Diploma thesis



# Subsurface flow and soil moisture responses to the clearcut harvest and forest conversion of a deciduous forest


submitted by:

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Diplomarbeit unter der Leitung von

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# List of Abbreviations

| | |
|---|---|
| a.s.l. | above sea level |
| ANCOVA | analysis of covariance |
| ANOVA | analysis of variance |
| BP | before present |
| DOF | days of flow |
| FDC | flow duration curve |
| H1 | Horizon 1, from 0 to 76 cm depth |
| H2 | Horizon 2, from 76 to 137 cm depth |
| H3 | Horizon 3, from 137 to 229 cm depth |
| H4 | Horizon 4, from 229 to 290 cm depth |
| LAI | Leaf Area Index |
| MAP | mean annual precipitation |
| MAR | mean annual runoff |
| MEF | Marcell Experimental Forest |
| SAI | Sapwood Area Index |
| SD | standard deviation |
| SPR | summarized plot runoff |
| SWE | snow water equivalent |
| YAT | years after treatment |

# Abstract

There exists a broad consensus in hydrological science, that reduction of forest cover increases water yield and that establishment of forest cover decreases water yield. In addition, it has been shown that different forest types exert varying impact on the water budget of a catchment. On an annual basis a coniferous forest usually transpires more water than a deciduous forest of the same size.
To study the impact of forest conversion on subsurface flowpaths and soil moisture reservoirs, long-term measurements of subsurface runoff, soil moisture and streamflow were conducted. At the Marcell Experimental Forest in northern Minnesota the deciduous aspen forest at the upland of watershed S6 has been subject to a clearcut harvest in 1980. After repressing regrowth for 3 years, young conifer seedlings, namely red pine and white spruce, have been planted in 1983. The deciduous forest at the upland of the adjacent watershed S2 has been left untreated as a control for the paired, small catchment approach. Surface and subsurface runoff plots have been installed for each aspect at the uplands of both watersheds in the early 1970s and provided continuous runoff data since 1981. Simultaneously, available soil moisture in different depths has been monitored on a quarterly basis, precipitation and streamflow have been monitored on a daily basis. For the compilation of a solid data base, data had to be digitized, quality checked and assorted.
All three parameters showed optically, and statistically significant ($p < 0.01$) long-term downward trends as the result of the newly establishing coniferous forest. The control catchment did neither optically nor statistically reveal any trends, indicating stationarity of the forest cover. Subsurface flow stopped 23 years after the planting of the coniferous trees and stayed on a very low level at both runoff plots of the treated watershed. Furthermore, subsurface flow revealed different seasonal reactions and runoff event volumes were decreasing in the course of time. Distinct reactions of soil moisture in a vertical sequence of consecutive horizons have been observed and assumptions concerning root growth rate have been formulated. No changes in soil moisture were observed for the May values, instead September values showed significant reactions to the growing of the coniferous forest. Differences in northern and southern sites were assigned to distinctions in solar energy input. The application of a regression model on streamflow data revealed the typical reaction of the catchment runoff to forest conversion, with higher than expected catchment runoff directly after the clearcut and in the early forest stage, and lower than expected catchment runoff in the later stage of forest growth.
The present study shows, that quantity of subsurface water seriously declined, which followed the expectation that coniferous trees had an emphasized water consumption compared to deciduous trees.

*Keywords*: Subsurface flow, interflow, soil moisture, paired catchment approach, clearcut, forest conversion, Marcell Experimental Forest, runoff plots, streamflow.

# Zusammenfassung

Es herrscht weitgehende Einigkeit darüber, dass die Abholzung von Forstflächen die Abflussspende eines Einzugsgebiets erhöht, die Aufforstung von kahlen und freien Flächen dagegen die Abflussspende eines Einzugsgebiets vermindert. Man ist sich auch darüber einig, dass verschiedene Waldtypen unterschiedlich starken Einfluss auf den Wasserhaushalt eines Einzugsgebietes ausüben. Bei einem zugrunde liegenden Betrachtungszeitraum von einem Jahr transpirieren Nadelwälder gewöhnlich mehr als Laubwälder der gleichen Größe.
Um den Einfluss der Umwandlung eines Laubwaldes auf unterirdische Fließwege und Bodenfeuchtespeicher zu untersuchen, wurden langjährige Datenreihen von Zwischenabfluss, Bodenfeuchte und Gebietsabfluss erhoben. Hierfür wurde der obere Teil des Untersuchungsgebietes S6 des „Marcell Experimental Forest“ in Nord-Minnesota im Jahre 1980 einer Komplettrodung unterzogen. In den anschließenden drei Jahren wurde das Nachwachsen der Vegetation konsequent unterbunden, bevor 1983 Nadelwaldjungpflanzen, vornehmlich Rotkiefer und Weißfichte, im oberen Teil des Untersuchungsgebiets angepflanzt wurden. Der Laubwald im oberen Teil des angrenzenden Einzugsgebiets S2 wurde als Kontrolleinheit unbehandelt belassen. Messvorrichtungen für Oberflächen- und Zwischenabfluss wurden in den frühen 1970er Jahren jeweils am nördlichen und südlichen Hang beider Einzugsgebiete errichtet. Seit 1981 wurden kontinuierlich Abflussdaten aufgezeichnet. Die Messung der Bodenfeuchte in unterschiedlichen Tiefen wurde vierteljährlich durchgeführt und Gebietsabflussdaten liegen in Tageswerten vor. Für die Zusammenstellung einer guten Datengrundlage, mussten Rohdaten digitalisiert und auf Fehler überprüft werden bevor sie ausgewertet werden konnten.
Alle drei untersuchten Parameter - Zwischenabfluss, Bodenfeuchte und Gebietsabfluss - zeigten als Folge des sich entwickelnden Nadelwaldes im langjährigen Verlauf einen stark signifikanten Abwärtstrend (Signifikanzniveau $p = 0.01$). Im Gegensatz dazu konnten im Kontrolleinzugsgebiet S2 weder optisch noch statistisch Trends nachgewiesen werden, was auf einen stationären Zustand des Laubwaldes schließen lässt. 23 Jahre nach Anpflanzen der Nadelbäume ist in keiner der beiden Messvorrichtungen im Einzugsgebiet S6 Zwischenabfluss gemessen worden. In den darauffolgenden Jahren wurde in beiden Messvorrichtungen sehr wenig Zwischenabfluss gemessen. Des Weiteren wurden saisonal unterschiedliche Reaktionen des Zwischenabflusses aufgedeckt und festgestellt, dass die mittleren Volumina der Abflussereignisse im Laufe der Zeit abnehmen. Es konnten deutliche Reaktionen der Bodenfeuchte in unterschiedlichen Tiefen beobachtet werden und daraus Rückschlüsse auf das Wurzelwachstum der Bäume gezogen werden. Der Verlauf der Bodenfeuchte im Mai zeigte keine Schwankungen aufgrund der Vegetationsänderung, allerdings wurden deutliche Auswirkungen des Pflanzenwachstums im Verlauf der im September gemessenen Bodenfeuchte festgestellt. Bodenfeuchtedifferenzen zwischen nördlicher

und südlicher Lage wurden auf Unterschiede im Energieeintrag zurückgeführt. Auf Basis der Gebietsabflussdaten beider Einzugsgebiete wurde ein Regressionsmodell erstellt, welches die Gebietsabflüsse des behandelten Einzugsgebiets darstellt, wären keine Vegetationsänderungen vorgenommen worden. Ein Vergleich der tatsächlich gemessenen und simulierten Gebietsabflussdaten zeigte daraufhin die typische Reaktion eines Einzugsgebiets auf eine Änderung des Waldtyps: Gebietsabflüsse nahmen als Folge des Kahlschlags im ersten Teil der Untersuchung zu, bevor zunehmendes Waldwachstum die Verhältnisse langsam umkehrte und die tatsächlich gemessenen Gebietsabflüsse unter den erwarteten Wert sanken.
Die vorliegende Arbeit zeigt, dass Zwischenabflüsse und Bodenfeuchte als Folge der Vegetationsänderung deutlich abnehmen, was der Erwartung entsprach, dass Nadelbäume höheren Wasserkonsum aufweisen als Laubbäume.

*Stichworte*: Zwischenabfluss, Interflow, Bodenfeuchte, „paired catchment“ Ansatz, Kahlschlag, Vegetationsänderung, Marcell Experimental Forest, Hangabflussmessung, Gebietsabfluss.

# 1. Introduction

## 1.1. Motivation

The role of forests in, and their impact on the water cycle has attracted the interest of science and public for centuries. In the course of the past century, hydrologic research on the topic of how and to which amount forests and vegetation cover generally affect the storage and movement of water, has been discussed intensly. A nearly unmanagable amount of studies concerning the impacts of presence and absence of forest on water yield can be found. It turned out, that the paired catchment approach is a useful technique to determine hydrological differences caused by an alternated vegetation cover. Thus, it has been applied many times to qualify and quantify hydrological differences in water yield, peak flows, low flows and snow accumulation.
The role of soil moisture and subsurface water is of particular interest in forest hydrology. They do not only influence the vegetation cover, vegetation also controls them. A broad literature review revealed, that especially interflow has not been subject to scientific hydrological research on a paired-watershed basis.
In northern Minnesota a long-term paired watershed study has been started in 1976 to examine subsurface water reactions to forest treatments. Therefore, a unique set of measurements was installed on two adjacent catchments to measure subsurface and surface flow amounts on forested upland slopes.
Since forest management is applied all over the world and deforestation and afforestation are common procedures in silviculture, it is important to know how the aftermath of those operations looks like, concerning water availability. The interaction of subsurface water content, vegetation species and streamflow are closely linked to the general water availability of a watershed. Maybe not in the study area of northern Minnesota, but in other areas where the same practices are applied, water availability may play a fundamental role for water supply or economical water use.
Thus the motivation of this study is to give new insights and contribute to the general understanding of the movement and storage of subsurface water and how they are affected by the modification of the vegetation cover.

## 1.2. Aims of the Study

The object of this study is to qualify and quantify temporal and spatial changes in the long term-behaviour of subsurface flow and soil moisture in a watershed, that has been subject to forest operations. These include clearcut harvesting of a northern deciduous aspen forest, cattle grazing and application of herbicides to prevent aspen regrowth, and forest conversion with red pine and white spruce seedlings. The main questions, which are aimed to be answered in this study are:

- Did soil water parameters, like soil moisture and subsurface runoff change in consequence to the clearcut and reforestation of the upland of a small watershed?
- What time scales have been affected by the forest manipulation? Are long-term trends identifiable? Are changes more visible in distinct seasons? Are there changes in the timing of flow?
- What are the differences in quantity for the affected parameters? Are reactions constant or more variable? Do reactions of different paramteres point into the same direction?
- Did northerly and southerly aspects influence flow patterns?
- Did characteristic relationships change?
- Are there informations on the forest cover that can be traced back on reactions of water parameters?

To meet these objectives, long-term datasets including data of subsurface and surface runoff, available soil moisture, streamflow and precipitation have been digitized, quality checked and presented. Subsequently results have been evaluated optically and statistically.
In the following sections an overview of the research area and its characteristics will be given. Furthermore a broad literature review will outline the scientific progress on the topic. In the subsequent chapter measurements and installations for the data monitoring as well as applied statistical methods will be presented. Results will be presented and discussed with emphasis on subsurface runoff and soil moisture in chapters 5 and 6, respectively. Finally an overall conclusion of the study will be given.

# 2. Study Area - Marcell Experimental Forest

## 2.1. Geography

The Marcell Experimental Forest (MEF) is situated in the north-central part of Minnesota at about 47°31'42"N and 93°28'07"W approximately 40 km north of Grand Rapids. It is part of the Chippewa National Forest and divided into a North and a South Unit. The MEF contains six experimental watersheds, each of which can be divided into an upland and a peatland portion. The North Unit is located on the sub-continental divide and consists of watersheds S4 and S5. Watersheds S1, S2, S3 and S6 define the South Unit. For an overview of the area see figure 2.1 on page 4.
The focus of this study lies on the watersheds S2 and S6, both of which belong to the South Unit and are quite similar in form, size and orientation. Oval shaped watershed S2 consists of a centrally located 3.24 ha peatland, which is surrounded by a 6.48 ha mineral soil upland, giving an overall area of 9.72 ha (*Verry & Timmons*, 1982). The more narrow wetland of S6 is 2.0 ha in area and lies in the center of the 6.9 ha upland (*Jeremiason et al.*, 2006).
The Morphology at the MEF is characterized by the strong influence of glacial activity in the last glacial epochs. Result of this is a flat topography landscape with gentle hills and depressions. The lowest elevation of S2 with 420 m above sea level (a.s.l.) is the outlet, and the highest elevation of the watershed is 430 m a.s.l. For S6 lowest and highest elevation are 423 and 435 m a.s.l., respectively. (*Sebestyen et al.*, unpublished)

## 2.2. Climate

The climate at the MEF is defined as subhumid and continental with a wide range of daily and annual temperature fluctuations (*Boelter & Verry*, 1977). For the time period from 1961 to 2006 mean annual air temperature was 3.4 °C, with average January and July air temperatures of -15.5 and 18.8 °C, respectively (*own calculation, USDA data*). The strongly continental climate may induce extreme air temperatures as far as -46 and +40 °C (*Verry et al.*, 1988).
Annual precipitation at the MEF ranges from 414 mm (1976) up to 947 mm (1977). Mean annual precipitation (MAP) was 777 mm for the time period from 1961 to 2006 with a maximum monthly precipitation occuring in July and a minimum monthly precipitation occuring in February (*own calculation, USDA data*). 75% of the precipitation fall as rain from mid April to early November, 25% fall as snow in the

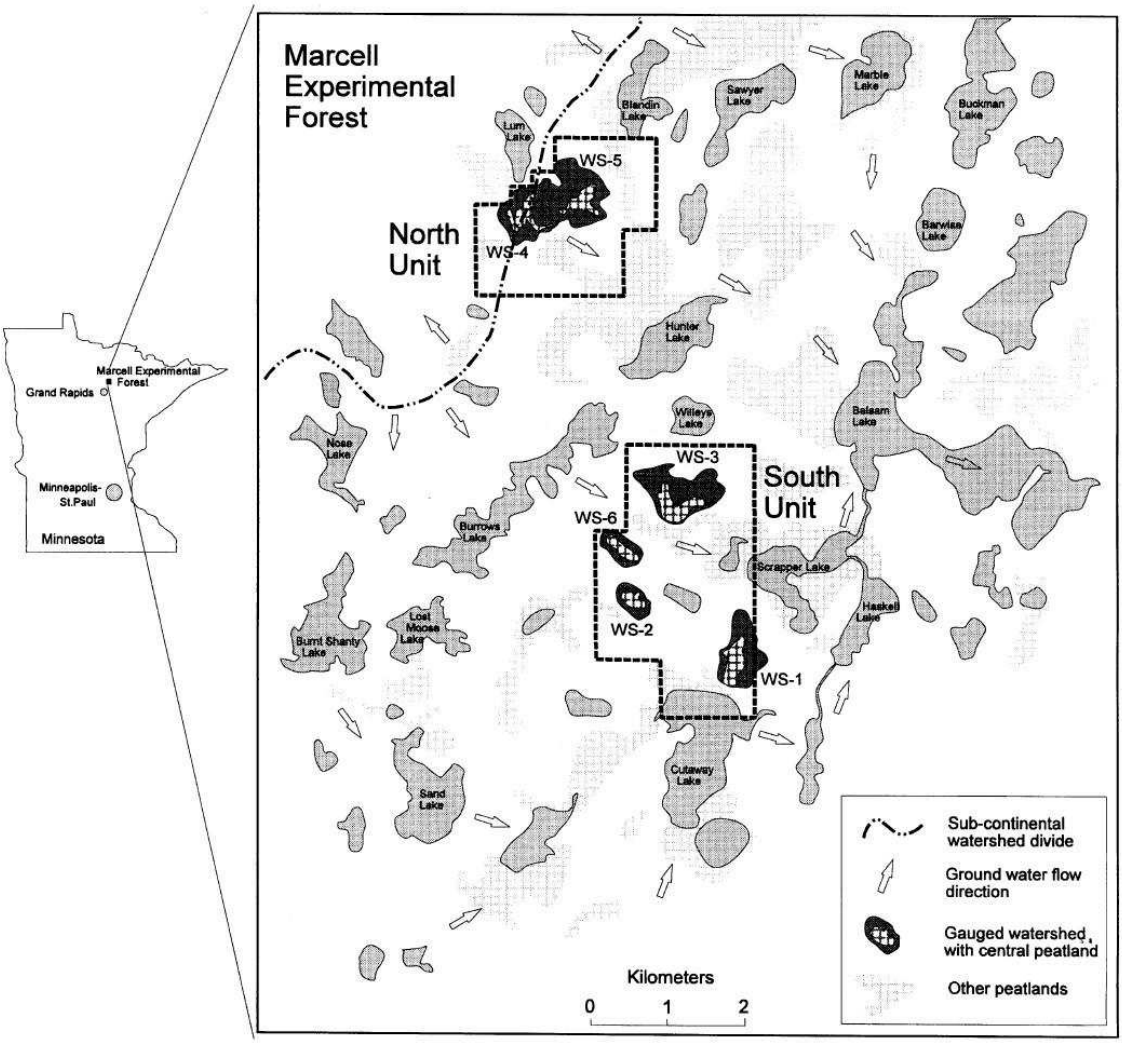



Figure 2.1.: The Marcell Experimental Forest. Watersheds S2 and S6 are situated in the South Unit of the research area (*Nichols & Verry*, 2001).

relatively dry winter months (*Verry*, 1984). For an overview of monthly precipitation and air temperature see figure 2.2.

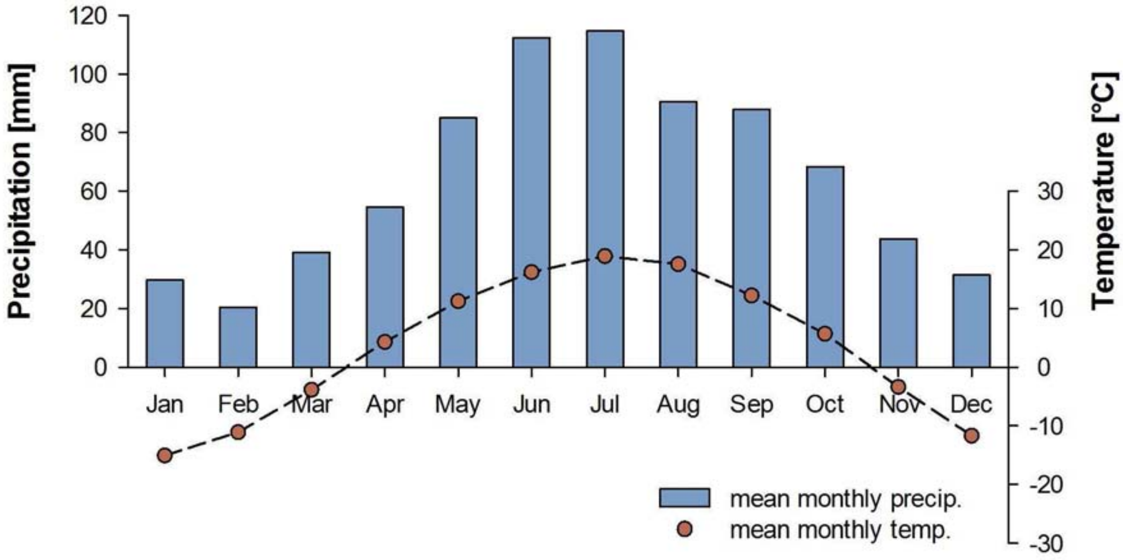



Figure 2.2.: Climate chart for the S2 watershed derived from long term data (1961-2006) measured at the upland portion of S2 watershed (*own graphic, USDA data*).

# 2.3. Geology

## 2.3.1. Glacial History

As mentioned above former glacial activity had a huge influence on the developement of the landscape in North Central Minnesota.

Minnesota has been covered, at least in part, by a continental ice sheet numerous times during the Quaternary. The Wisconsin Glacial Episode was the last major advance of the Laurentide Ice Sheet, a massive glacier centered upon what is now Hudson Bay (*Ojakangas & Matsch*, 1982). Being the last it was also the most formative glacial epoch regarding the features and characteristics of the present land surface.

