Water

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Chapter 1

Introduction

1.1 Groundwater management in The Netherlands

In the beginning of the 1900's, inundations occurred regularly in The Netherlands. These inundations were mainly caused by a too small discharge capacity. To improve this situation the Land Consolidation Act of 1955 was put in place. This act stimulated measures to improve drainage and to accelerate discharge of water, leading to intensification of the surface and subsurface drainage system in combination with an enlargement of the drainage capacity of the surface water system. This improvement of the drainage system was one of the main causes of the lowering of the groundwater table at the second half of the 1950's and the first half of the 1960's (Rolf, 1989). Other causes of the lowering of the groundwater table were (Dufour, 2000):

- Increase in groundwater abstractions for drinking water and agriculture,
- Increase in evapotranspiration by higher crop yields per hectare and afforestation, and
- Decrease of the groundwater recharge by increased urbanization leading to an increase in impermeable paved area.

The lowering of the groundwater table created areas in which the connection between the ecosystems at the surface and the groundwater table disappeared. To reduce the area with desiccated natural ecosystems a regulation was implemented by the Dutch government in 1995. In this regulation a goal was set for the year 2000 to reduce the desiccated natural ecosystems area with at least 25% as compared to the reference year 1985. To realize this goal, the groundwater table needed to be increased to the desired level. To achieve an increase in the groundwater table, a number of compensating measures were proposed. Besides these measures aimed at reducing the groundwater extraction, also measures were proposed to reduce the discharge of ditches and brooks by impediment of drainage, promotion of meandering and allowing for more vegetation growth in the ditches as well as measures to increase groundwater recharge.

1.2 Deforestation increases groundwater recharge?

If afforestation did cause a decrease in the groundwater table, would deforestation then not increase the groundwater table? With this in mind water managers and foresters started to look at forest in a different perspective.

Most forested areas in the Netherlands are important infiltration regions for groundwater bodies. To increase the amount of available groundwater proposals were made to convert the predominantly dark and dense coniferous forests to deciduous forests or even deforest complete areas and replant them with vegetation of lower canopy height, i.e. heather (Stuurgroep-Grondwaterbeheer-Midden-Nederland, 1992). This discussion was stimulated by published reports that indicated high interception losses for forest (Evers et al., 1991). The main forest type studied at that time was Douglas fir because the main interest was to study acid rain and dry deposition. Douglas fir is among the trees with the highest leaf area index (up to $L_{AI} = 11$ m^{2}m^{-2}) and the highest water storage capacity (2.5 mm). Characteristics that are leading to high levels of deposition. According to common use, the benefits and effects were translated directly into economic values. Water supply companies became interested and were willing to compensate forest owners for changing the tree species from coniferous with a high interception storage to a land cover with a presumed much lower water loss, such as deciduous forest or grassland. The financial feasibility of such a change in vegetation depends primarily on the difference in volume of rechargeable water from the different types of tree species and secondary on the economic value of the tree species harvested (Filius and Roosenschoon, 1993). From the point of view of hydrologists and meteorologists this raised the question which eventually led to the present PhD thesis:

"What is the difference in water use between different tree species in the Netherlands?".

These developments are particularly important in the sandy areas of the Netherlands. In the lower parts of the Netherlands with mainly clay soils combined with relatively high water tables other developments brought about additional questions. Here organizations responsible for the management of large forested areas were confronted with increasing costs. On the one hand due to increasing taxes of the water boards and on the other hand due to increasing costs of compulsory maintenance of the ditches. Reducing these costs would be possible if the dimensions of the required water works could be reduced without increasing the discharge, especially the peak discharge of these areas. This became even more important in view of the goals set by the government to increase the area of forested land. First primarily for recreation and nature development, later also as a possibility to sequester CO_2. The total area of forest in the Netherlands is estimated in 2005 on 360.000 ha, i.e. 10% of the total

