesis was on average similar to the contribution of undergrowth to the evaporation rate. Thus the undergrowth also plays an important role in the total photosynthesis of a forest. In addition, the undergrowth has an effect on the respiration rate through the input of substrate and the influence on the soil water content of the top soil layer can have a significant effect on net carbon exchange of a forest. Research on the separate contribution to evaporation and photosynthesis of trees and undergrowth will improve our understanding of the net carbon exchange. Emphasis on drought situations will add to our knowledge on the effect of lowering groundwater tables on the net carbon sequestration by forests.