During the Wisconsin phase of glaciation, which began about 75000 years before present (BP) and ended about 12000 years BP, three ice lobes affected North Central Minnesota. The Winnipeg lobe, which advanced from the north into the central part of the state, the Rainy Lobe, which made its way into the state from the northeast and the Koochiching lobe, which approached from the northwest (*Tracy*, 1997). Climate and precipitation changes caused those ice lobes to advance and retreat several times. Thus the directions of ice flow and the margins of the ice have shifted over the time.

The glacial drift was transported in and on the glacier and deposited when the climate got warmer and the ice melted. Each ice lobe produced glacial drift of distinctive color, texture and stone content, depending on the dominant rock types that it traversed. Nonetheless the glacial record is highly complex, because of the interaction of the three main lobes and several sub-lobes.

### 2.3.2. Parent material

The glacial till and outwash, produced by the different ice lobes from the Wisconsin Glacial Episode are the basis for soil developement at the MEF. As mentioned above each glacial drift has its own characteristics. According to *Paulson* (1968) the material from the Rainy Lobe is non calcareous, yellowish brown, coarse textured and of granite origin, while the Koochiching lobe produced slightly calcareous, light olive brown, medium textured material, which contains cretaceous shale fragments. Deposits from the Winnipeg lobe are grey in color and contain Paleozoic limestone (*Lusardi*, 1997).
At the study site those glacial drift layers overly Ely greenstone, Canadian Shield granite and gneiss for about 50 m. Commonly the Winnipeg basal till lies right on top of the bedrock, being the oldest of the three glacial deposits. Following the Rainy lobe drift, which is exposed to the surface at about one-third of the study sites area. However, at most of the study sites ground moraine till from the Koochiching lobe, overlying the Rainy lobe drift, is exposed (*Adams et al.*, 2003).

## 2.4. Pedology

About 12000 years ago, the change of the climate forced the glaciers to melt. The vanishing of the ice went along with the emerging of depressions in the landscape. By and by those depressions filled with snowmelt and rainwater and water bodies in diverse shapes and sizes developed, like Glacial Lake Agassiz. By 11000 years ago, Minnesota was mostly ice free, and the glaciers had retreated northwards (*Lusardi*, 1997). Fluvial and aeolen erosion and sedimentation as well as plant and animal developement became main processes in the postglacial history to produce today's soils of North Central Minnesota ( *Wright*, 1972; *Paulson*, 1968).

### 2.4.1. Upland soils

After *Verry* (1969b) the predominant mineral upland soil at the study watershed S2 has been classified as Warba series. This soil developed in slightly calcareous, medium-textured glacial till. Menahga loamy sand, which developed in noncalcareous, coarse-textured alluvial outwash, dominates the upland of watershed S6 ( *Verry*, 1969b; *Nyberg*, 1987)
Both soils show a typical forest litter cover (O horizon) of about two to five cm, followed by an aeolian loess layer of about ten cm. Below the loess layer the Warba soils show a less permeable Bt horizon, with a thickness of up to 90 cm, where clay has accumulated from leaching (*Nyberg*, 1987). In the Menahga series the subsoil

horizon is less developed and has less clay amount than in the Warba series. This horizon is adressed as Bw horizon and has a thickness of up to 65 cm (*Randy Kolka, USDA; personal communication*, 10/16/2009). Coarse sand to sandy clay loam parent material (C horizon) is reached within a depth of 95 to 175 cm for Menahga and 120 to 150 cm for Warba series (*Paulson*, 1968).

### 2.4.2. Peatland soils

The peatland soils in the center of the presented watersheds also developed in a weakly calcareous ground moraine, but differ seriously from the surrounding upland soils (*Verry & Timmons*, 1982).
The peat soils arised in post-glacial lakes, which originated from ice block depressions within an area of glacial moraines. A clay loam horizon with low hydraulic conductivity, similar to the Bt horizon of the Warba series, acted as aquitard and within the postglacial episode the lakes gradually filled with organic matter.
Peat depths range from less than 1 m to more than 8 m (*Bay*, 1967a). The organic soil profiles are characterized by an aquatic peat layer at the bottom with several layers of compacted and decomposed sedge and woody material on top of it (*Bay*, 1969). The surface layers consists of 30 to 100 cm of poorly to moderately decomposed sphagnum (*Nichols & Verry*, 2001). In literature these soils are reffered to as Loxley series for the S2 peatland and depressional Borosaprist for the S6 peatland (*Nyberg*, 1987).

## 2.5. Vegetation

### 2.5.1. Historic developement

After the glaciers had retreated from northern Minnesota, consecutive climate change forced vegetation to undergo several transformations. Tundra vegetation and spruce forest gave way to pine forest about 10000 years BP. The trend towards a warmer and drier climate continued and prairie vegetation was spreading to central Minnesota. With a reversal of the climatic trend about 7000 years BP, prairie gradually got invaded by forest. Over the years conifer trees advanced into deciduous forest (*Wright*, 1972). By the time of first European settlement, white (*Pinus strobus*), red (*Pinus resinosa*) and jack (*Pinus banksiana*) pine were predominant throughout northern Minnesota.

### 2.5.2. Current vegetation cover

European settlers strongly influenced vegetation cover by harvesting (*Sebestyen et al.*, unpublished). Almost all of the current stands originated after logging and fire treatment of the conifer trees in the early 1900's. Meanwhile predominant species at the uplands of MEF are mainly mature quaking aspen (*Populus tremuloides*), with scattered individuals of balsam fir (*Abies balsamea*), white spruce (*Picea glauca*) and some northern hardwoods like paper birch (*Betula papyrifera*) (*Nichols & Verry*,

2001; *Bay*, 1967b). Understory cover is mainly dominated by beaked (*Corylus cornuta*) and American hazel (*Corylus americana*), some fern species and herbaceous cover. It occurs over much of the upland area (*Tracy*, 1997).
The contrast between uplands and peatlands clearly emerges not only when observing the soils but especially the vegetation. Peatland vegetation differs significantly from upland vegetation. Because of a special hydrologic situation (as described in chapter 2.6) and the resulting acidic nature of the bogs ($pH \sim 4.0$), peatland overstory of S2 is almost entirely composed of black spruce (*Picea mariana*). In S6 peatland overstory is composed of black spruce and tamarack trees (*Larix laricina*) about equally. (*Jeremiason et al.*, 2006). Brush cover on the bogs is primarily heath shrubs (*Ericacea*), like leatherleaf (*Chamaedaphne calyculata*) or labrador tea (*Ledum groenlandicum*). The bog surface is covered with sphagnum and other mosses. (*Bay*, 1968).

### 2.5.3. Forest conversion

The 6.9 ha upland of study watershed S6 was clearcut during March and June 1980 to study effects of forest conversion from deciduous forests to conifers. Peatland vegetation remained untouched. To prevent aspen regrowth, cattle grazing was applied in the years 1980, 1981 and 1982. In the growing season of 1983 red pine (*Pinus resinosa*) seedlings were planted over most of S6 upland along with white spruce seedlings in the remaining area. By the time of planting both tree seedling species were 4-years-old. By 1987 application of herbicides was carried out to reduce growth of deciduous trees, that were endangering the young conifer seedlings (*Sebestyen et al.*, unpublished). By the time of this study S6 upland is comprised of mature red pine and white spruce trees, about 30 years in age.
Watershed S2 remained untouched as control watershed. The prevailing aspen population at the upland of S2 aged about 50 years by the time of 1967 (*Verry*, 1969a). So by 1980, when the upland of S6 was harvested, the stand age of the upland of S2 was assumed to be about 63 years. For a summary of attributes for each observed study site see tables 2.1 and 2.2.

## 2.6. Hydrology

As mentioned above the MEF is located on the sub-continental divide. Watershed S4 has two outlets, one draining north into the Rainy River system and further to Hudson Bay, the other one draining south into the Mississippi and further to the Gulf of Mexico. Watersheds S2 and S6 both lie in the South Unit and drain to the southeast into tributaries of the Mississippi (*Nichols & Verry*, 2001).
When precipitation hits the surrounding upland area, surface runoff over frozen soils, through leaves or through the duff layer of the forest floor occurs. Interflow through the subsurface layers of mineral soils occurs in the snowmelt season when frozen soils begin to melt and on precipitation events when soil moisture from previous events is high (*Sebestyen et al.*, unpublished). Water flow from the upland is routed into the lagg zone of the peatland, a belt, about 5 m in width, which surrounds

the slightly higher peatland dome (*Verry*, 1984). Peatlands from both S2 and S6 are perched on top of a very low permeable clay layer and disconnected from the regional groundwater aquifer. This affects the bog character in two ways. Nutrient rich groundwater is cut off from the water movement of the peatland and only runoff from the surrounding mineral upland and precipitation reaches the peatland. Peatlands that recieve their water mainly from the atmosphere and are therefore acid and low in plant nutrients are called ombrotrophic (*Charman*, 2002). As presented in 2.5.2 only very few species are able to grow on these conditions.

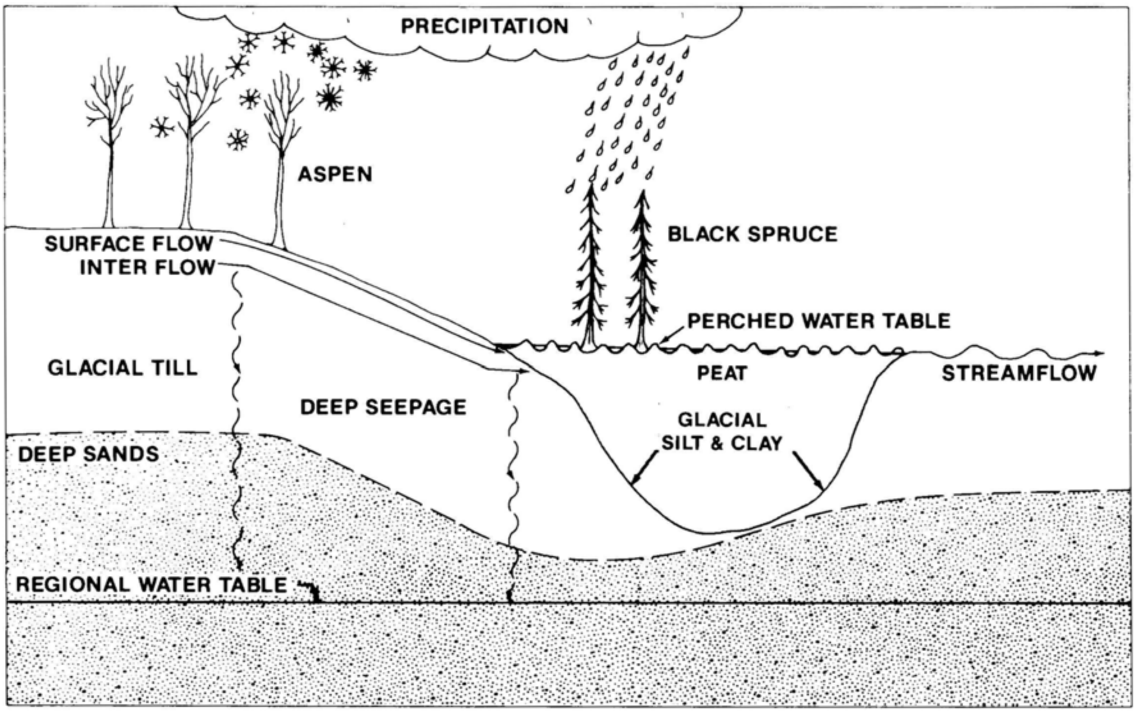



Figure 2.3.: Schematic view of watershed S2 and main hydrological prozesses (*Verry & Timmons*, 1982).

Not only the quality but also the quantity of water in the peatland is affected. Groundwater connection would secure a permanent water input to the peatland. But due to the clay loam barrier on the bottom of the peat soils, stream runoff from those peatlands is not influenced by groundwater movement and very event-dependent and may stop several times throughout the year. So intermittend streams as well as the unique bog-vegetation are direct consequences of the confining clay layer at the bottom of the peatland. Anyhow, there is water that doesn't runoff surficially or subsurficially or is consumed by evapotranspiration. *Nichols & Verry* (2001) found out that seepage to the groundwater system is not negligible, as one could assume due to the low hydraulic conductivities of the clay loam barrier. Water table reactions pointed out that about 40% of the total water yield on the MEF contributes to ground water recharge. In a simplified view, the hydrological situation at S2 could look like presented in figure 2.3 by *Verry & Timmons* (1982).
As can be seen in Fig. 2.4, the flow regime is characterized by high stream runoff during the snowmelt season in April and May. Although monthly rainfall amounts

are highest in June and July, water yields are generally declining in the course of the summer flow period. Increasing water demand from the vegetation during the growing season along with high solar energy input results in evaporation and transpiration, which use most of the water brought to the watershed by summer rainfalls. This may lead to a complete stop of flow. Only extended summer rainfalls can account for considerable high water yields in that period. By the end of summer, evapotranspiration decreases. A considerable amount of the precipitation input is used to refill the soil moisture reservoir of the uplands and so fall stream runoff is usually low (*Bay*, 1967b). During late fall and winter, precipitation accumulates as snow and streamflow decreases to zero (*Nichols & Verry*, 2001).
Mean annual runoff (MAR) for watershed S2 in the time period from 1961 through 2006 was 169 mm. Thus, by dividing MAR through MAP, the discharge coefficient for watershed S2 is calculated to be 22%. About half of the annual runoff occurs in the time period March through May (mean of 84 mm for 1961-2006) and is mainly attributed to snowmelt.

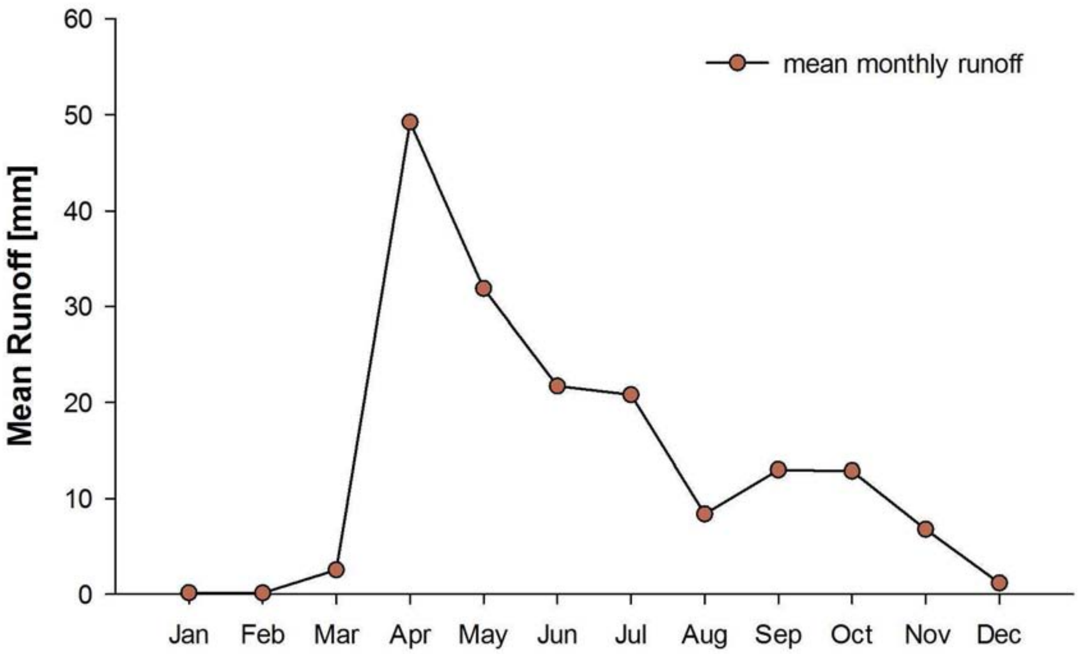



Figure 2.4.: Stream runoff regime for watershed S2 derived from long term data (1961-2006), measured at the V-Notch weir of the S2 watershed outlet (*own graphic, USDA data*).

In the typical wetland-upland configuration of northern Minnesota, stream runoff is mainly composed of water from the wetland part of the catchment. *Verry & Kolka* (2003) analyzed bog-only and upland-only streamflow via hydrograph separation and found out, that wetlands produce more than half, up to 70% of the stream flow, even though they only cover 1/3$^{rd}$ of the basin. Furthermore, concerning floods, wetland stormpeaks are five to ten times greater than upland storm peaks, which are delayed about an hour.

## 2.7. Summary

The watersheds observed in this study were chosen because of a strong resemblance of most of their features. High resemblance is required for this so called paired-catchment approach, which will be presented more detailed in chapter 3.1.1. In S2 and S6, orientation, climate and parent material show close similarities, while catchment size, soils and vegetation are slightly different. Tab 2.1 and 2.2 highlight the main differences of the two watersheds.

Table 2.1.: Upland characteristics of watersheds S2 and S6.

| | Control watershed S2 | Treated watershed S6 |
|---|---|---|
| Size (ha) | 6.48 | 6.9 |
| Soils | Warba series; distinctive Bt horizon | Menahga series; less developed Bw horizon |
| Vegetation | deciduous forest; mainly quaking aspen, individuals of balsam fir, white spruce, paper birch; stand age in 1980 about 63 years | deciduous forest until clearcut in 1980, regrowth suppresed by grazing and herbicide application; conifer forest planted in 1983; mainly red pine, some white spruce |

Table 2.2.: Peatland characteristics of watersheds S2 and S6.

| | Control watershed S2 | Treated watershed S6 |
|---|---|---|
| Size (ha) | 3.24 | 2.0 |
| Soils | Loxley series | depressional Borosaprist |
| Vegetation | conifer overstory, mainly black spruce, individuals of tamarack | conifer overstory, black spruce and tamarack about half and half |

# 3. Literature Review

## 3.1. Forests and water

The relationship of forests and water has attracted the interest not only of scientists, but of the public for centuries. Historical observations on the influence of forests on the water cycle, which go back to antiquity, have been reported in *Andréassian* (2004). The topic has been intensively discussed especially during the 18th and 19th century, when foresters and engineers argued, that alterations of vegetal cover must affect the quantity of water in streams and lakes positively or negatively.
Scientific investigation on the hydrological and meteorological role of forests began around the turn of the last century. First studies on the catchment scale were carried out by *Engler* (1919), who measured streamflow, precipitation and climate parameters of two small mountainous catchments in Switzerland to determine the influence of the forest on the water economy. One watershed was almost completely forested, the other mostly pastureland. Unfortunately the differences in streamflow *Engler* (1919) observed could not be traced back distinctly and solely to the differences in forest cover.
The paired watershed design, which was introduced only short time after the study of *Engler* points out a solution to the ambiguousness of the results. It was first applied by *Bates & Henry* (1928) in the Colorado mountains on two adjacent forested watersheds. They demonstrated convincingly that cutting aspen and coniferous vegetation on one of the watersheds did increase streamflow for several successive years. Since then the method of paired watersheds has been intensively studied and applied in more than 166 studies all over the world (*Brown et al.*, 2005).

### 3.1.1. Paired catchment studies

The paired watershed design remains to be the reference method for studies of the impact of land-use changes on hydrological behaviour and rests upon a simple assumption described by *Hewlett* (1971). He states, that the ‘relation between two basins experienced in the past will continue into the future unless some change is made on one of the basins’. The principle of the paired watershed design is simple. It is based on the selection of two watersheds, adjacent or close to each other and similar in their characteristics like size, morphology, geology, climatic conditions and land use (*Andréassian*, 2004). With a high degree of similarity in their characteristics, it is thought that both basins will also react similarly to climatic inputs. Naturally, each basin has its own specific features, therefore it is inevitable to observe both watersheds during an adequate time period. Ideally, this calibration period covers a high variation of climatic inputs, to characterize the hydrology of both basins. At the end of the calibration period follows the treatment period, where one watershed ('experimental' or 'treated' watershed) underlies a modification of land use, while the other one ('reference' or 'control' watershed) remains untouched (*McCulloch & Robinson*, 1993). Now, with the relationship from the calibration period prior to the treatment, compared to the current behaviour of the experimental watershed it is possible to compute the impact of the treatment, for instance on streamflow. Figure 3.1 shows an idealized scheme of the paired watershed design.