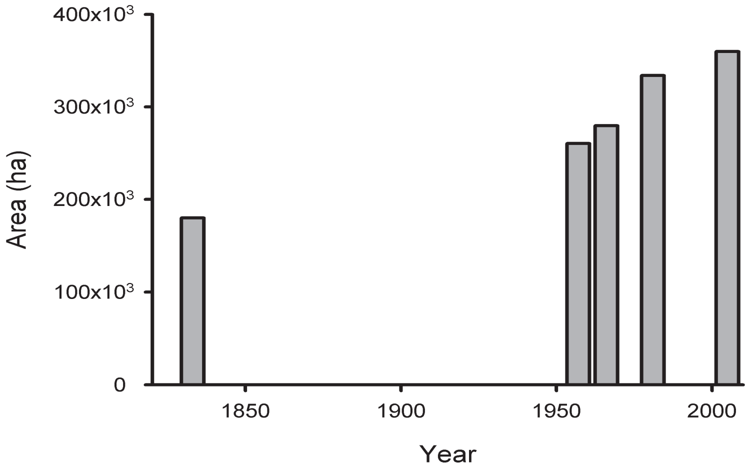

Figure 1.1: *Changes in forested area in the Netherlands (based on Dirkse et al., 2006).*

land surface. Figure 1.1 shows the increase in forested area in the Netherlands; a doubling compared to 1833 (MFV-Bos, 2006).

Even with this areal increase, forest in the Netherlands is still strongly dispersed; there are only a few extended forested areas and many small isolated plots. About half of the forest is mixed forest, the main mono species forest type is coniferous forest (32% in 2005, Dirkse et al., 2006). The last decades the average age of the forest has increased. Due to this ongoing land use change, two questions emerged:

- "Does a forested catchment have lower (peak) discharges than catchments with other land-use?"
- "Does a decrease in the number of maintained ditches of a forested catchment increase the (peak) discharge?"

A positive answer to the first and a negative to the second question would make it possible to reduce the dimensions of the infrastructural works required in a catchment that is to be afforested.

Later, after the high river levels of 1993 and 1995 and after the occasional flooding in some parts of the Netherlands became more and more serious, the possible effects of a climate change became more evident. This caused a growing interest in the possibility to retain water in forested catchments to decrease the peak discharge during high water periods and to put even more weight on the required knowledge of the storage and discharge properties of forests.

These problems were combined into the following three leading questions for this study:

- "What are the main processes controlling the magnitude of the different components of the water balance of forested areas in the Netherlands?";
- "What are the controlling parameters of these processes and are they related to tree species?";
- "Will this knowledge be of added value to predict effects of different tree species on the water balance?".

The before mentioned problems and the associated questions were reason for the Ministry of Agriculture, Nature and Food Quality of the Netherlands to initiate in 1994 a study on the management of water resources of forests in the Netherlands. The study was executed by the Winand Staring Centre (which later became part of Alterra-Wageningen UR) and named "Hydrology of forests and forested areas in the Netherlands". The data collected for this project are the basis for the present thesis. This dataset was extended with financial support and a number of datasets of other projects.

1.3 The forest hydrology project 1994-1998

The increased number of stakeholders in demand for water, the decreasing volume of high quality water and the scarcity of land causes more and more demand for accurate and often small scale hydrological management strategies to comply to the needs of all stakeholders. This will only be possible if all the terms in the water balance can be estimated at a high level of certainty. The component of the water balance that is generally considered as a loss is evaporation. Hydrologists normally estimate evaporation losses as the residue of the water balance. This causes all errors of estimate of the other components of the water balance to accumulate in the estimated evaporation.

An alternative is to measure the change in soil water, either by (micro-)lysimeters or soil water sensors using for example the TDR-technique (Time Domain Reflectometry). The main disadvantage of these methods is the small measuring volume ($\pm 0.2 \cdot 10^{-3}$ m^3) and thus the problem to upscale the measurements to a larger area.