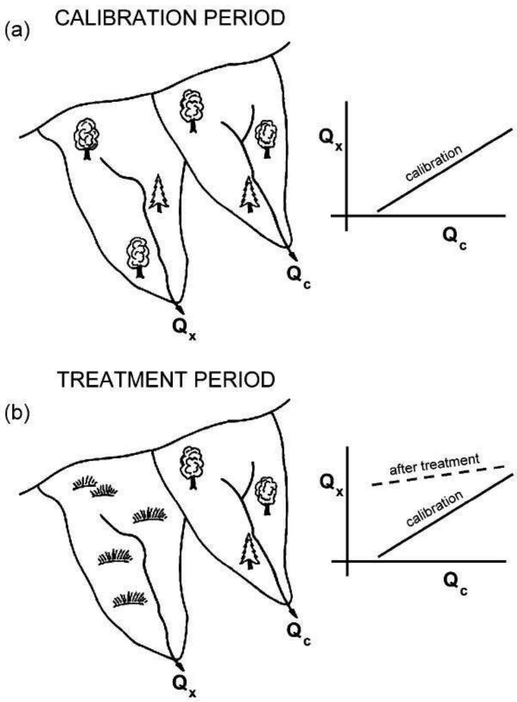



Figure 3.1.: Schematic view of the paired watershed concept (*Hewlett*, 1982).

While *Hewlett* (1971) remarks, that a calibration period is only necessary if 'a high degree of precision and confidence is required', *Andréassian* (2004) points out legitimately, that without a calibration period it is impossible to distinguish between land-cover impact and natural watershed behaviour. In other words, a main advantage of the paired watershed design is the insensitivity of the method concerning climate variability and inter-basin variability. Most of the studies that are discussed in literature use regression analysis for the calibration period, which will be explained in a later chapter.
*Brown et al.* (2005) defined four categories of plant cover treatment in their review of paired catchment studies:

1. Afforestation experiments—conversions of shorter vegetation (e.g. pasture) to forest.
2. Regrowth experiments—these look at the effects of forest harvesting where regrowth is permitted.

3. Deforestation experiments—the conversion of densely vegetated land to grass or pasture
4. Forest conversion experiments—the replacement of one forest type with another.

The majority of the experiments they reviewed were regrowth experiments. They point out, that regrowth experiments generally influence the water yield of a catchment in a shorter time period, while afforestation and deforestation experiments have a greater long term impact on streamflow. A major problem when using regrowth experiments comes up, because there is only a short time period, that can be used to develop the relationship between changes in cover and changes in water yield. Within a time period of 3 to 10 years, data is already affected by regrowth of a new generation of plants, depending on the species (*Hornbeck et al.*, 1993). Regularly mentioned in literature (*Stone & Elioff*, 1998; *Brown et al.*, 2005) is also the fact, that logging and burning of vegetation cover can affect the soil in a way that may change the pattern of streamflow. So the measured runoff in a stream may not only be the result of the alteration of the plant cover, but rather the sum of both, vegetation change and, for instance, soil compaction.
Summarized, one should keep in mind, that besides a long calibration period, which reduces the influence of climate variability it is important to remember that it takes time for a catchment to adjust runoff behaviour due to vegetation change and that treatment of a catchment may actually disturb soil properties, which also may affect streamflow, at least in the first few post-treatment years.
Besides the cover changes named above, paired watershed experiments have also been used to assess other land use activities and natural disturbances like timber blowdown, insect infestations, forest fire, grazing, partial cutting, riparian vegetation conversion and selective timber harvesting (*Stednick*, 1996). In the following chapters reactions of some of those treatments on different hydrological parameters will be presented.

### 3.1.2. Effects of treatments on water yield

The first review of paired watershed studies was published by *Hibbert* (1967). In his paper he summarizes results of 39 experimental catchments and draws the following general conclusions on afforestation and deforestation:

- Reduction of forest cover increases water yield;
- Establishment of forest cover on sparsely vegetated land decreases water yield;
- Response to treatment is highly variable and, for the most part, unpredictable;

Those statements have been approved many times in literature (*Bosch & Hewlett*, 1982; *Stednick*, 1996; *Andréassian*, 2004; *Brown et al.*, 2005) and haven't lost their validity to this day. Still, one has to consider that Hibberts conclusions, as well as conclusions drawn by subsequent reviewers, are mainly based on studies of catchments of smaller size. *Bosch & Hewlett* (1982) mention an average size of 80 ha for

their reviewed catchments, while the range goes from 1 to 2500 ha. So the statements above may not be projected by implication on different catchment sizes. If the basin is too small the difference between surface and subsurface water divide may be substantial and produce large errors. For catchments too large in size it becomes difficult to control treatments and to estimate precipitation accurately enough.
To illustrate the effects of afforestation and deforestation on water yield, figure 3.2 by *Andréassian* (2004) is presented.

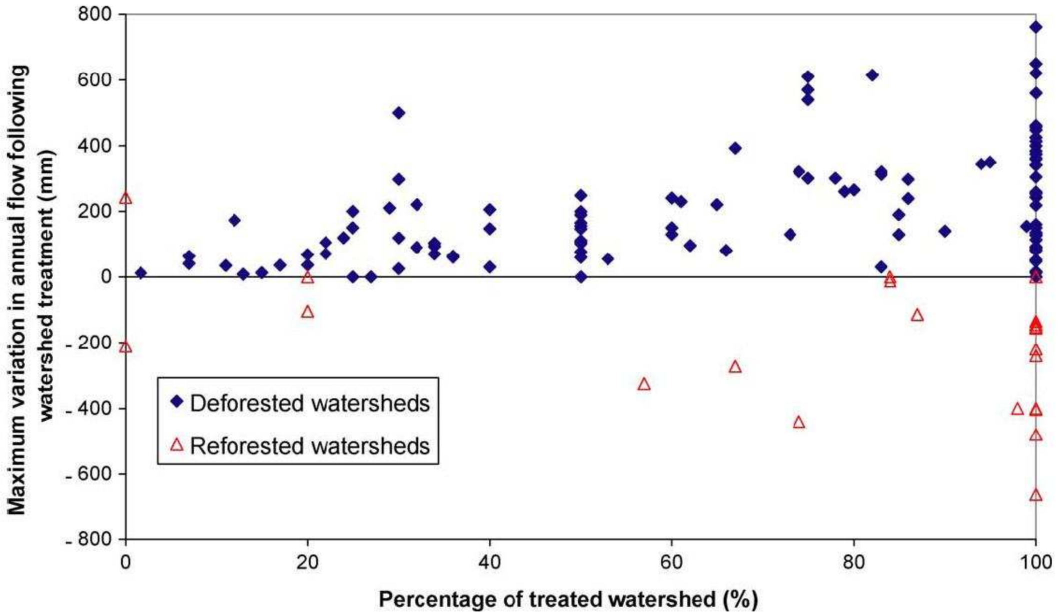



Figure 3.2.: Maximum variation in annual flow following watershed treatment (*Andréassian*, 2004).

All three statements by *Hibbert* (1967) can easily be reconstructed by observing the graph. Nonetheless, one has to keep in mind, that the maximum variation in annual flow during the first years after treatment is dependent on the annual rainfall amount during the first years after treatment. *Andréassian* (2004) proposes a comparison of the slopes of the rainfall-runoff relationship before and after treatment, to achieve more significant results. Furthermore some of the examined experiments presented in figure 3.2 were regrowth experiments and therefore non-stationary in the years after treatment.
The gain of streamflow is mainly attributed to reductions in transpiration and canopy interception of the prevailing plant cover (*Hornbeck et al.*, 1993). Thus it seems comprehensible, that different plant cover induce alterations in the quantity of streamflow, due to differing transpiration rates, Leaf Area Indices (LAI) , albedo or root distribution just to name a few. *Bosch & Hewlett* (1982) added their conclusions to the results from *Hibbert* (1967) and made distinctions for three vegetation types:

- Coniferous and eucalypt cover types cause ∼40 mm change in annual water yield per 10% change in cover;

- Deciduous hardwoods are associated with ∼25 mm change in annual water yield per 10% change in cover;
- Brush and grasslands are associated with ∼10 mm change in annual water yield per 10% change in cover;
- Reductions of less than 20% apparently cannot be detected by measuring streamflow;
- Streamflow response to deforestation depends on both the MAP of the catchment and on the precipitation for the year under treatment;

Both reviews were based on catchment experiments with typical record lengths of less than 10 years following treatment. It is important to keep in mind, that experiments with longer record periods may show higher sensitivity concerning the impacts of a reduction of less than 20% of the treated area. Still, similar values from 20 to 25% can be found in other studies, like *Stednick* (1996) and *Hornbeck et al.* (1993), respectively. While *Hibbert* (1967) found out, that 'there appears to be little relation between the amount of increase and percent reduction of forest', *Bosch & Hewlett* (1982) present relations of cover change and change in annual water yield, depending on vegetation types, as presented above. The quantities of change of streamflow for different plant types clearly indicates the trend from conifer to grassland cover.
This trend was validated by the study from *Sahin & Hall* (1996), although the annual change in water yield for each plant type was reduced compared to the values from *Bosch & Hewlett* (1982), simply because *Sahin & Hall* (1996) didn't use maximum but rather average water yield changes in the years after treatment. The relationship of cover change vs. change in annual water yield from four different review studies is presented in figure 3.3. Nonetheless the linear relationship presented in the four plots should be understood as an estimate. As can be seen every plot still shows a significant within group variability. How can the high variability be explained?
First of all, the reviews presented above summarize the results from different catchment studies all over the world. It is obvious, that the climatic conditions for the catchments observed scatter significantly and hence the MAP lies in a wide range of values. As listed above, MAP is highly correlated to streamflow response and thus can be held responsible for some of the variation presented in the plots.
*Hornbeck et al.* (1993) present results from experiments at the Leading Ridge Watershed Research Unit in central Pennsylvania, the Fernow Experimental Forest in north-central West Virginia and the Hubbard Brook Experimental Forest in central New Hampshire. 24% of the basal area of Catchment 2 at Leading Ridge was cut, about 33% of both Catchment 4 at Hubbard Brook and Catchment 2 at Fernow were cut. The cutting at Leading Ridge produced a nearly two-fold larger increase in first year water yield than the experiments at Fernow and Hubbard Brook. How can that contradiction be explained? While at Hubbard Brook and Fernow cutting was carried out in a series of equidistant strips and harvesting of individual trees, respectivly, at Leading Ridge the cutting was in a single block on the lowest portion of the catchment. The author reasons, that the cutting of single trees and strips may actually increase the crown exposure and transpiration rate of residual trees and thus reduce the increase of runoff, compared to a treatment of a whole area. In

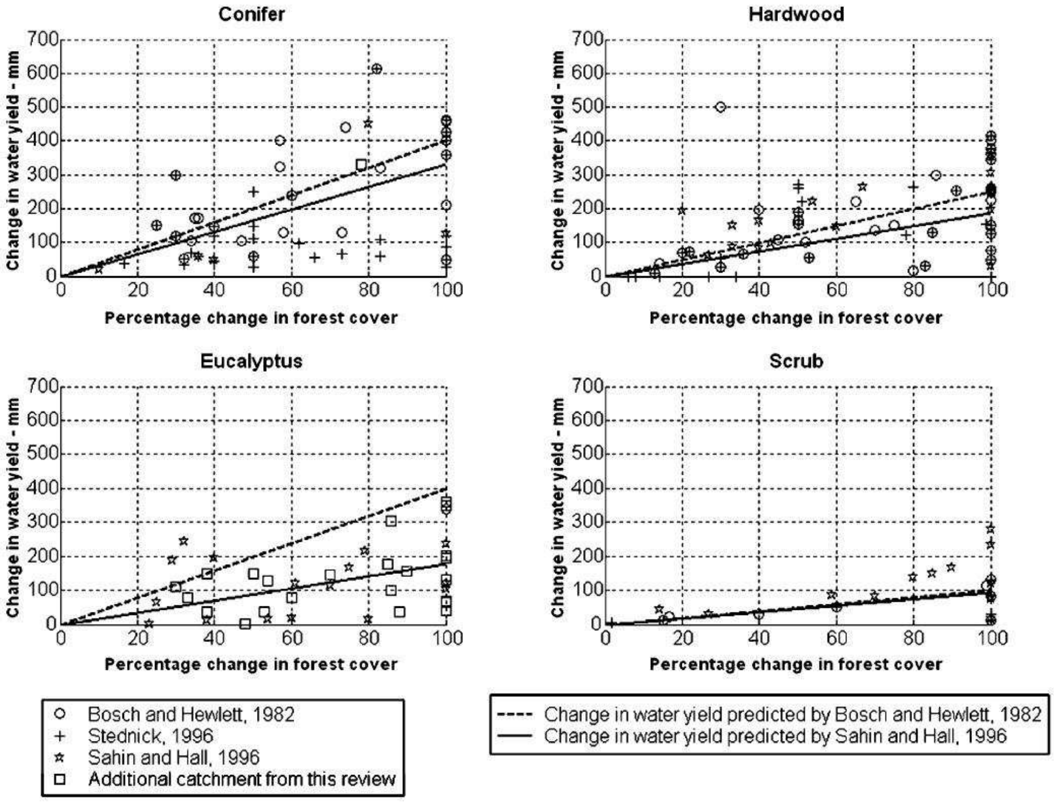



Figure 3.3.: Water yield changes as a result of changes in vegetation cover with data sets from four different review studies (*Brown et al.*, 2005).

literature this is reffered to as the role of configuration of the treatment.
Studies from the watersheds at the Coweeta Hydrologic Laboratory (*Swank et al.*, 1988) showed remarkable difference in response to vegetation change, which is justified by the authors with the catchment's aspect. Indeed, the energy input by solar radiation onto a catchment's area is affected amongst others by aspect, slope and latitude. At Coweeta, this effect appears with a nearly three-fold increase of water yield of catchments with polar aspect compared to catchments with equitorial aspect.
Next to climatic conditions, configuration of treatment and aspect, the large variability may also be traced back to timing of cutting, method of cutting and control of regrowth. Maximum variation of annual water yield due to afforestation and deforestation have been presented in figure 3.2. To illustrate the effects of forest conversion on annual water yield, two long-term studies from the Coweeta Hydrologic Laboratory by *Swank et al.* (1988) are presented. Both, north-facing watershed 17 and south-facing watershed 1, have been subjected to a conversion from hardwood vegetation (oak-hickory) to conifer (white pine). Streamflow reactions after the planting of white pine seedlings are given in figure 3.4.

As can be seen, both of these conversions have produced dramatic changes in streamflow. For a period of about six years after the planting of the conifers, streamflow

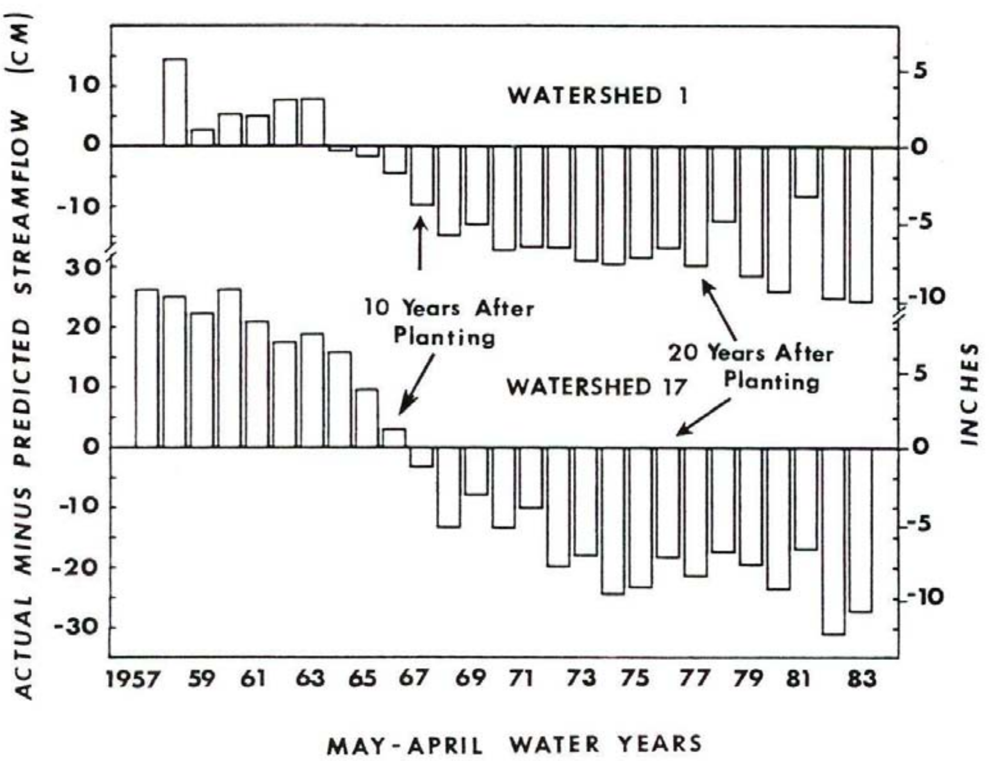



Figure 3.4.: Annual variation in flow on two Coweeta watersheds following conversion from mixed hardwoods to white pine (*Swank et al.*, 1988).

increases remained on a relative constant level. As the white pine stands developed, the increases began to decline at a rate of about 20 to 50 mm per year below the level expected for hardwoods until about 1972. Then a relative constant period followed again, with fluctuations of annual reductions in flow between 100 and 200 mm, depending on annual precipitation. The decline in the last years of measurement was still going on and it is obvious, that the water consumption of the young pines was significantly higher than that from the mature hardwood cover. As already mentioned on page 16, reasons for the increased water consumption of the vegetation are attributed mainly to higher interception losses and transpiration rates of conifers compared to hardwoods. *Swank & Miner* (1968) point out, that those transpiration and interception differences show a seaonalitiy. Interception and transpiration differences are highest especially during the dormant season, when LAI of the hardwoods is greatly reduced by leaf fall. Thus less precipitation reaches the soil under pine and the result is lower streamflow in the dormant season. While transpiration values in the period May-October might even be slightly higher for hardwoods than for conifers, the sum of interception and evapotranspiration causes, that water yield from the white pine forests is lower during every month of the year than that from hardwood forest (*Swank & Douglass*, 1974).

### 3.1.3. Effects of treatments on peak flows

The relationship of forest treatments and floods is still discussed much more controversely than the topic presented above. Public interest in flood reactions following forest treatment is high, not only in the field of hydrology but also in ecology (water quality), engineering (road drainage), geomorphology (sediment transport) or socioeconomy, to name just a few (*Beschta et al.*, 2000). Besides that, results published by different authors don't offer such a high uniformity as i.e. in the topic of forest treatment on water yield, and thus fuel the discussion. Note, for example, the quotation by *Thomas & Megahan* (1998): 'Given the complex nature of the effects of forest cutting [...] on streamflow, it is not surprising that the literature provides mixed messages about peak flow responses [...]'.
The 'complex nature of the effects', mentioned by the authors, can be followed by looking at figure 3.5, which illustrates important interrelations affecting storm peaks due to forest treatment.

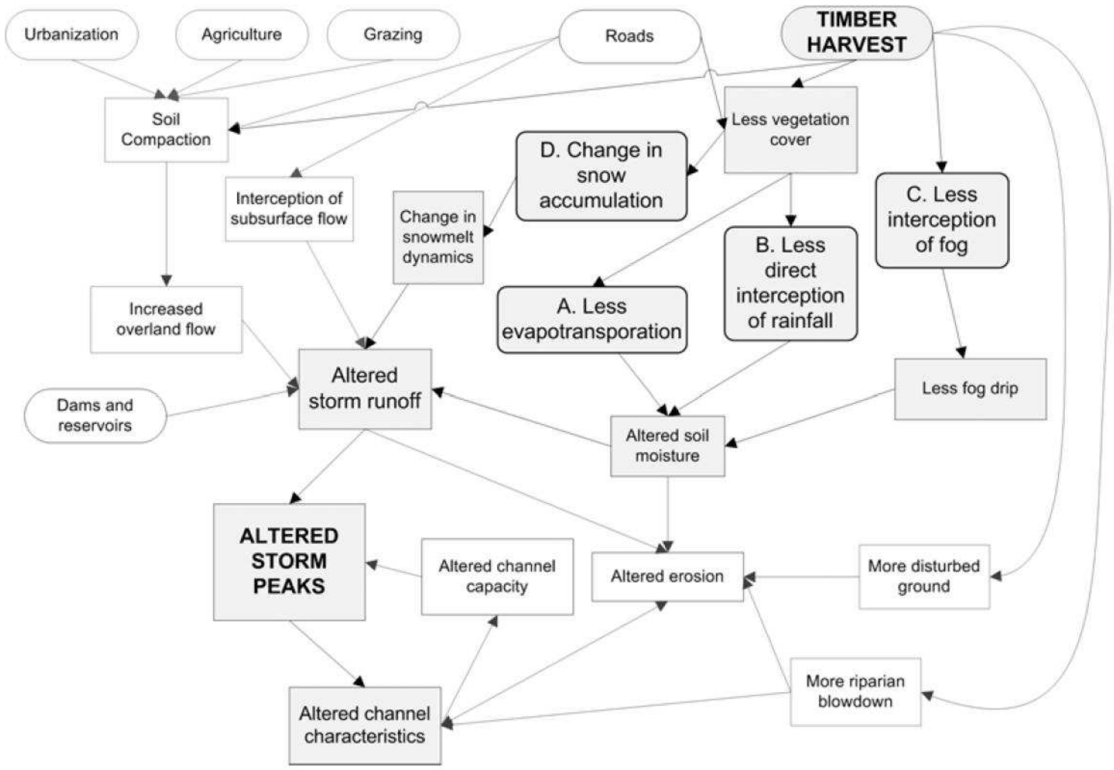


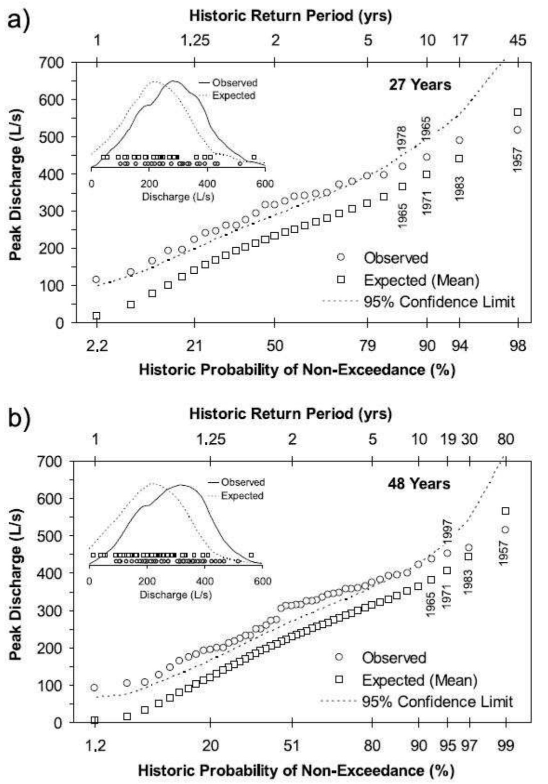

Figure 3.5.: Involved processes in the context of timber harvest and peak flows after *Ziemer* (1998) edited by *Grant et al.* (2008).

After *Grant et al.* (2008) most dominant processes affecting peak flow are evapotranspiration and interception and their essential impact on soil moisture as well as snow accumulation, melt rates and soil compaction. Characteristics of the soil moisture reservoir (i.e. infiltration capacity, rate of depletion, antecedent moisture conditions) oftentimes is drawn as a deciding parameter linked to peak flow response (*Ziemer*, 1981; *Eisenbies et al.*, 2007). Still, a wide array of factors, including climatic, bi-

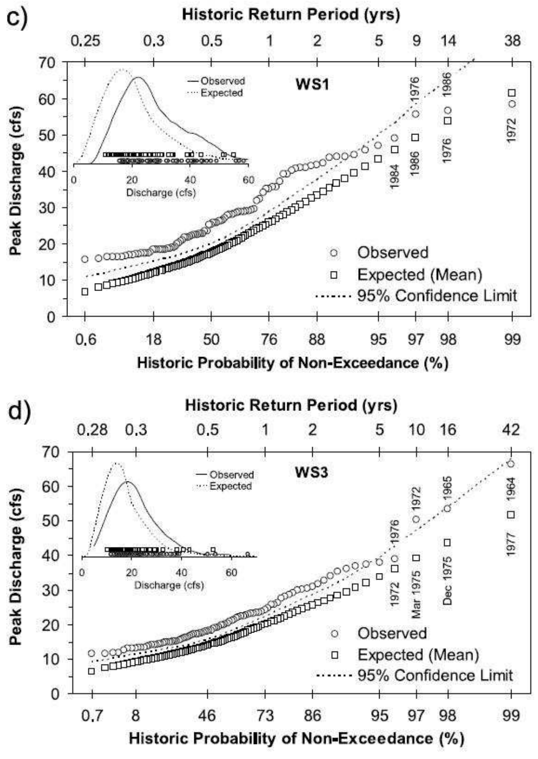
otic and geophysical processes, natural disturbances and management practices (i.e. road construciton), influence the behavior of the watershed on producing floods.
Forest impact on floods has been subject to research since the first studies at Wagon Wheel Gap (*Bates & Henry*, 1928). Since then, some key aspects of the discussion have been shaped out. In the recent debate, many authors pronounce a different behavior of 'small storms' compared to 'large storms', whereas the definition of small and large may differ from author to author. Furthermore, observations have been made, which clearly indicate different behaviors of small watersheds compared to larger river basins and hence suggest a differentiation by watershed size.
Floods are defined by the peak flow frequency distribution: A flood with a given magnitude (volume per time) has a specific return interval, depending on physographic and climatic conditions of the watershed. Paired-watershed studies have been widely used (*Troendle & King*, 1985; *Jones & Grant*, 1996), mainly to observe and compare magnitude of control and treatment peak flows to the same meteorological input. After *Alila et al.* (2009), this method is referred to as 'chronological pairing'. Results of covariance analysis (ANCOVA) and extended ANCOVA (i.e. comparison of pretreatment and posttreatment regression models) from various small watershed studies (*Thomas & Megahan*, 1998; *Beschta et al.*, 2000) support the hypothesis, that forest harvesting affects the magnitude of small to medium peak flows, but not that of larger floods. Analysis of variance (ANOVA) , which was applied by *Jones & Grant* (1996), brought similar results for small watersheds. Results for large basins ('forest harvesting has increased peak discharge by as much as 100%') on the other hand didn't show consensus to other studies for instance from *Thomas & Megahan* (1998) ('We could not detect any effect of cutting on peak flows in one of the large basin pairs[...]'), who used the same data as *Jones & Grant* (1996). This discussion indicates that the results are quite variable and seem to dependent on the applied method.
*Alila et al.* (2009) recently sharply critizized the method of chronological-pairing, which has been widely used to determine peak flow changes, simply because it does not consider the frequency but just the magnitude of an event. They state, that magnitude and frequency are 'inextricably linked and require a method that assesses both simultaneously'. They present three main considerations, that haven't been taken into account in the history of peak flood analysis with extended ANCOVA and ANOVA:

- By not accounting for changes in frequency, these methods do not even reveal the correct changes in magnitude.
- By decoupling magnitude and frequency, these methods fail to account for and preserve the all-important nonlinear and inverse relation between these two attributes.
- The extensions of these analyses, originally designed for means, does not account for a potential change in variance and its effect on the frequency and magnitude of floods.

Instead of a chronological pairing the authors propose a frequency-paired event analysis. They present data gained by the methods of regression analysis, frequency analysis and flow duration curve analysis (FDC) for two small paired-watershed studies, at the Fraser Experimental Forest, Colorado, and at the H. J. Andrews Experimental Forest, Oregon, respectively. They show conclusively, not only that all peak flows of the treatment watershed at Fraser (40% harvest), except the largest one, have shifted upward, but also that the positive or negative alteration of large floods (i.e. return periods >17 years) is very sensitive to sample size, if stationarity of the data is guaranteed (figure 3.6.1). While the change from positive to negative effect of treatment for the 27-year time series lies within the range of 17 to 45 years return period, it lies within the range of 30 to 80 years return period for the 48-year time series. This indicates, that the positive effect of treatment on larger floods, may shift upwards, simply by extending the observed time period.




3.6.1: FDC analysis for observed and expected daily peak flows at Fraser Experimental Forest (a) 27 years posttreatment (1957-1983); (b) 48 years posttreatment (1957-2004).




3.6.2: FDC analysis for observed and expected daily peak flows at H.J. Andrews Experimental Forest (c) WS1 23 years posttreatment (1966-1988); (d) WS3 25 years posttreatment (1964-1988).

Figure 3.6.: Results from the study on forests and floods from *Alila et al.* (2009).

Results from two watersheds at H. J. Andrews Experimental Forest are given in figure 3.6.2. Watershed 1 was 100% clearcut, watershed 3 was roaded and 25% patch-cut. Treatment has shifted all peak flows upward at both watersheds, except the largest observation on watershed 1. The effects of treatment at watershed 1 (see figure 3.6.2(c)) for the largest floods remains somewhat ambigious, possibly due to

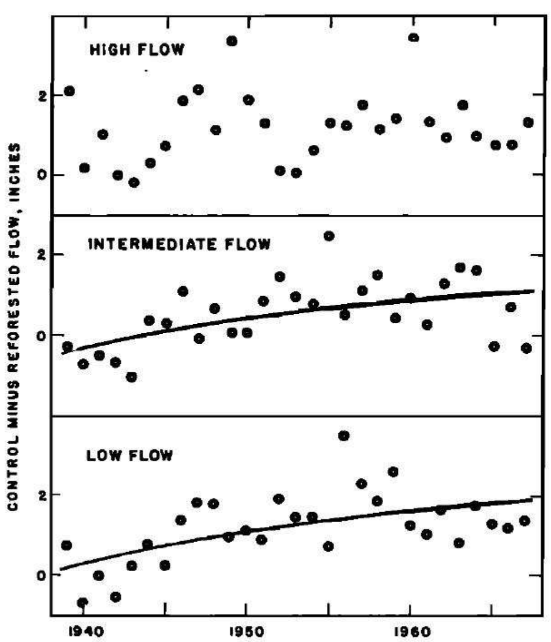
effects of small sample size as mentioned above or uncertainty affected by the plotting position equation. Still, the reaction of watershed 3 is conclusive. The additon of roads to partial clear-cutting seems to generate a different peak flow response, which is reasoned by the authors with increased stream network density.
The study of *Alila et al.* (2009) not only differs considerably from previous studies by applying the method of frequency-paired event analysis, but moreover by their presented results, that large floods are indeed affected by forest treatment, which disagrees with results from *Ziemer* (1981), *Wright et al.* (1990), *Beschta et al.* (2000), *Eisenbies et al.* (2007), *Grant et al.* (2008), who conclude, that peak flow reactions diminish as events become larger. Furthermore, it is clearly emphasized, that conclusions regarding flood peaks with high return periods highly depend on the observed time-period, i.e. that it is difficult to make statements about 100-year floods, by looking at a 25-year record.
The discussion on forest treatment and peak flows remains suspenseful. It shapes out, that the lively discussion especially on large peak flows may also be caused by the fact, that major storms occur very irregularly and thus make comparison more difficult. The large scatter of results presented above may furthermore be provided by the fact, that different climatic conditions, different catchment sizes and different time-periods have been subject to research. Many studies introduced here are based on changes in magnitude of peak flows. The method provided by *Alila et al.* (2009), who looked at the combination of magnitude and frequency, shows promise for new insights into the field of extreme events.

### 3.1.4. Effects of treatments on low flows

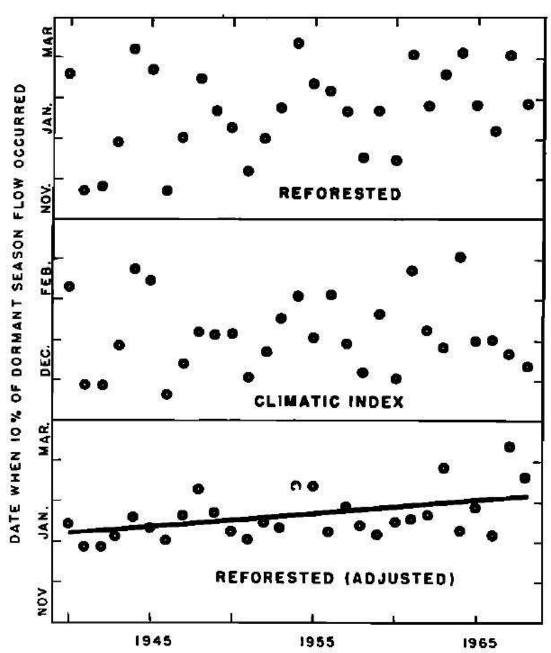
Most studies on forest cover alterations deal with impacts on annual water yield and peak flows as presented in chapters 3.1.2 and 3.1.3, respectively. The number of studies, dealing exclusively with low flows, due to forest treatment is rather limited. Nonetheless low flow is of particular interest, concerning a river's flow regime, which may be important for the perpetuation of water supplies. It may also be important for the maintenance of water quality standards through the dilution of effluents (*Johnson*, 1998).
There are several methods for the quantification of low flows, including statistical methods like regression analysis or flow duration curve analysis. Many parameters have been introduced to describe low flow conditons, in particular MNxQ [1], $Q_{95}$ [2] or MAM(x) [3] and temporal parameters like time of shortfall under a predetermined value, timing of low flow or half-flow [4].
The impact of forest cover on low flows seems more straightforward than the impact on floods. As cited above, forest regrowth leads to increases in interception and transpiration, the latter particularly during the growing season. This may result in decreased recharge to the soil and increased depletion of the soil moisture reservoir. Since during dry summers low flows are mainly fed by water from the surrounding

[1] MNxQ = lowest mean discharge of a sequence of x days
[2] $Q_{95}$ = discharge that is exceeded in 95% of the time
[3] MAM(x) = mean annual x day minimum
[4] half-flow = the time, when half of the annual streamflow has passed the gage

aquifer, it is this recharge to the aquifer, which has essential impact on the low flow characteristics (*Johnson*, 1998). On the other hand it has also been argued, that forests might sustain low flows, by encouraging infiltration into the soil due to the permeable litter layer, created by the forest (*Robinson et al.*, 1991). Nonetheless, the examples presented below identify patterns of rather uniform reactions due to forest treatments, where a general reduction in low flows occurs as the forest grows, and low flows increase, once a forest is clearfelled.
*McGuinness & Harrold* (1971) examined two small watersheds located at the North Appalachian Experimental Watershed in Ohio. On the basis of FDC and half-flow date analysis they examined differences on low flow as a result of change in forest cover. After segmenting FDCs into high flows, intermediate flows and low flows, they determined the area between the treatment and control FDC for each segment and plotted the difference in relation to the years under investigation. They observed statistical significant trends for low and intermediate flows by regressing the plots with a hyperbolic function and found a negative correlation between reforestation and low flows over the first 15 years of tree growth (figure 3.7.1).




3.7.1: Differences between control and reforested watersheds for high flow, intermediate flow and low flow over 29 years.




3.7.2: Date when 10% of dormant season flow occurred on reforested and control watershed and time trend of adjusted values.

Figure 3.7.: Reforestation influences on low flow and timing of flow (*McGuinness & Harrold*, 1971).

*Smith & Scott* (1992) analyzed the effects of afforestation on low-flows in five paired-watershed studies in South Africa. Low flow was defined as follows: For each control catchment a cut-off volume was selected, which was just above the flow from the two to three driest months of the year. Thus, months with streamflow below the cut off value were chosen for analysis and matched with the respective value for monthly low flow in the treated catchments. Regression models were fitted to the plots to predict low flows, should the catchment not have been afforested. All paired-catchment studies showed highly significant reductions in annual low flows to afforestation, both with pines and eucalypts, whereas the low-flow reaction to afforestation with eucalypts occured earlier than with pine. At the Mokobulaan research Catchments A and B, which were also subject of the study from *Scott & Lesch* (1997), eucalypt and pine afforestation led to a complete stop of flow, nine and twelve years after planting, respectively. Clearfelling of the eucalypts in 1985 in Catchment A couldn't compensate that effect considerably.

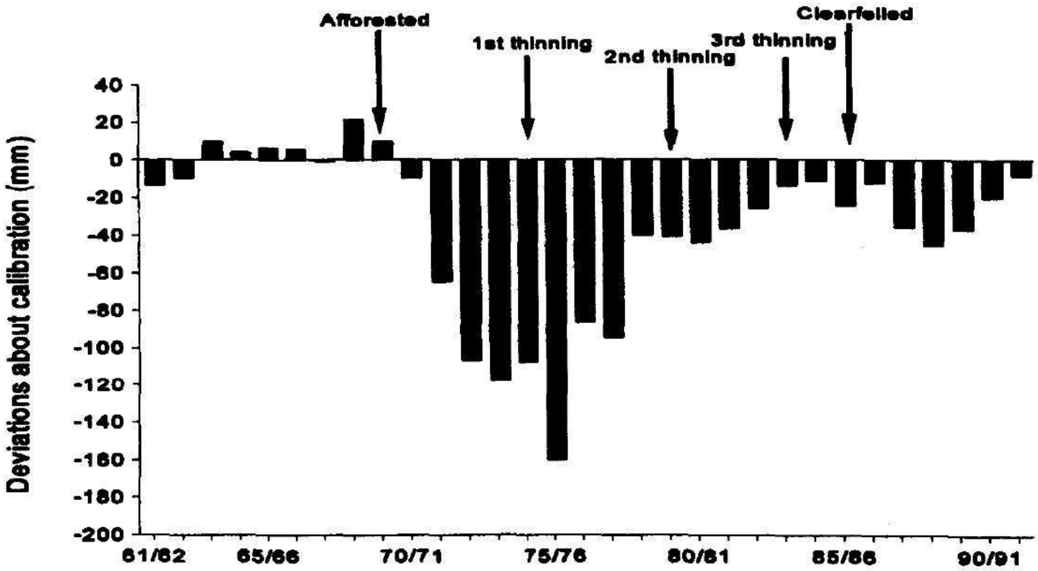



Figure 3.8.: Actual minus predicted dry-season streamflow at the Mokobulaan Catchment A (eucalypt afforestation) after *Scott & Lesch* (1997).

The fact, that streams in some of the examined catchments dried up is not surprising, if one remembers the relationship of percentage of treatment versus change in water yield from *Brown et al.* (2005) as presented on page 18. Expected annual water yield difference for a catchment 100% treated would be around 400 mm for eucalypt/pine according to figure 3.3. So with a pre-afforestation streamflow average of 236 mm for Catchment A, a complete stop of flow was likely to occur. Surprising on the other hand is the fact, that clearcutting of Catchment A didn't show any meaningful increases neither for low flow (figure 3.8) nor for annual flow for about five years. Other studies in South Africa showed, that clearfelling immediately may lead to considerable streamflow increases (*Smith*, 1991). *Scott & Lesch* (1997) reason, that the large soil mantle reservoir needed to be recharged over several years, before streamflow could return to normal. Findings from *Smith & Scott* (1992) also didn't support the hypothesis, that low flow following afforestation would be positive related to MAP, as it is for annual water yields after *Bosch & Hewlett* (1982). In fact in the study of *Smith & Scott* (1992) reductions appear to be more likely related to tree species and growth rate.

### 3.1.5. Effects of treatments on time-distribution of flows

*Hornbeck et al.* (1997) found low flow changes by creating FDCs for three different paired-catchment studies at Hubbard Brook Experimental Forest. Figure 3.9 depicts FDCs for the first year after a clear-felling experiment for the whole water year period, but also for the growing season and the dormant season exclusively. Discussion of the data not only revealed, that a bulk of the streamflow volume changes occurs for daily low flows below 1 mm, but also that most of the change occurs in the growing season. Almost no change was observed in the dormant season.

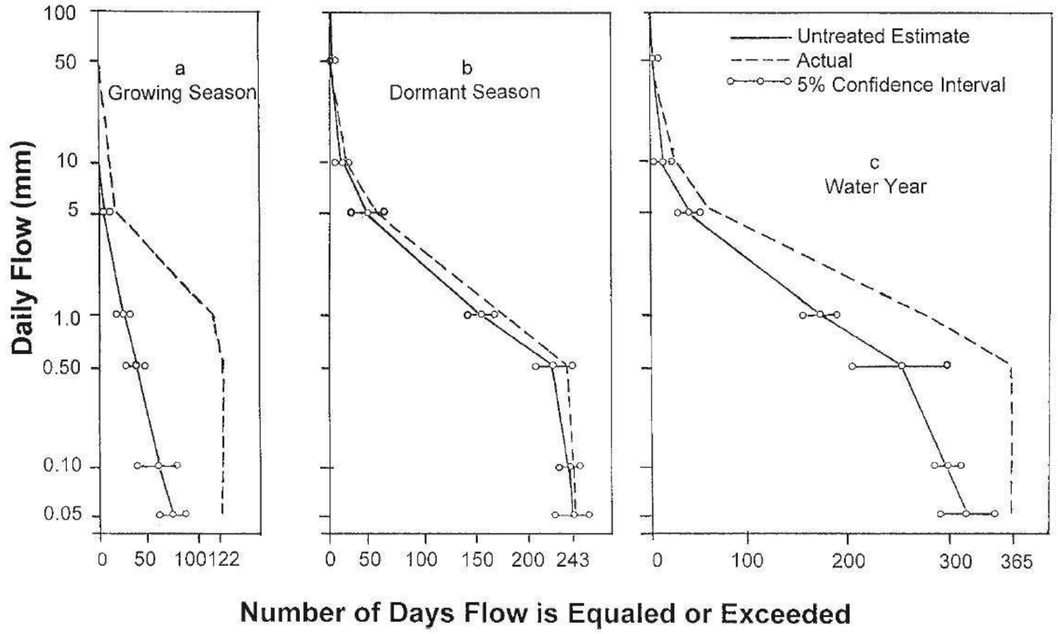



Figure 3.9.: Flow duration curves for water year, growing season and dormant season of the clear-felled watershed 2 at Hubbard Brook Experimental Forest (*Hornbeck et al.*, 1997).