Other alternatives are methods that depend on micro-meteorological techniques. For these methods the energy balance together with measurements of gradients of temperature, humidity and wind speed (e.g. the Bowen-ratio method) can determine the evaporation rate. Or, alternatively, high frequency measurements of wind speed and humidity and the fact that the vertical wind speed and scalars such as temperature and humidity are correlated can be used to determine the evaporation rate directly (e.g. the eddy-correlation method). Both types of methods have the benefit that they integrate over a relatively large area ($\approx$0.04-1 km^2) depending on the atmospheric stability and the height of the sensors above the forest. The main disadvantage of the Bowen-ratio is the fact that this method derives the amount of energy available for evaporation as the residue of the energy balance. This implies that all other components of the energy balance should be measured accurately. Here the same problem arises as mentioned earlier for the water balance. The most important drawback of the eddy-correlation method is the uncertainty associated with the time averaging and frequency response corrections.

In this study on nearly all sites the eddy-correlation method is used as it has shown to give reliable results (e.g. Aubinet et al., 2000; Moncrieff et al., 1997). It does not need additional measurements of other components of the energy balance, and the equipment has a low power consumption. This last quality was important as all sites were remote and main power was not available.

1.4 Research objectives and site selection

To answer the three leading questions as identified above the following research topics will be addressed in this thesis:

- Determine representative parameter sets to model the water use of the main forest types in the Netherlands;
- Quantify the effect of forest on the water balance.

The study areas were selected to represent the main forest types in the Netherlands. It was taken into account that the results of intensive studies on Douglas fir (*Pseudotsuga menziessii*) in the centre of The Netherlands (Bosveld, 1999) and on oak (*Querqus robur*) at the coast (Dolman, 1988) were already available or would come available in due course. With this in mind four forest types were selected: the main forest type in the Netherlands i.e. Scots pine (*Pinus sylvestrus*), an alternative to coniferous forest without needles in winter i.e. larch (*Larix kaempiferi*), a fast growing forest that was thought to be used in afforestation plans for parts in the west of the Netherlands with mainly clay and peat soils and a high groundwater table i.e. poplar (*Populus "Robusta"*) and a mixed forest consisting of different deciduous and coniferous trees and also with trees in different age classes. The last site was selected because it was considered to be the forest of the future and it was expected that the same management would be used in the future in naturally managed forest. Although these four forests compose the main study area, data of one additional forest was added: an American oak (*Querqus rubra*) forest. This American oak forest was subject of an earlier study (Ogink-Hendriks, 1995). The site was interesting as it complemented the other sites being a deciduous forest on a sandy soil with a deep groundwater table.

These sites with their different forest types spread over a relatively small spatial area, making climate differences relatively small, together with an almost identical measurement set-up provided a unique opportunity to address the above mentioned research topics.

1.5 Outline of the thesis

The evaporation of a forest consists of two major components: interception loss and transpiration. Throughout this thesis distinction will be made between evaporation of a wet forest, i.e. interception loss and the evaporation of a dry forest, i.e. transpiration and soil evaporation. In general soil evaporation is relatively small under dry conditions, but the evaporation of the undergrowth may be substantial. How substantial the contribution of the undergrowth to the total evaporation is, is part of this study.

One of the possible changes in climate are shifts in precipitation and temperature distribution combined with a rise in CO_2 concentration causing more severe periods of droughts (e.g. Davi et al., 2006; Kruijt et al., 2008; Baldocchi and Xu, 2007). The impact of these on the water balance in general will among others depend on the water use of forests. Two main characteristics determine the water use of vegetated surfaces: the stomata and the root system. The loss of water is regulated by the stomatal closure and the availability of water for transpiration is determined by the root water uptake. It has been shown that vegetation and especially trees are able to extract water from deep layers enabling them to survive periods of drought (e.g. Rambal, 1984; Talsma and Gardner, 1986). As it is expected that climate change will come with prolonged periods without rain (Christensen et al., 2007), in this study special attention is paid to derive parametrizations for water stress. For areas like the lower parts of The Netherlands, the connection between the root zone and the groundwater table often determines the quality of the natural vegetation cover. Prolonged desiccation because of the cessation of connection between groundwater and root zone may have serious consequences for such ecosystems.