According to the authors, this seasonal alteration of water yield is caused by the transpiration deficit due to the absence of forest cover after clearfelling, since plant water consumption is highest in the growing season.
Advance of the timing of snowmelt runoff was reported in *Hornbeck* (1975), who analyzed streamflow response to forest cutting and revegetation. While the total volume of snowmelt stayed about the same after treatment, streamflow increases for the first month of major snowmelt were reported, while one or two subsequent months showed streamflow decreases. This time shift may be understood as an indication to the behaviour of the watershed, since the study only analyzed a very short clear-cut period, which was followed by quick natural regrowth. Still, similar results have been reported by *Troendle & King* (1985), who applied ANCOVA to determine the effects of timber harvest on peak discharge of the Fool Creek Watershed at Fraser Experimental Forest, Colorado. Their results show that on average, peak mean daily discharge occurs about 7.5 days earlier in the year for the 15-year posttreatment period, compared to the 15-year pretreatment period. As commented

by the authors, timber harvest caused an advance in snowmelt, which resulted in a faster recharge of the soil moisture reservoir.
The timing of flow was also examined in the study from *McGuinness & Harrold* (1971), by analyzing the dates when flow reached 10% of the dormant season total (November 1 through April 30) on both the treated and control watershed. Since plant regrowth might have an intensified effect on soil moisture depletion in summer, the rise of streamflow in fall might get delayed, because fall precipitation is used to refill the soil reservoir first, and then account for streamflow rises. The 10% flow date was adjusted (regression) to remove climatic trends and plotted against the 29-year period of record. The data indicates, that the 10% flow date was delayed 31 days from January 6 in 1940 to February 6 in 1969 (figure 3.7.2 bottom).

Table 3.1.: Seasonal response in water yield for different climatic conditions after *Brown et al.* (2005).

| Climate | Absolute response | Proportional response |
|---|---|---|
| Tropical/summer dominant rainfall | Larger changes in summer months, when rainfall is greater than monthly average | Two types of responses observed: (1) Similar changes in all months (2) larger changes in winter months, when rainfall is below monthly average |
| Snow affected catchment | Largest changes in months of snow melt | Larger change in summer growing season |
| Winter dominant rainfall | Largest changes in winter months when rainfall is above monthly average | Largest change in summer months when rainfall is below monthly average |
| Uniform rainfall | Uniform change across all seasons | With deciduous vegetation there is a larger change during the spring months. Evergreen vegetation shows uniform change across all seasons |

As one can see, both, delay and advance of flow, may be the reactions of a catchment to forest treatment. Figure 3.9 also demonstrates, that changes of annual water yield do not necessarily implicate changes for every month of the year. Moreover, it is important to mention, that flow alterations may underly a very distinct seasonality, dependending on many factors, like climatic conditions, vegetation cover or configuration of treatment. Although it seems difficult to generalize, *Brown et al.* (2005) tried to classify seasonal responses of water yield to climate. They reviewed more than thirty papers on seasonal effects of vegetation change and distinguished between summer dominant rainfall, snow affected catchment, winter dominant rainfall and uniform rainfall. Total volume change (absolute responses) and change with respect to the flow under the original vegetation type (proportional responses) for each climate class can be found in table 3.1. Still, the authors emphasize, that the results presented are based on some 'broad generalizations', due to 'different definitions of seasons and the graphical and descriptive nature of the results'.

### 3.1.6. Effects of treatments on snow accumulation

As already described in chapter 3.1.3, the impact of forest treatment on floods is of fundamental interest and part of a lively discussion. In many inland watersheds in montane and boreal environments, snow accumulation and melt dominate the hydrology and may result in peak streamflows of impressive magnitude. Therefore, forest impact on those snow-affected processes is object of many past and present catchment studies.

The impact of forest cover on snow accumulation results from its interception capacity and its influence on the snowpack energy balance. Interception of snow precipitation and subsequent sublimation alters the snow cover under the canopy. Sublimation represents a direct loss from the soil-snow system, while meltwater drip and mass release are processes, which release intercepted water to the ground, where it may be stored by the snowpack or routed directly to the soil (*Storck et al.*, 2002). The energy balance of the snowpack is affected through the canopy by attenuating short-wave radiation to the ground surface and enhancing long-wave radiation transfer. In addition, the absorbed short-wave radiation through the canopy, is redirected to the ground as long-wave radiation. Furthermore, turbulent heat fluxes are damped down by forest canopy (*Storck et al.*, 1999). Due to these processes, snow accumulation under forest canopy is generally lower, compared to clearcut areas and non-forested landscapes (*Jost et al.*, 2007), producing a snowpack with spatially heterogenous depths and snow water equivalents (SWE). Snowmelt on the other hand, may be altered positively and negatively by forest canopy, depending on the event-type. During events with prevailing short-wave radiation and turbulent energy fluxes, canopy existence usually suppresses snowmelt (*Storck et al.*, 1999). The structure and species of trees within a stand influence both, amount and variability of snow accumulation under the forest cover. With increasing forest canopy density and leaf area, thus increasing interception efficiency, snow accumulation and melt rates decline (*Hedstrom & Pomeroy*, 1998; *Pomeroy et al.*, 2002). Therefore, it seems comprehensible, that coniferous forests retain more snow precipitation from the ground and have a higher attenuation of radiation than hardwood forests, due to a higher LAI.

Although many processes concerning deposition and melt of snow are discovered, snow accumulation may still show a high degree of spatial and temporal variability. Besides the impacts of forest cover, snow accumulation is especially influenced by topography, in particular elevation and aspect, which oftentimes account for large parts of the variability. Furthermore, wind redistribution is a frequently-cited factor, concerning the deposition of snow at the plot-scale (*Hedstrom & Pomeroy*, 1998; *Luce et al.*, 1998).

A great majority of studies concerning forest treatment effects on snow accumulation deal with conifer rather than with hardwood forests (see: *Murray & Buttle*, 2003, page 203). Most of these studies show high uniformity of SWE differences between open sites and forest stands. SWE increases from 9 to 300% are reported for open

sites in percentage of SWE under conifer forest stands.
Results from a study in southern British Columbia on the impacts of cleared, juvenile and mature conifer forest on snow accumulation and melt rate are given by *Winkler et al.* (2005). SWE was measured for three successive years and four experimental sites, one being clearcut and reforested with a very young pine population (height <1m), two being reforested with juvenile pine population (15 years of age) and thinned juvenile pine population (15 years of age; half of the original stocking), respectively, and one being forested with a mature conifer forest (>100 year spruce-fir-population). On average, 23 and 14% less 1 April SWE was found in the mature spruce-fir and juvenile pine stands, respectively, than in the clearcut. Ratios of forested versus clearcut average snowmelt rates ranged between 0.4 for the mature stand and 0.8 to 0.9 for juvenile and thinned juvenile stands, respectively. Snowmelt lysimeter measurements showed, that snowmelt started earlier, accumulated more rapidly and ceased earlier in the thinned-juvenile stand than in either the unthinned juvenile stand or the clearcut. Those results not only demonstrate, that accumulation and melt of snow differs considerably between cleared, juvenile and mature stands, but also, that different structures in even-aged stands cause modified snowmelt patterns.
*Murray & Buttle* (2003) studied the effects of clearcutting on snow accumulation and melt rates at north- and south-facing slopes of a mature hardwood stand in the Turkey Lakes watershed, central Ontario. For two consecutive years, snow accumulation, daily melt rates and canopy coverage was measured at clearcut and mature hardwood stands, each for northerly and southerly aspects. Differences in accumulation between clearcut and forested stands were greatest on the ridge crest of the study area and the south facing slope. Wind redistribution from the northerly-aspect clearcut was accounted as a major factor for those differences. Daily melt rates tended to be higher in the clearcut than in the adjacent forest. Nonetheless aspect was identified to have greater impact on melt rates than clearcutting. Canopy coverage couldn't explain any of the differences observed at the northerly aspect. Still, on the south facing slope, differences between clearcut and forest stands seemed to be a result of canopy coverage, since the effects of canopy shading are more pronounced due to higher solar radiation input. In general, the authors conclude, that differences in accumulation and melt rates are not as distinctive as has been observed under coniferous forest cover, which they mainly attribute to the more open canopy in the hardwood forest.
Snow accumulation in open areas may also produce snowpacks of variable depths and non-uniformity. There are several studies, which adress the size of open stands and the SWE depending on the distance to forested stands. *Golding & Swanson* (1978) name two factors for different snow accumulation in openings: (1) disturbance of air flow over the openings, due to a discontinuity of the canopy; (2) increase of wind speed and turbulence in the forest opening, affecting snow distribution within and around the opening. SWE maximums in relation to distance to forested stands for several studies have been summarized in *Stegman* (1996). Those lie in a distance of 1 to 6 tree heights, depending on each author. Keeping in mind, that in general air fluxes are very unpredictable and that disturbance of air flow and wind speed are

related to the size of the open area, it does not surprise, that literature findings on this topic differ considerably.

### 3.1.7. Effects of treatments on subsurface water content

The soil moisture reservoir naturally underlies an annual cycle of filling, storing and depleting of water (*Bethlahmy*, 1962). Through its porous character, the soil storage is able to hold water against the pull of gravity until field capacity is reached. Evaporation and transpiration are the most important processes to consume soil water and thus deplete the soil moisture reservoir. Infiltration of precipitation water is used to refill the reservoir until field capacity is reached again. Water entering the soil in excess of this capacity percolates to lower levels under the pull of gravity.

As already adressed above, clearcutting may alter soil moisture characteristics considerably. Clearcutting temporarily reduces plant cover, which not only decreases interception losses, but also water uptake by tranpiration. Thus more precipitation water may reach the soil surface and account for refilling of the reservoir, and less water is removed from it by plant transpiration.

In a study at the H.J. Andrews Experimental Forest in Oregon, *Adams et al.* (1991) examined the long-term soil moisture developement of a clearcut stand, compared to an old-growth Douglas-fir stand. Two neighbouring, parallel transects were established, one located within the boundary of a clearcut and subsequently broadcast-burned patch (treatment in winter 1962-63), the other one located in undisturbed forest (control). Soil moisture measurements were conducted for five sampling points per transect and depths of 0-30 cm, 30-60 cm and 60-120 cm in a time period from 1960 to 1980.

Figure 3.10 displays the differences in average seasonal soil moisture for the total depth observed (0-120 cm). Although no calibration period was used by the authors, the pattern of the reaction clearly shows that clearcutting can affect soil moisture for the depth under investigation. The highest reaction to the treatment occured in the two years immediately after treatment (1963 and 1964), especially in summer and fall, when the new plant cover just slightly started to reestablish. The fast decline of the soil moisture difference and the eventual decrease were explained by the authors with a fast regrowth, from 1966 to following years. The long period of decreased soil moisture (1966 to 1980) on the other hand seemed unexpected, since regrowth put the forest cover more and more to its initial state. By analyzing soil moisture differences for different soil depths and seasons (see figure 3.11), it turned out, that soil moisture in the surface soil layer (0-30 cm) declined most rapidly and most severe not only in summer, but in every season. This was attributed to the dramatic spreading of shallow-rooting low shrubs, in the years 1965 and 1966. Apparently moisture deficits can occur well in advance of full plant occupation, since total cover in 1967 was only 48%. While the moisture of the medium soil layer (30-60 cm) seemed to even out near the no-difference level after some years, subsoil moisture was declining continuously since 1965. This was attributed to the simultaneous increase in tree and tall shrub cover over time, which may root well into the subsoil even at young age.

A study on the effects of forest harvest on soil moisture on Boreal Plain hillslopes

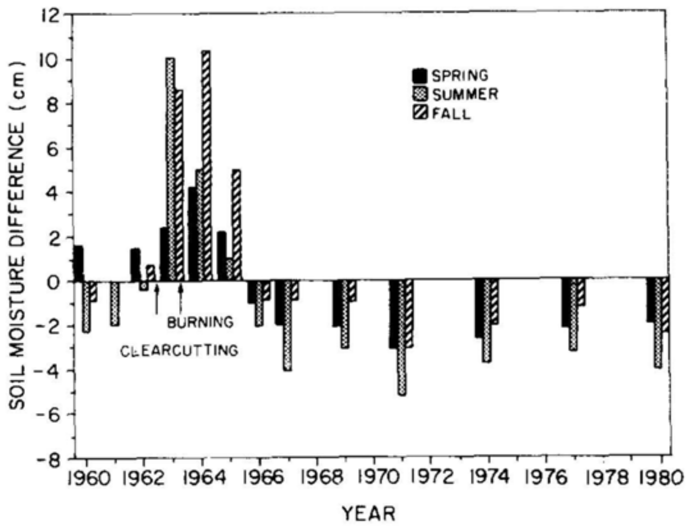



Figure 3.10.: Differences in average seasonal soil moisture between a clearcut and a forested stand at the H.J. Andrews Experimental Forest, Oregon. Average seasonal soil moisture was cummulated over entire depth (0-120 cm) of observation and illustrated for the time period between 1960 and 1980. Positive values indicate higher soil moisture in the clearcut area (*Adams et al.*, 1991).

in northern Alberta, Canada was conducted by *Whitson et al.* (2005). Although mean soil moisture by depth showed a trend towards wetter conditions at harvested sites, differences in integrated soil moisture contents were not detectable for the most months at a statistically significant level. The authors trace the unexpected low moisture content in the harvested sites back to the exceptionally dry weather conditions. Other reasons given by the authors are possible processing errors in the sampling design (sampling spatially too close) and rapid regrowth of aspen in some forested stands as consequence of applied harvest techniques.

## 3.2. Forest attributes and water consumption

A review study by *Wullschleger et al.* (1998) was conducted to summarize findings of 52 studies on the maximum transpiration rate of individual tree species. The results ranged from 10 kg day$^{-1}$ for oak stands in eastern France up to 1180 kg day$^{-1}$ for trees growing in the Amazonian rainforest. Most maximum daily rates for pine *Pinus* and spruce *Picea* species ranged between about 25 and 150 kg day$^{-1}$. For hydrologists those results are not applicable without further ado, since most hydrological studies discuss the effect of plant water use for a certain stand or ground area. So results, which are gained by the analysis of a limited number of trees, need to be scaled up to the whole area under investigation. This upscaling process mainly depends on the particular characteristics of the forest cover itself and may be based upon parameters like distance between stems, area covered by the crown, basal area, stem diameter, leaf area or sapwood area (*Wullschleger et al.*, 1998).

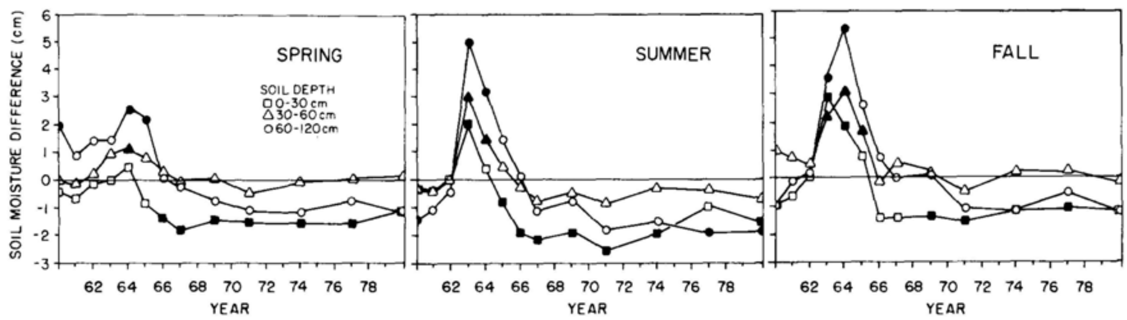



Figure 3.11.: Average differences in soil moisture between the clearcut and the forested areas. Reactions during spring (Apr-Jun), summer (Jul-Sep) and fall (Oct-Nov) are presented for the years 1960 to 1980. Positive values indicate higher soil moisture in the clearcut area (*Adams et al.*, 1991).

Upscaling into another spatial scale may give valuable information on the transpiration rate of the area under investigation. For regrowth and conversion experiments, as presented in the chapters above, temporal scaling is of fundamental interst. Australian forest hydrologists are amongst the most active, concerning the determination of forest water consumption in relation to forest age. Several studies on management practices of mountain ash forests and their impact on water yield have been conducted, with particular focus on forest age (*Langford*, 1976; *Vertessy et al.*, 2001). It seems well understood, that the amount of water yield from mountain ash forest catchments is related to stand age. This implies, that the transpiration rate of the forest is controlled by its age. *Kuczera* (1987) reassessed earlier work on long-term water yield trends in mountain ash catchments, following wildfires. He proposed a two-parameter model of the long-term yield trend and successfully fitted it on rainfall-runoff data for eight catchments.

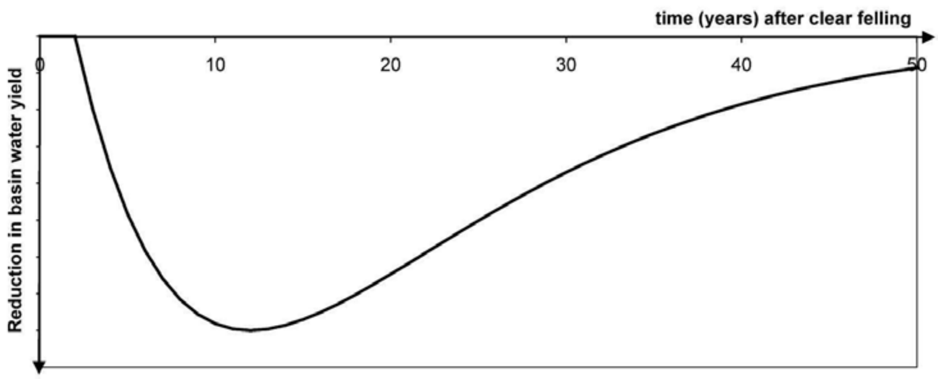



Figure 3.12.: Trend curve proposed by *Kuczera* (1987) to describe reductions of water yield due to eucalypt regrowth. Observed increases in water yield immediately after treatment are not shown in the graph (*Andréassian*, 2004).

Based on these findings, the 'Kuczera curve' simulation model was developed, aiming to illustrate the effects of future bushfires in mountain ash catchments (figure 3.12). Although observed, first year water yield increases were not included in the model. The 'Kuczera curve' is characterized by the following features:

- The mean annual water yield from large catchments covered by pure mountain ash forest in an old growth state (<200 years) is about 1195 mm for a region with MAR of about 1800 mm;
- after burning and full regeneration of mountain ash forest, the mean annual water yield reduces rapidely to 580 mm by age 27 years; and
- after 27 years of age, mean annual water yield slowly returns to pre-disturbance levels, taking as long as 150 years to recover fully.

Additional work for the relations between stand age and catchment water balance was provided by *Vertessy et al.* (2001). Total LAI, sapwood area indices (SAI), transpiration rates, rainfall interception and soil and litter evaporation were either measured or calculated for several mountain ash stands ranging in age between 5 and 240 years. Their results showed, that sap velocity does not change considerably amongst stands of different ages. The more determining parameter was found to be SAI, which declines with age and thus is held responsible for the decrease in stand transpiration.

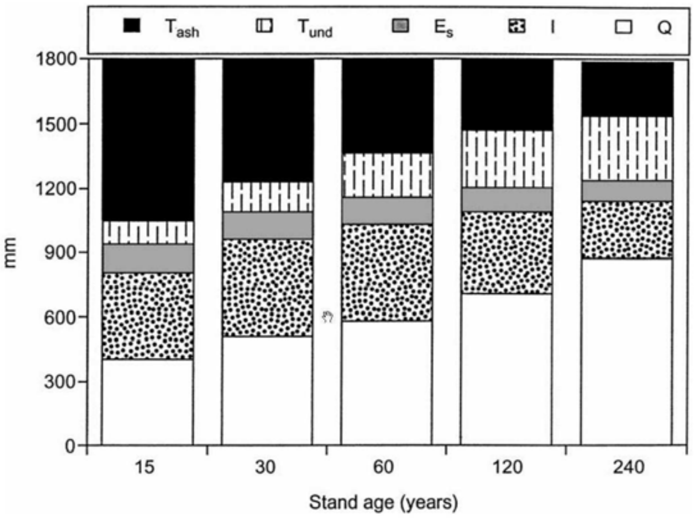



Figure 3.13.: Water balance estimates for different aged (15, 30, 60, 120, 240 years) mountain ash forest stands after *Vertessy et al.* (2001). MAR is assumed to be 1800 mm. $T_{ash}$ denotes mean annual transpiration by the mountain ash overstory, $T_{und}$ denotes mean annual understory transpiration, $E_s$ denotes mean annual soil and litter evaporation, $I$ denotes mean annual rainfall interception, and $Q$ denotes mean annual water yield.

Worth noting is also the fact, that the decline in overstory SAI was accompanied by a decline in overstory LAI, which, for itself, had the consequence that understory LAI

was increasing. Understory LAI increases (as to see in figure 3.13) however could not compensate the transpiration losses of the overstory, since it only transpires about 63% of the mountain ash rate per unit leaf area. The overall water balance developement is shown in figure 3.13. Finally, the difference in evapotranspiration between a 15- and a 240-year old mountain ash forest was estimated to be 460 mm per year for sites with 1800 mm MAR.
While most of the work, regarding the relation of forest age and transpiration has been conducted only under distinct climatic conditions of southeastern Australia and for specific plant species, it seems obvious that the transpiration rate of all plants is controlled at least partially by their age. LAI, SAI and root biomass developement underly dynamic alterations in the stages of a plants' life and thus have variable impact on the transpiration capability of the plant. In the context of management practices and vegetation change, dynamics in root growth become particularly important, when observing the temporal and spatial distribution of soil water content after management practices. The vertical distribution of soil water content may be remarkably influenced by the extend of root growth which itself is controlled by the plants age.
Maximum rooting depth values of 290 observations were summarized in a literature review provided by *Canadell et al.* (1996). Values ranged from 0.3 m for some tundra species up to 68 m for species growing in very arid regions. Average maximum rooting depths for temperate deciduous and temperate coniferous forests were $2.9 \pm 0.2$ m and $3.9 \pm 0.4$ m, respectively. Data, given in table 3.2 are taken from the study by *Canadell et al.* (1996) and shall give a rough impression of the potential rooting depth of plant species, that can also be found at the MEF.

Table 3.2.: Maximum rooting depth (m) for white spruce (*Picea glauca*), red pine (*Pinus resinosa*) and quaking aspen (*Populus tremuloides*) for several soil types and countries of observation, as provided by a literature review of *Canadell et al.* (1996). Note that the values represent the maximum capacity of a given species, to send roots deep into the soil, which may not be reached by all trees of a stand.

| Dominant species | Maximum rooting depth (m) | Soil type | Country |
|---|---|---|---|
| *Picea glauca* | 1.8 | medium-loamy | Russia |
| *Pinus resinosa* | 2.7 | Hinckley coarse sand | New York, USA |
| *Pinus resinosa* | 5.0 | sandy outwash | New York, USA |
| *Populus tremuloides* | 2.0 | sandy substrate | S-Canada |
| *Populus tremuloides* | 2.3 | grey clay | Michigan, USA |
| *Populus tremuloides* | 2.9 | sandy laom | Utah, USA |

Table 3.2 demonstrates, that even for the same plant species maximum root growth values differ considerably. This suggests, that roots-spread must be linked to soil properties somehow. Next to soil characteristics like texture, compaction and fertility, factors like temperature, depth to water table and even soil moisture content

are listed in literature. *Gilman* (1990) even points out, that the largest influence on root growth of all environmental conditions are soil moisture and temperature, which have been estimated to account for 80% of the variability in root growth activities. Considering the fact that root growth both affects and highly depends on soil moisture, it is perspicuous that this parameter is difficult to predict.

## 3.3. Interflow as important runoff component in forested watersheds

Forest soils are generally characterized by high infiltration rates, which leads to the fact that more than 90% of annual precipitation in a forested watershed interacts with the soil before contributing to streamflow or returning to the atmosphere (*Kirkby*, 1988). Water that flows downslope between the soil surface and the regional water table is referred to as interflow (*Eisenbies et al.*, 2007). In forested areas interflow, which is also known as subsurface stormflow, is usually the main contributor to streamflow. Saturation overland flow, which occurs when precipitation or snowmelt adds water to already saturated areas is less likely to occur (*Tarboton*, 2003). In literature interflow is referred to different processes. Water flowing through the soil matrix and inter-granular pores is described as unsaturated Darcian flow (*Dingman*, 2002). Infiltrated water may also flow through larger channels, which were caused by animal activities or decaying roots and is then referred to as macropore flow or pipe flow. Macropores may also include larger voids and thus transport water in preferential pathways and over considerable distances downslope. In many regions, hillslopes consist of several soil layers of different permeability. Oftentimes a thin layer of permeable soil overlies a deeper layer of relatively impermeable materials. In such situations a thin saturated zone may develop above the interface of the lower permeable to the higher permeable soil layer. In these saturated zones, water may flow laterally through the soil matrix, enter macropores and rapidly reach the stream in the form of interflow (*Tarboton*, 2003).
As already presented in chapter 2.6, interflow at the MEF is caused by the soil characteristics of the Warba and Menahga series. A rather impermeable B horizon is overlain by a more permeable loess layer. Both soils are forested, so interflow at the MEF may occur as the combination of flow in the saturated zones at the interface of two layers and macropore flow.

## 3.4. Conclusion

As can be seen from an overwhelming number of studies at the basin scale, forests undoubtedly have considerable impact on the water balance, in particular on the quantity, storage and movement of water. Paired catchment studies provide a useful method for determining changes in hydrological parameters due to changes in forest cover. One of the advantages of paired catchment studies is that the influence of climate variability is minimized through the comparison of two catchments, which are subject to different land uses, but under the same climatic conditions. A major limitation of paired watershed on the other hand is the obvious lack of replication across different natural conditions. Furthermore, the paired watershed design is reffered to as a 'black box' system, which may give valuable insight on the overall behaviour of the catchment, caused by the cummulative effect of different processes. But the identification and contribution of single hydrological processes is masked by the method.

Forest treatment operations are usually divided into four broad categories: afforestation experiments, deforestation experiments, regrowth experiments and forest conversion experiments. Expectations for each of those treatment operations can be made by presuming main contributive processes, still, the outcome may be highly variable due to the fact that streamflow is the integrated product of the character of climatic, topographic, geologic, pedologic and vegetational conditions of individual watersheds. While climate, geology and the geometry of a watershed are rather fixed factors, soils, topography and vegetation can be influenced by the treatment practices themselves. Thus it may be problematic to separate the effects of e.g. soil disturbance, road construciton or channelization from the actual effect of treatment.

Many studies discuss the effects of forest treatment on water yield. The effects of vegetation change on mean annual water yield seem well understood. The removal of trees through harvesting reduces water demand and will affect water yield positively. Afforestation on the other hand generally decreases annual water yield. The research on seasonal water yield is more limited and oftentimes of a descriptive rather than a quantitative nature (see table 3.1). Seasonal effects should be most evident in the growing season, when plant water consumption usually reaches its maximum. Anyhow, chapter 3.1.5 shows, that both, advance and delay of flow have been observed in different seasons.

Results are more heterogenous regarding the effects of forest operations on peak discharge. Results presented in chapter 3.1.3 give the impression, that forest removal at least in the catchment scale, increases peak flows. And indeed a large number of studies strengthen this impression. Nonetheless, the effect isn't as obvious as for annual water yield. It is important to mention, that management practices influence hydrological flowpaths and streamflow components by altering not only the volume, but also the timing of flow. But whether the sum of timing and volume causes a synchronization or desynchronization of flow is very difficult to predict and depends on many factors. Furthermore, it lies in the nature of extreme events to occur infrequently and thus handicap the gain of reliable scientific conclusions.

The impact of low flows seems well substantiated: deforestation increases low flows, particularly in the growing season, reforestation decreases low flows. Flow periods are shortened by reforestation, which can even lead to a complete ceasing of flow. Variation of the transpiration rate might occur for different forest stages and thus low flow characteristics might be changed, as the forest grows.

It is obvious, that snow accumulation in a harvested stand is more extensive than in a forested, since interception losses are omitted. All but two studies in a review by *Murray & Buttle* (2003) had a positive effect on snow accumulation after harvesting, ranging from 9 to 300%. Direct comparisons between coniferous and deciduous stands concerning the effects of clearfelling on SWE couldn't be found in this lit-

erature review. But since snow accumulation is closely related to canopy density and leaf area, it is expected to be higher under deciduous trees. Radiation and heat flux processes within and at the border of the stand, as well as topography of the research site are important controls for the developement of the snow cover.
It seems logical, that increases in soil moisture come along with decreases in plant cover. Interception capacity and transpiration rates are heavily diminished by deforestation. Reactions like those presented by *Adams et al.* (1991) however clearly indicate, that the vegetation-soil-water system does not always react like expected. Certain processes might be accentuated over time, depending on climatic conditions, soil characteristics or vegetation species.
Stand age certainly has an impact on a forests' transpiration rate, as presented by a number of studies, discussing regrowth of Australian mountain ash forests. Total annual stand evapotranspiration differences of up to 50% have been observed for 15- and 240-year old mountain ash stands. The 'Kuczera curve' model successfully simulated this reaction for several catchments in southern Australia. Although the evidence is missing due to a lack of research studies, similar reactions might as well be imaginable for temperate deciduous and conifer stands of the northern hemisphere, if not with the same magnitude. Root growth in relation to stand age on the other hand seems more unpredictable due to parameters re-affecting each other and site specific soil properties. *Gilman* (1990) coined the phrase, that 'operators of landscapes [...] could more precisely manage trees and shrubs under their care by digging in the soil to determine the location of roots'. Still, maximum rooting depth, observed in literature are valuable information and should be kept in mind when analyzing the data.
Interflow is a well understood, and often referred hydrological process in hillslope hydrology. Interflow at the MEF is predominantly occuring due to permeability differences in the forest soils. When speaking of subsurface flow in the following chapters, the author refers to interflow processes as described in chapter 3.3.

# 4. Methods and Materials

A quick overview of the applied materials and installations, the data sampling methods, and data availability is given in the following chapter. Furthermore, statistical methods, which have been used in the data processing, are presented.

## 4.1. Measurements and installations

### 4.1.1. Streamflow

Both watersheds observed in this study have single channel outlets where streamflow is permanently monitored. Streamflow monitoring began in the 1960s, when the Marcell Experimental Forest was established. A V-notch weir was installed at the outlet of Watershed S2, while watershed S6 was originally configured with a type 'H' flume (*Bay*, 1967c). This flume was replaced in the mid 1970s with a V-notch weir, which caused a shift in streamflow volumes. Therefore in this study runoff volumes were only used for the time period from 1976 to present.
The weirs are constructed of 120° V-notch blades, which are attached to concrete cutoff walls. The walls have been installed perpendicular to the natural channel and most of them is buried into the soil to minimize leakage around or below the weir. The bottom of the V is placed at the level of the natural stream bottom. Runoff is measured with a precision of 95% for the V-notch weirs (*URL1*, 2009). Both weirs are equipped with strip chart recorders. Strip charts are digitalized and stream discharge is calculated from a stage-discharge relationship. Daily streamflow is computed by integrating the area under the hydrograph (*Sebestyen et al.*, unpublished). Afterwards, daily streamflow volumes are converted into mm.

### 4.1.2. Precipitation

Precipitation is monitored at the meteorological station at the upland of watershed S2. A standard precipitation gauge and a recording precipitation gauge are emptied on a weekly basis. Gauges are painted silver to reduce evaporation and have a windshield installed. Precipitation is measured at the gauge tops, 1.52 m above the ground. Each year, the recording gauges are lubricated and calibrated. During the summer, weekly precipitation is measured with a measuring stick to the nearest 0.25 mm, and gauges are emptied afterwards (*Sebestyen et al.*, unpublished). In the winter, antifreeze and oil is added to the gauge to melt snow precipitation and reduce evaporation from the gauge, respectively. Differences in weekly weight of the gauge are then converted into inches of precipitation and later on into metric units (mm).

Daily precipitation is given by the recording gauge and weekly sums are compared and corrected with the weekly precipitation of the standard gauge (*URL1*, 2009).

### 4.1.3. Soil Moisture

Available soil water content is measured at two sites of each watershed, using neutron probes, which are inserted into aluminium access tubes, 3.8 cm in diameter (*Nichols & Verry*, 2001). For each site soil moisture readings are taken at 1 foot intervals (every 30.48 cm) to a maximum depth of up to 10.5 feet (320 cm). Available soil moisture is recorded three times a year, in mid May prior to leaf out of the trees, in late September at the time of leaf off, and in November at the time of freeze. Raw data as percentage moisture by volume is converted to available soil water after substracting the wilting point constants for each soil horizon. Finally, the data entries are converted to metric units (*URL1*, 2009). Watershed S6 has a northern and a southern sample site, S2 has a southern and an eastern sample site (see figure 4.1 for exact locations) Both datasets for the S2 sites are complete for a time period from 1968 to present. Data for the S2 sites is available from 1985 to present.

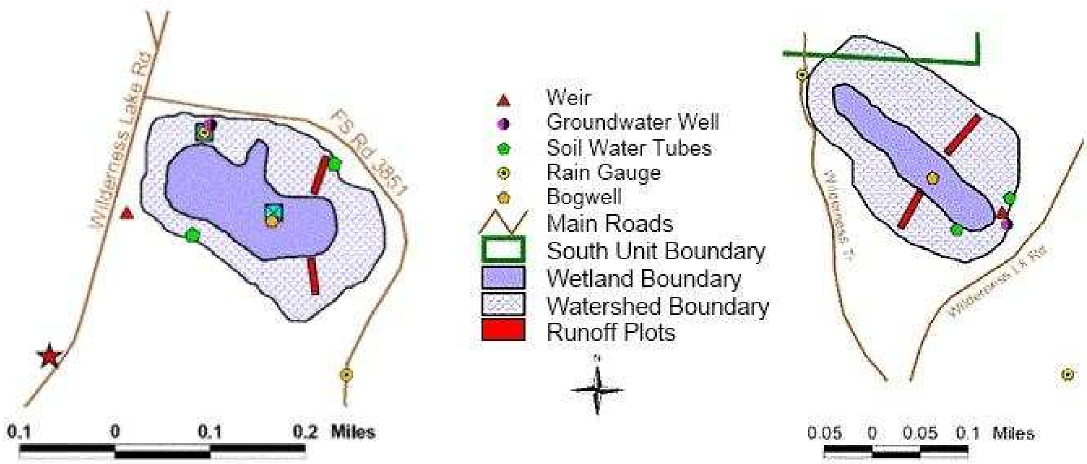



Figure 4.1.: Approximate locations of weirs, soil moisture sites, meteorological stations and runoff plots for the control watershed S2 on the left and the treated watershed S6 on the right (*URL1*, 2009, modified).

### 4.1.4. Subsurface and surface runoff

Runoff collectors were installed in the early 1970s to collect surface and subsurface runoff from upland slopes of the watersheds S2 and S6. The plots were originally based on a design by the USDA Agricultural Research Service, provided by *Mutchler* (1963). First studies including data from the newly installed runoff plots analyzed nutrient transport differences in interflow and surface runoff (*Timmons et al.*, 1977). One surface and one subsurface plot were installed on a northern and a southern site of each watershed. The surface water collectors are installed as 1.83 m wide

and 18 to 23 m long rectangular strips, bounded by galvanized metal sheets. Each surface runoff plot ranges from base of the slope near the bog to the top of the slope. Slopes vary between 22 and 26% (*Timmons et al.*, 1977). Surface water flows over and through the surface organic horizon to the downslope end into a metal sheet funnel. The subsurface water collectors consist of a perforated steel well point, which is situated perpendicular to the slope at the contact area of the A and the lower permeable B horizon, for S2 at about 33 cm. It is not quite sure, which depth the subsurface runoff collectors in S6 are installed at. Since soil characteristics of S6 are slightly different to those of S2 the lower permeable B horizon may occur in a slightly larger depth than in S2 (see Appendix for soil characteristics). Parts of the water that infiltrates into the soil after rainfall or snowmelt events flows along the boundary of the two soil layers and further into the subsurface collector. Water from the surface and subsurface collectors is then routed through a PVC pipe and further into a collector tank, which is situated inside a shelter. Water volumes can be read from a calibrated leveling rule. Afterwards, water in the tanks is drained through the bottom hole of the tank. In winter months, the shelters can be optionally heated to prevent freezing. Since 1986, stripchart recorders have been set up in S2 plots to gain temporal information about the water levels of the tanks (*Sebestyen et al.*, unpublished).
Some problemtaic issues concerning the data sampling and processing are known. Currently, polyethylene collector tanks of different volumes are installed at the plots. Both S6 North tanks have a capacity of 690 L, before they overflow. S6 South tanks collect 710 L, S2 North tanks collect 840 L, and S2 South tanks collect respectively 840 (Subsurface) and 690 L (Surface), before they overflow. Different overflow values complicate the comparison of runoff volumes within one catchment and between treated and control catchment. Furthermore, overflowing of the tanks causes a general underestimation of runoff volumes. Overflowing not only occurs over night, between measurements of two days, but also for longer time spans. Some strip charts of S2 show, that when overflowing occurred and the tanks were drained at the next sampling day, water was still running at a certain rate. It may be possible, that water was running during the time, when the tank was overflowing for the first time and emptied at the next sampling day. It may also be possible that runoff stopped for one or more times between those dates. Since no additional information are available, the error produced by the overflowing of the tanks for unknown time periods could not be quantified on a scientific basis. Thus, all runoff volumes, which are presented in chapter 5.3 are minimum volumes for the particular runoff plot. Additional difficulties concerning the uniformity of the runoff data emerged from the fact, that collector tanks have been replaced within the time period of observation. Data sampling for S6 started in 1979, one year prior to the clearcut. S2 data has been monitored since 1981, one year after the clearcut. In 1984, the original galvanized metal tanks, uniform in size and volume, have been replaced by the aforementioned polyethylene tanks, which are used up to today. The relationship between stage height and runoff volume for the previous tanks had to be assumed with regression analysis, since no reliable information were available. Maximum volume before overflowing for the former tanks was set to 840 L.

Tanks have been drained usually in less than three days for small events. In the dormant season it may occur, that the tanks will be sampled on a weekly basis, when runoff is at a low level. In the snowmelt season and at high runoff events tanks will be drained at least daily. Summarized, subsurface and surface runoff plots at the MEF provide rare and unique information to the runoff behaviour at upland slopes. Still, one has to mention, that the data quality is afflicted with several uncertainties. Overflowing occurred for every runoff plot, but in particular for the subsurface plots, thus the underestimation of volumes may be emphasized for the subsurface plots. For data analysis especially monthly and annual sums have been used, so the differences in actual tank overflow volumes (690 to 840 L) may be amplified by the summation. The approximate location of the runoff plots can be seen in figure 4.1.

## 4.2. Statistical methods

### 4.2.1. Regression

Regression analysis is a useful tool for determining the association between two or more variables. The objective of regression analysis is to quantify the relationship between a dependent variable and one or more independent variables. We will look at the simple linear regression with only one independent variable. Equation 4.1 shows the model for the simple linear regression, where $y_i$ is the dependent variable, $x_i$ the independent variable, $b_0$ the intercept, $b_1$ the slope, $e_i$ the random error and n the sample size:

$$y_i = b_0 + b_1 x_i + e_i \qquad i = 1, 2, \ldots, n \tag{4.1}$$

By determining the values of the constants $b_0$ and $b_1$, the regression line will be fitted in its best possible position. The best fit of the line is achieved by the method of least squares.

To get information about the goodness of a fit of a model, the coefficient of determination $R^2$ is introduced. It is a statistical measure of how well the regression line approximates the real data points, and lies between the range of 0 and 1 for linear regression. It denotes the strength of a linear regression, an $R^2$ of 1 indicates that the dependent variable $y_i$ is perfectly explained by the regression model, In case of linear regression $R^2$ is the square of the sample correlation coefficient after Pearson between the outcomes and their predicted values (*Helsel & Hirsch*, 1993; *Husch et al.*, 2003).