The theory and equations governing the water and energy flow of a forested plot are introduced in Chapter 2 "Theory of forest evaporation". These equations also form the basis for the parametrizations of a numerical model. The concepts behind these equations will be evaluated to determine possible conceptual improvements to simulate the effects of different forest types on the water balance.

To assure practical applicability of the findings, field data are a prerequisite. For this thesis an extensive amount of data have been collected at five different forest sites in the Netherlands. A detailed description including most of the parameters representing the characteristics of the vegetation and the soil at these sites is provided in Chapter 3 "Characteristics of the research sites". The measurement set-up including a discussion on the associated uncertainties is given in Chapter 4 "Hydrometeorological measurements at the sites".

Chapter 5 "Quality control of the flux measurements" discusses the quality of the measurements of the latent and sensible heat flux under dry and wet conditions. As the fetch conditions of the site determine the location and the magnitude of the contribution of the sources upwind of the flux sensor, an estimation is made of the length of the fetch. The footprint of the flux measurements together with the quality assessment of the measurements are also discussed in Chapter 5.

The behaviour of ecosystems in relation to their environment is often explained and projected into the future by the use of models. To test if such models and their parametrizations are adequate, the models should be fed by data series that cover the widest possible data space. In most cases an extensive enough data space is only obtained by collecting long term data series. For this study the records varied from 2 to more than 10 years. However, as it is almost impossible to obtain continuous series of measured data, methods to derive data to fill the gaps in the series are explored in Chapter 6 "Gap filling to generate continuous datasets".

Chapter 7 "Dry canopy evaporation" describes the variation in parameter values determining the transpiration rate for five typical forests in the Netherlands and the contribution of the undergrowth for two of these forest stands. The main objective in Chapter 7 is to improve our understanding of the processes determining the transpiration rate of forest, with special attention to the differences between stands with different tree species and the contribution of the undergrowth. The evaporation rate is measured using different methods: eddy correlation and Bowen ratio (see Chapter 4). As an independent check on the model performance sap flow measurements done at the Loobos site will be used. In view of the increasing periods of prolonged droughts, special attention will paid to the root water uptake and the parametrization of water stress. For the two sites with more abundant undergrowth an attempt will be made to separate the evaporation rate of the undergrowth and the trees. To explain the variation in evaporation between years and the variation between sites the Jarvis-Stewart parametrization using a sparse canopy single and dual source model will be optimized for different periods. Besides giving insight in the variation of these parameters, it will also enable us to investigate the uncertainty in the parameter values based on relatively short measurement periods.

The precipitation input to a catchment is of paramount importance in obtaining a good prediction of the run-off. In forested catchments the throughfall rate determines the net precipitation input to the system. The throughfall amount is the gross precipitation minus the interception loss, which is defined here as the amount of precipitation intercepted by the (vegetated) surface and directly evaporated without reaching the soil. In Chapter 8 "Wet canopy evaporation" the parameters determining the water holding characteristics of that vegetation, i.e. the storage capacity C and the evaporation rate E_i will be explored. The discussion on the correct parametrization of E_i is a long standing one. In Chapter 8 we will try to answer the intriguing question originating from the discussion by Gash et al. (1999) is: "Is there a relation between the canopy cover and the ratio of the surface roughness lengths of momentum and heat z_{0M}/z_{0H} and does this ratio change during showers?". In this Chapter attention will also be paid to dependency of the storage capacity C on variables such as leaf area and wind speed and how these relations may change with season over the year.

To provide the answers to the three main research questions of this thesis, the findings of the earlier chapters will be integrated in Chapter 9 "Epilogue". A short note will describe how the techniques used in this thesis may support the knowledge water managers may need for e.g. extreme dry conditions. The thesis ends with suggestions how to improve the derivation of the actual evaporation rate of forests in the Netherlands and suggestions for further research on this topic.

To facilitate the reader, in the chapters where comparison of tree species is important, the main tree species of this study are set in italics. Most data used for this research are available on-line: www.climateXchange.nl (see "verdamping - boshydrolgie project", or select the sites by their name).