### 4.2.2. Correlation

Correlation analysis measures the strength of association between two or more random variables. It is of interest whether one variable generally increases/decreases as the second increases or whether they are totally unrelated. The correlation coefficient $\rho$ is the measure of the degree of association between two variables x and y and can have a numerical value varying between the limits of $-1$ to $+1$. When

$\rho = 0$, there is no correlation. When one variable increases as the second increases, $\rho$ is positive. When they vary in opposite directions $\rho$ is negative (*Husch et al.*, 2003). The linear correlation coefficient or Pearson correlation coefficient is the most commonly-used measure of correlation. Still, it assumes a linear association between two variables, which is not always given. The only condition for the Spearman correlation coefficient is a monotonic relation, which may also be given for other than linear relations (*Helsel & Hirsch*, 1993). In this thesis, the Spearman correlation coefficient is used, because the assumption of linearity is not always given.

### 4.2.3. Mann-Kendall trend test

The non-parametric Mann-Kendall trend test has been widely used in environmental sciences for trend detection in time series (*Mann*, 1945; *Kendall*, 1970; *Hirsch & Slack*, 1984; *Libiseller & Grimvall*, 2003). It is based on ranks and therefore robust against outliers. Furthermore it is argued, that due to its non-normal characteristics it is a good tool for analyzing hydrological data (*Hirsch & Slack*, 1984).
Null hypothesis for the Mann-Kendall trend test states, that the time series $\{x_t, t = 1, 2, \ldots, n\}$ with $n$ being the data set record length, is independent and randomly ordered, thus no trend exists. Alternative hypothesis states: A trend is given for $x_t$:

$$H_0 : P\left(x_j > x_i\right) = 0.5, j > i \tag{4.2}$$

$$H_A : P\left(x_j > x_i\right) \neq 0.5, \text{(twosided test)} \tag{4.3}$$

The Mann-Kendall test statistic $S$ is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{4.4}$$

where $x_j$ and $x_k$ represent the annual data values, and $y > k$, and $sgn(x_j - x_k)$ is the signum function, defined as

$$sgn(x_j - x_k) = \begin{cases} +1 & x_j - x_k > 0 \\ 0 & x_j - x_k = 0 \\ -1 & x_j - x_k < 0 \end{cases} \tag{4.5}$$

Resulting parameters of the Mann-Kendall test are the $p$-value and the test statistic $Z$. The $p$-value represents the probability of getting a sample as extreme (or worse) assuming the null hypothesis is true. The lower the $p$-value, the less likely the result, assuming the null hypothesis, so the more significant the result. Generally, the null hypothesis is rejected, if the p-value is smaller than or equal to the significance level $\alpha$ (common values for $\alpha$: 5%, 1% or 0.1%). The test statistic $Z$ indicates, whether an upward, a downward or no trend exists, but does not provide a value for the true slope of the trend. The method to estimate the true slope of an existing trend is known as the Theil-Sen-Approach, provided by *Theil* (1950) and *Sen* (1968) (in *Helsel & Hirsch*, 1993).
All calculations concerning Mann-Kendall trend statistics, which are the p-value

and the true slope after Theil-Sen have been calculated with a Macro-plugin for the spreadsheet program Microsoft Excel© provided by *Grimvall et al.* (2009).

## 4.3. Data processing

The data processing in the following chapters is generally presented in the temporal scale as ‘years after treatment’ (YAT) . Since 1980 was the year of first change in natural conditions of the S6 upland, 1980 represents the time measure ‘0 years after treatment’. So 1983, the year of the second change, when 3-year old conifer seedlings were planted, would be reffered to as ‘3 years after treatment’. Thus the time of cattle grazing to prevent aspen regrowth would have occurred in 0, 1 and 2 YAT. Although runoff water years and precipitation water years are usually calculated for March 1 to February 28/29 and November 1 to October 31, respectively, at this study for better comparison of annual data, years are referred to the time period January 1 to December 31.

Data availability was not always conform for different parameters, sometimes not even for different plots of the same parameter. 2007 has been the last year, for which data for all parameters were available, so data analysis is only performed until the end of 2007. The recording of consistent datasets for both, S6 and S2 streamflow started in 1976, so 32 years of streamflow data could be analyzed. Precipitation data was available since 1961, but was only used for the time period 1976 to 2007. Soil moisture data recording started in 1968 and is available for S2, but the dataset for S6 shows a gap from 1969 to 1985. For comparison of the results only the shared time period from 1985 to 2007 has been considered. A consistent soil moisture dataset for the time period 1985 to 2007 was only available for depths up to 290 cm (9.5 ft), so only this depth has been taken into account. Regular data sampling for the S6 runoff plots started in 1979 and is continued until today. S2 runoff plots were monitored since 1981, thus no continuous data for both plots prior to 1980 are available. Consequently, runoff plot data has been analyzed for the time period 1981 to 2007.

Subsurface runoff was also analyzed on an event basis. Events have been defined in a uniform manner but separately for each runoff plot. An event has been defined as the summarized runoff of consecutive days with no more than two consecutive days of no-flow in between. In this manner a pool of events of a given length and runoff volume has been gained, which subsequently has been classified for three periods of equal length. The first period goes from 1 to 9, the second period from 10 to 18, and the third period from 19 to 27 YAT. Hence, a comparison of the periods is possible not only for the event volumes but also for the number of events, since periods of equal length are observed.

Soil moisture data as well as subsurface and surface runoff data are denominated as ‘S6 North’ or ‘S2 South’. When speaking of orientation, the northern site of the catchment would actually be the site in the northern part of the catchment but with a southerly aspect. Thus, ‘S2 South’ would be the southern site in S2 with a northerly aspect. In addition, when speaking of runoff measured at the surface and subsurface collectors, ‘plot runoff’ is referred to the runoff from one single plot, for instance the runoff from the northern subsurface plot in S6. 'Summarized plot runoff' (SPR) is reffered to the runoff sum of all runoff collectors of one catchment, for instance the summarized runoff from the southern surface, the northern surface, the southern subsurface, and the northern subsurface plot in S6.

## 4.4. Conclusion

Data will be analyzed for three main parameters. Those are whole catchment runoff [mm] for both catchments, available soil moisture [mm] for a northern and a southern plot in S6 and a southern plot in S2, and slope runoff [L] for two surface and two subsurface plots in each catchment. Optical analysis received priority in the presentation and the discussion of the results. Statistical methods have been used to pronounce several results.

# 5. Results

The following sections provide the results, gained from data of the long-term measurements at the catchments S6 and S2 of the MEF. First, data of streamflow reactions for both, treated and control catchment, are presented to get an overview of the overall behaviour of each catchment. Following this, results from the long-term soil moisture measurements for S6 and S2 and for different aspects of the treated catchment are presented. Finally, results of the runoff plot installations are shown in chapter 5.3.

Most of the data is presented and analyzed in different temporal scales, like annual, seasonal or monthly reactions of the observed parameter. Additionally, for the runoff plots events have been defined in a certain manner, which will be explained later on. The general approach of presenting the results is to look at large spatial and temporal scales first, and going more into detail afterwards. Absolute differences of parameters are usually presented in the way 'treated parameter minus control paramter'. Hence, if the value of S6 is lower than the value of S2, the difference is referred to as a negative difference, if the value of S6 is higher than the value of S2, the difference is referred to as a positive difference. Relative differences are computed by dividing the absolute difference by the 'basic' value. E.g. in the case of S6 and S2, the relative difference would be based on the S2 value.

## 5.1. Streamflow responses to forest conversion

Annual catchment runoff of the treated and the control catchment and annual precipitation input, measured at the S2 catchment, are presented in figure 5.1. MAP for the presented time period is 777 mm with a standard deviation (SD) of 111 mm. Precipitation generally shows a quite constant progress, only for 21 to 27 YAT a slight decrease is recognizable. Lowest annual precipitation of 414 mm in the whole 32 years of observation occured in 1976 (in the graph reffered to as −4 YAT), while the highest annual precipitation (947 mm) occured only one year later in 1977 (−3 YAT). MAR for S6 and S2 were 144 and 167 mm, respectively, with a slightly higher SD for S6 (65 mm), than for S2 (62 mm). Both reactions seem to follow the general pattern of precipitation. Exceptional is the runoff reaction in 1977 (−3 YAT), where the highest precipitation on record produced only runoffs of 61% and 97% of the long-term mean, for S6 and S2 respectively. Striking is the fact, that S6 runoffs are generally lower for the time period 12 to 27 YAT. For the years prior to 12 YAT no generalization can be made. Analysis of correlation in the period −4 to 27 YAT has been conducted for each catchment runoff with precipitation and yielded $\rho = 0.66$ and $\rho = 0.73$ for S6 and S2, respectively.

Annual runoff data is available for the years 1976 to 2007, which means that in

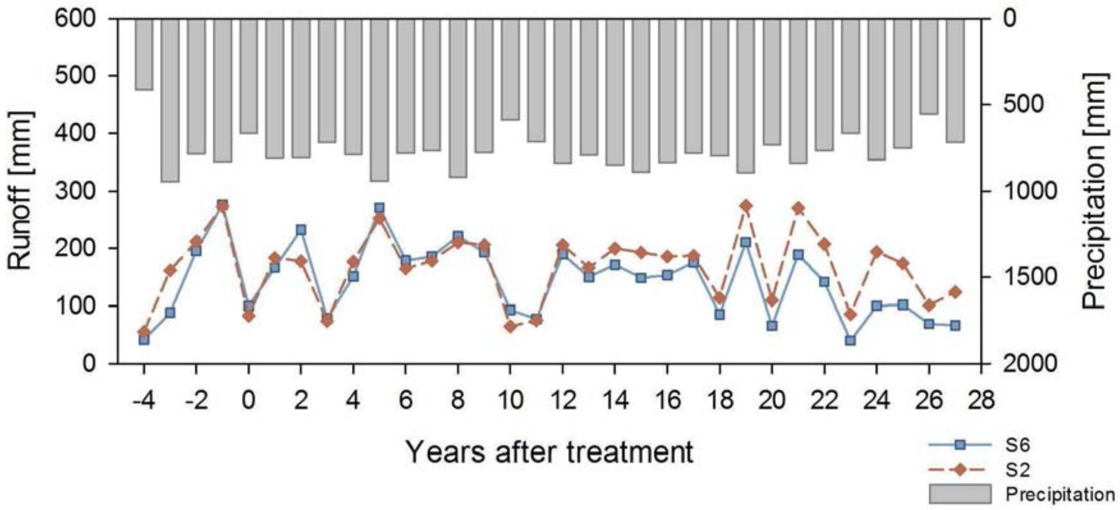



Figure 5.1.: Annual catchment runoff for S6 and S2 [mm] and annual precipitation data [mm] monitored at S2.

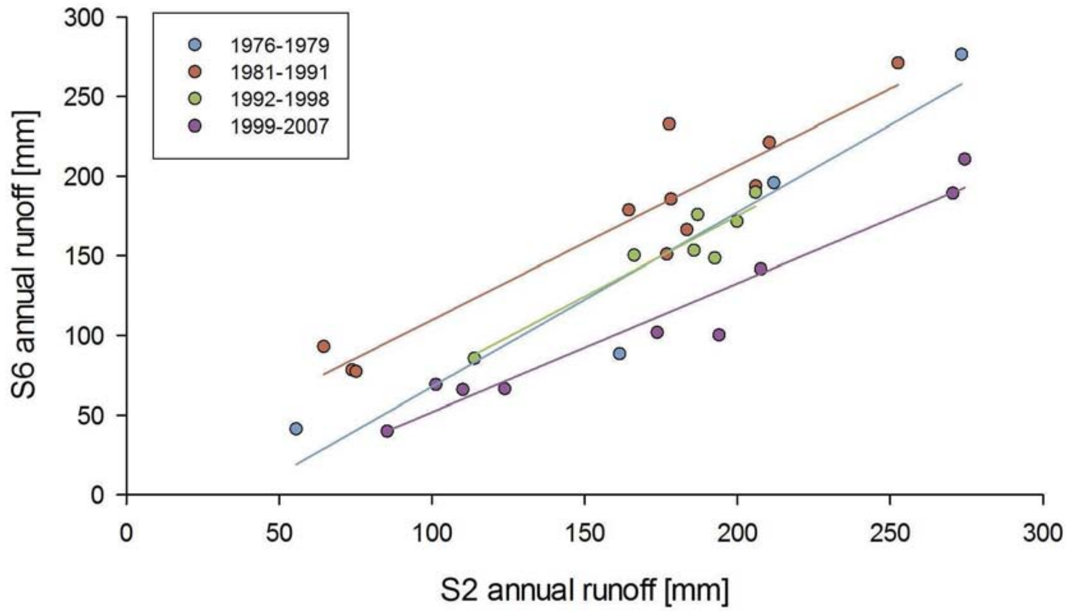



Figure 5.2.: Regression lines for annual catchment runoff volumes of different periods.

the four pre-treatment years (1976-1979) runoff data were already collected, before clearcutting took place at the upland of S6. Those four years were used, to develop a regression model, with the purpose of simulating annual S6 runoffs, by observing annual S2 runoff data. Figure 5.2 shows the relation of annual S6 and S2 runoff for the four pre-treatment years 1976 to 1979. The equation for the regression model is given by

$$y = 1.10x - 41.7 \tag{5.1}$$

with y being the simulated runoff for S6 and x being the observed runoff from S2. The readout of the coefficient of determination gave a value of $R^2 = 0.91$. Finally Equation 5.1 has been used to calculate simulated annual runoff for S6.

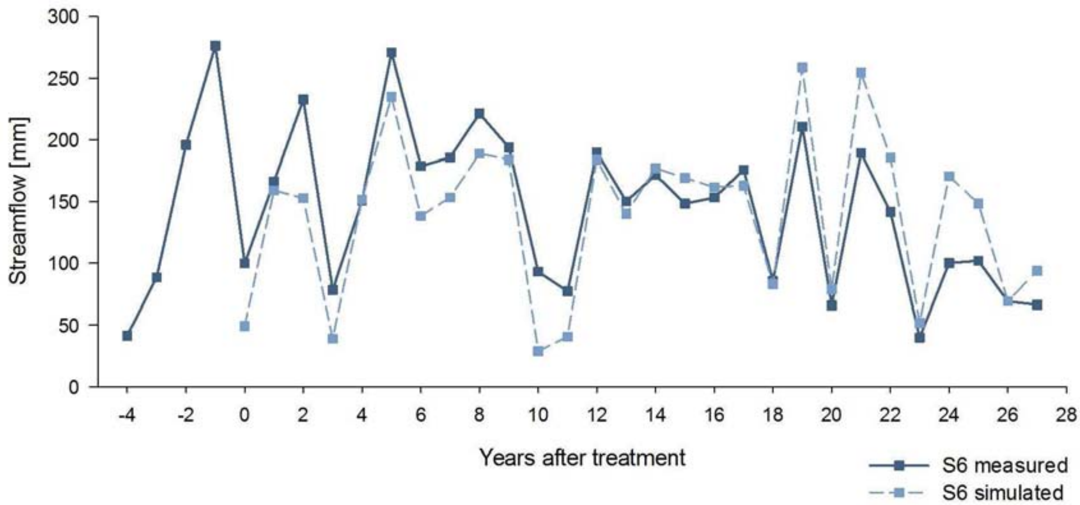



Figure 5.3.: Application of the regression model gives the simulated course of annual runoff of S6 for the years after treatment. For comparison the actual curve of S6 is also shown.

As it can be seen in figure 5.3, both curves show a good uniformity in their annual reactions. Still, there are obvious differences in the course of both curves. The graph may be separated into three periods. The first one from 0 to about 11 YAT shows a general underestimation of the actual annual runoff by the model. The second period from about 12 to 18 YAT shows a good agreement with only slight scatters between the modeled and actual annual runoff. In the last period from about 19 to 27 YAT the regression model produces annual runoffs, generally higher than the observed ones.

Figure 5.4 makes the differences between the observed and modelled curve presented in figure 5.3 more clear. Absolute differences between measured and simulated S6 annual runoff are shown for the time period 0 to 27 YAT. Positive values indicate a higher measured runoff. The largest absolute difference in annual runoff with 79.8 mm was examined for year 2 after treatment. Second largest absolute difference

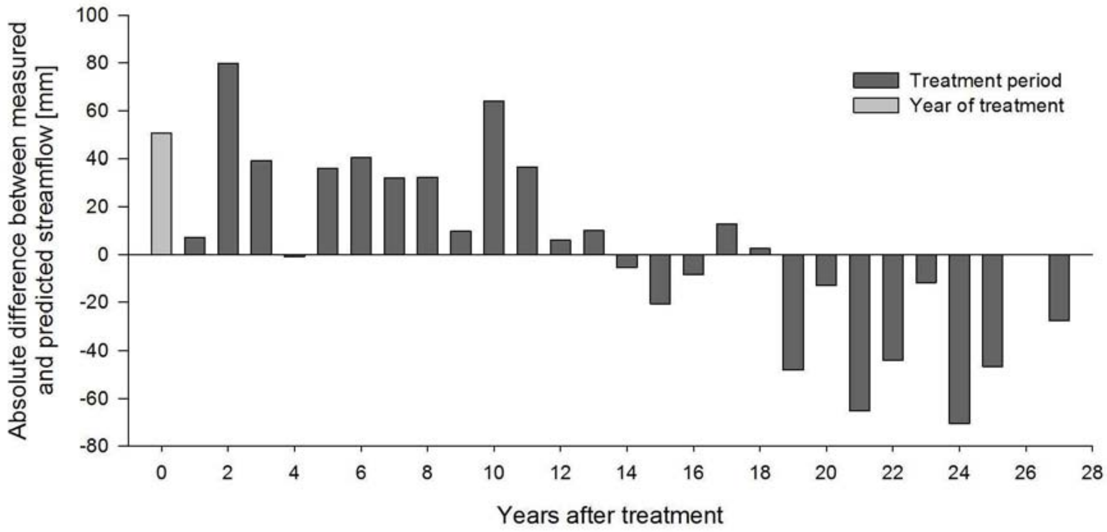



Figure 5.4.: Absolute differences between observed and simulated S6 runoff in [mm] for the time period 1980-2007.

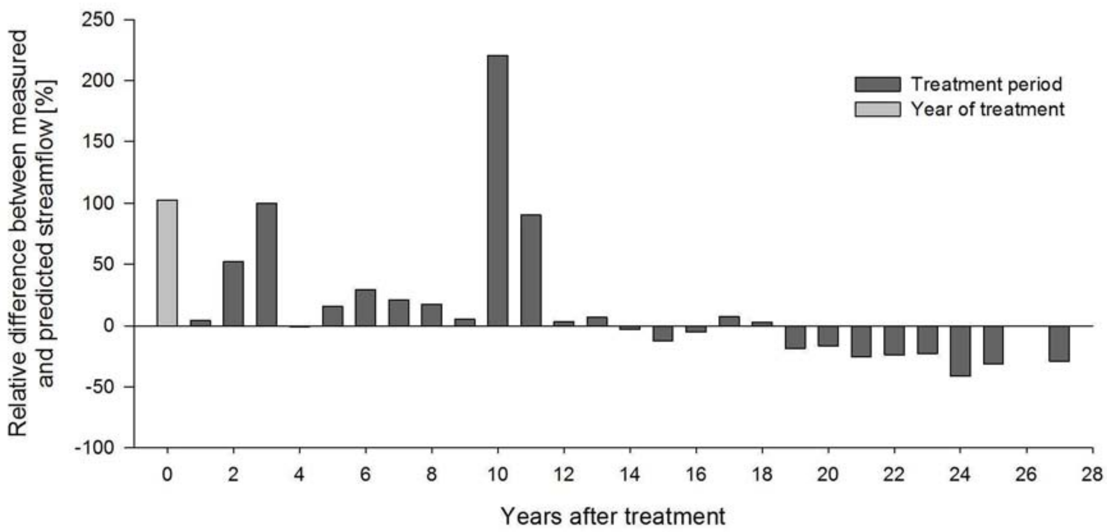



Figure 5.5.: Relative differences between observed and simulated S6 runoff in [%] for the time period 1980-2007. Basic value for the relative difference is the simulated S6 runoff.

with −70.4 mm was examined 24 YAT. Mean absolute differences for the above outlined time periods of 1 to 11, 12 to 18 and 19 to 27 YAT, are 34.2, −0.5 and −36.3 mm, respectively. The curve in figure 5.4 follows the general pattern of regrowth and conversion experiments, as presented in figure 3.4 of chapter 3.1.2, with a prevailing increase in runoff immediatly after clearcut, and a decrease under pre-treatment level about 16 years after planting of the conifer seedlings. The time between clearcut and planting of the seedlings is characterized by a considerable high increase of absolute runoff differences, whereas the year immediately after planting of the conifer seedlings shows almost no difference compared to simulated runoff. Relative differences between observed and simulated S6 runoff are illustrated in figure 5.5. The highest relative difference of 221% has been recorded 10 YAT. Noticeably high differences also occur for 2,3 and 11 YAT. The period from 19 to 27 YAT is characterized by a rather constant level of negative relative differences. Mean and standard deviation for that time period are −23% and 11%, respectively, whereas the period from 1 to 11 YAT is characterized by a mean annual relative difference of 50% with a standard deviation of 66%. Regression analysis for annual runoff values of both catchments has been conducted for all periods, that have been outlined in the section above. Regression lines are displayed in figure 5.2, linear equations and coefficients of determination are shown in table 5.1. The slopes of the four regression lines lie in the range between 0.81 and 1.1. Highest S6 runoff values in relation to S2 are denoted for the period 1 to 11 YAT, lowest relation occurs in the latest period from 19 to 27 YAT.

Table 5.1.: Linear equations and coefficients of determination for each regression model presented in figure 5.2.

| period | equation | coefficient of determintation $R^2$ |
|---|---|---|
| 1976-1979 | $1.10x - 41.7$ | 0.91 |
| 1981-1991 | $0.97x + 13.2$ | 0.88 |
| 1992-1998 | $1.01x - 27.4$ | 0.88 |
| 1999-2007 | $0.81x - 28.8$ | 0.95 |

Streamflow data has also been categorized on a seasonal basis. The time periods March to May, June to September, and October to February have been classified as snowmelt, growing and dormant season, respectively. Figure 5.6 shows the growing season streamflow in percentage of total annual streamflow for S6 and S2 for the whole period of observation, as well as the growing season precipitation in percentage of total annual precipitation. Growing season was analyzed, because it was expected to show the most severe reactions to forest clearcutting and conversion.
Curves for S6 and S2 show rather uniform reactions. Also both sites seem to follow the general behaviour of precipitation. Several ‘blocks’ of elevated runoff values with declining runoff for the subsequent years can be identified, e.g. for −3 to 2 YAT, 8 to 11 YAT, 12 to 16 YAT or 22 to 26 YAT. S2 values seem to be generally higher than S6 values for the first 25 years, for the last 7 years of observation both values seem to range at the same level.

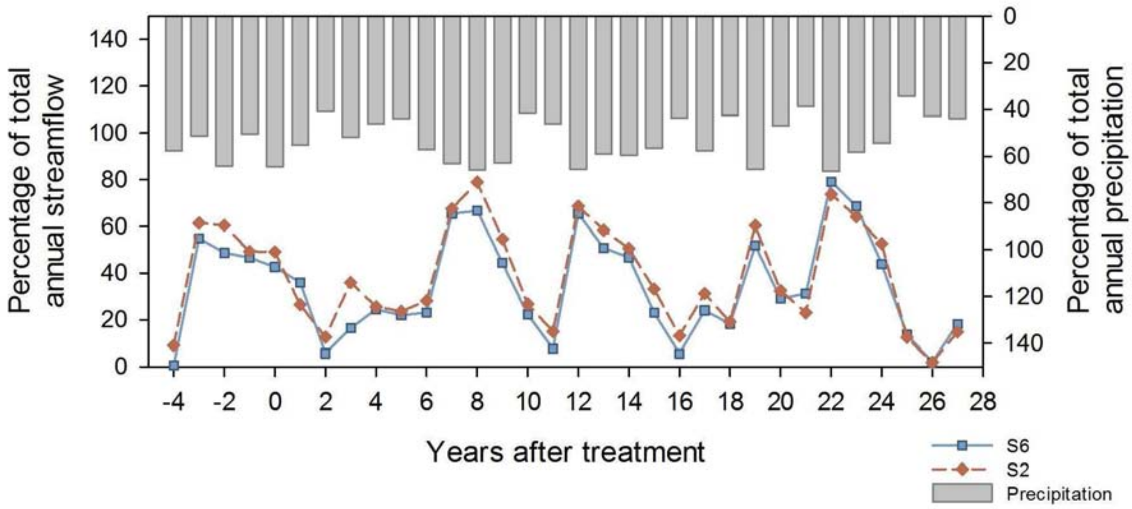



Figure 5.6.: Growing season streamflow in percentage of total annual streamflow for S6 and S2. Growing season precipitation in percentage of total annual precipitation is plotted on the second y-coordinate.

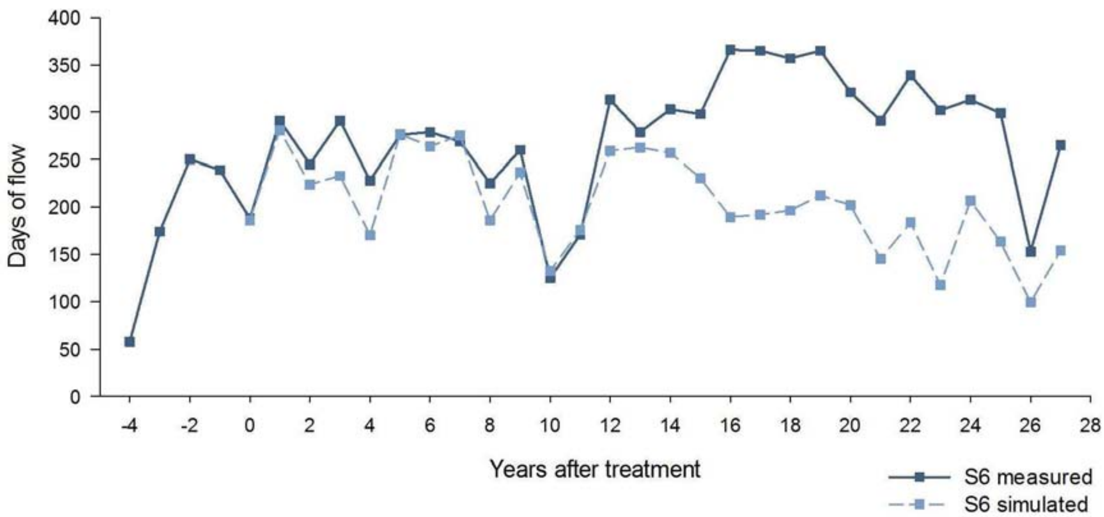



Figure 5.7.: Simulated and actual curves of DOF in S6.

Since runoff data for both sites were available on a daily basis, they could be used to introduce the paramter 'days of flow' (DOF) , representing the number of days per year, when water was flowing at the weir. The same type of analysis, that has been conducted for runoff in the section above has been adopted for DOF. First, DOF values from 1976 to 1979 for control and treated catchments have been plotted in a diagram. Afterwards, again a linear regression model has been developed, yielding the following equation:

$$y = 1.14x - 50.5 \tag{5.2}$$

with y being the simulated DOF for S6 and x being the observed DOF for S2. The coefficient of determination was $R^2 = 0.95$. Finally, the simulated and observed curves for DOF of the S6 catchment have been projected for the time of analysis as to see in figure 5.7. While both curves show a good conformity for the time period from 1 to 11 YAT, with differences ranging from 0 to 58 days, a sudden gap for both curves occurs in year 12 after treatment and persists up to present. Differences in this time period range from 16 to 184 days. Mean and standard deviation of the absolute difference in DOF are: 19 and 24 DOF for 1 to 11 YAT, and 116 and 53 DOF for 12 to 27 YAT.

## 5.2. Soil moisture reactions

In this section, soil water reactions to the forest treatment are presented. As already written in chapter 4.1.3 three soil moisture samples per year have been taken on a largely regular basis since 1985. Figure 5.8 illustrates the progression of the annual sum of integrated soil moisture for the southern plots of the treated and the control catchment, in the following referred to as 'S6S' and 'S2S'.
Gaps in the curves are caused by missing May samples 5 YAT in S6S, and by missing September and November samples 9 YAT for both S6S and S2S. Thus data for both years has been discarded from the annual analysis. No May samples were available for year 8 after treatment, instead August samples have been taken into account, which showed only marginal differences to the long-term mean of the May values. As it can be observed in figure 5.8, the initial difference between S6S and S2S of about 98 mm 6 YAT turned into a difference of about −372 mm for the year 27 after treatment. Optically, a negative slope for the curve of S6S is clearly identifiable, which is emphasized by the total difference of 649 mm between 6 and 27 YAT for S6S values. A Mann-Kendall trend test revealed a statistically significant downward trend on a significance level of 0.1% for soil moisture at S6S. The true slope of the downward trend was computed to be −25 mm/year.
To observe changes in soil water content for different depths, soil moisture values have been summarized for successive soil horizons, which are defined as follows: Horizon 1 (H1) from 0 to 76, Horizon 2 (H2) from 76 to 137, Horizon 3 (H3) from 137 to 229, and Horizon 4 (H4) from 229 to 290 cm depth. The curves of the annual sum of soil water content for each horizon are given by figures 5.9, 5.10, 5.11, and 5.12. For years 6 and 7 after treatment both curves in H1 range in a similar level, before S6S values drop rapidly under S2S. Still, for the longest observation time (8

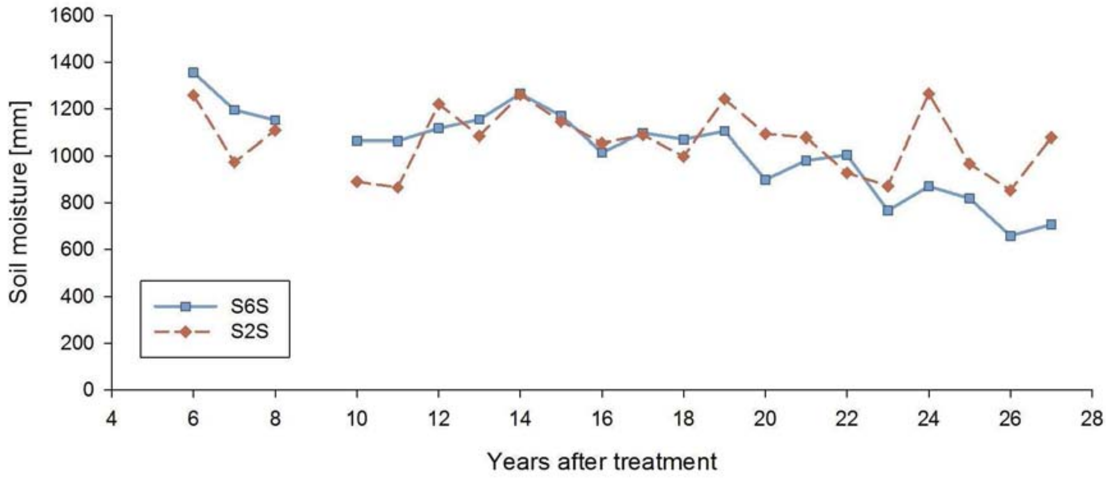



Figure 5.8.: Developement of the annual sum of soil moisture for the southern plots of S6 and S2. Values have been gained by integrating soil moisture over the enitre depth of observation (0-290 cm).

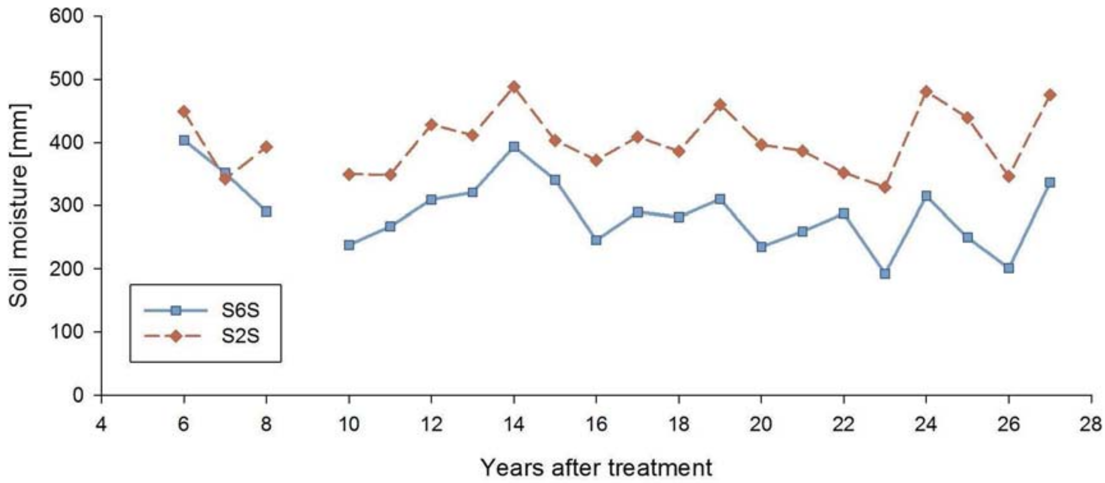



Figure 5.9.: Developement of the annual sum of soil moisture for the southern plots of S6 and S2. Values have been gained by integrating soil moisture over the depth of 0 to 76 cm.

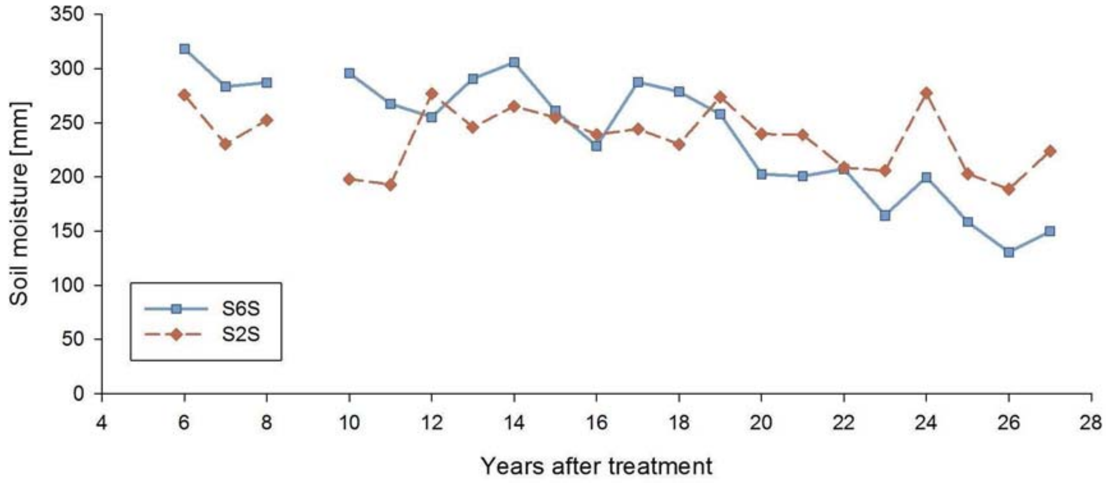



Figure 5.10.: Developement of the annual sum of soil moisture for the southern plots of S6 and S2. Values have been gained by integrating soil moisture over the depth of 76 to 137 cm.

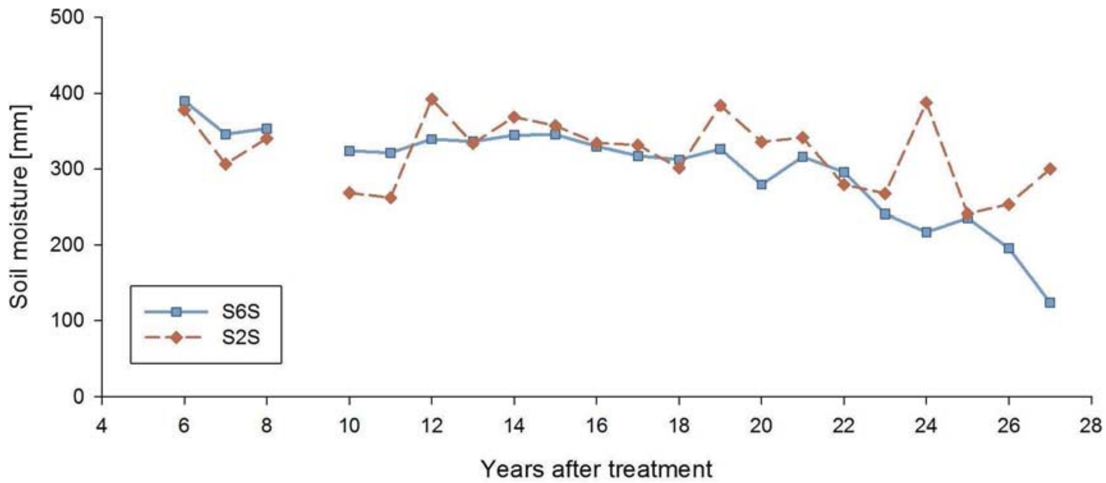



Figure 5.11.: Developement of the annual sum of soil moisture for the southern plots of S6 and S2. Values have been gained by integrating soil moisture over the depth of 229 to 290 cm.

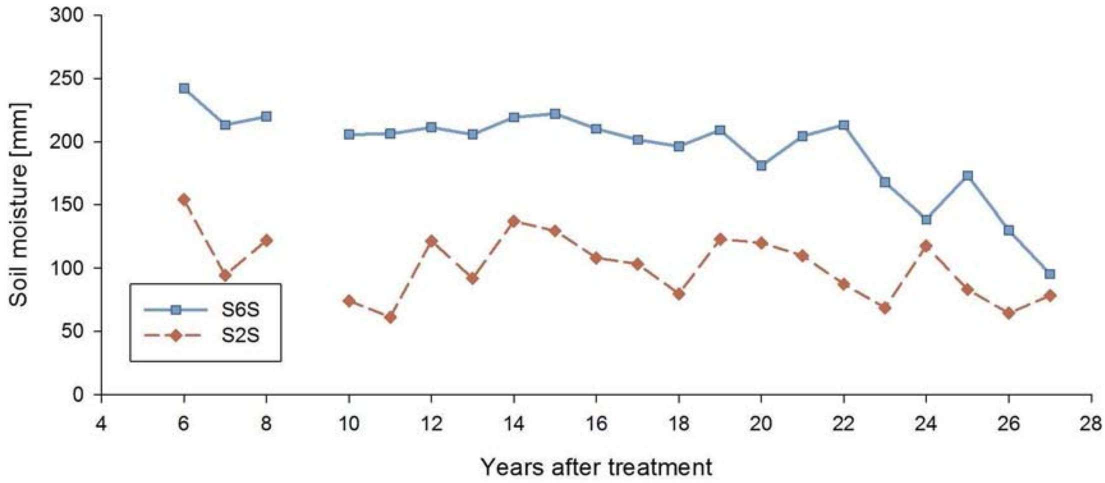



Figure 5.12.: Developement of the annual sum of soil moisture for the southern plots of S6 and S2. Values have been gained by integrating soil moisture over the depth of 137 to 229 cm.

to 27 YAT) the curves show a strong and rather consistent absolute soil moisture difference (mean difference = −111 mm, SD of difference = 46 mm).
Both S6S reactions in H2 and H3 follow a decreasing trend, with absolute differences of 187 and 266 mm, respectively. S2S curves in both medium horizons seem to scatter around a distinct range of 100 to 150 mm similar to the S2S curve in H1, but optically considerable down- or upward trends are not identifiable. The situation for the lowest soil horizon seems contrary to the uppermost. Soil moisture for S6S is constantly on a higher level then for S2S. A quite stable soil moisture level has been established for 7 to 22 YAT for S6S. From then on a downward trend is noticeable. Except for the uppermost horizon reactions of the curve pairs show low uniformity. Sometimes even contrary reactions can be observed as in H3 and H4, 24 years after treatment. Mean relative difference between S6S and S2S for the lowest and the topmost horizon are 99 and −28%, respectively. Soil moisture of S6S in H2, H3 and H4 showed statistically significant downward trends on the 0.1% significance level. Only for H1 no significant trend could be observed with the Mann-Kendall trend test.
To determine seasonal soil moisture effects, each of the three seasonal measurements per year has been observed seperately. The course of May, September and November soil moisture is illustrated in figures 5.13($a$), ($b$), and ($c$), respectively. For both catchments, May soil moisture values range in the same magnitude of about 400 to 450 mm, still, for the whole time of observation S6S values range below S2S. For the largest part, uniform reactions of both curves can be observed. In the last third of the monitoring, amplitudes start to increase. Both curves don't show a noticeable up- or downward trend. September reactions show considerable differences to the May reactions. First of all, positive differences of 139 mm 5 YAT turned into differences of −86 mm 27 YAT. Furthermore, mean soil moisture in September is lower for both

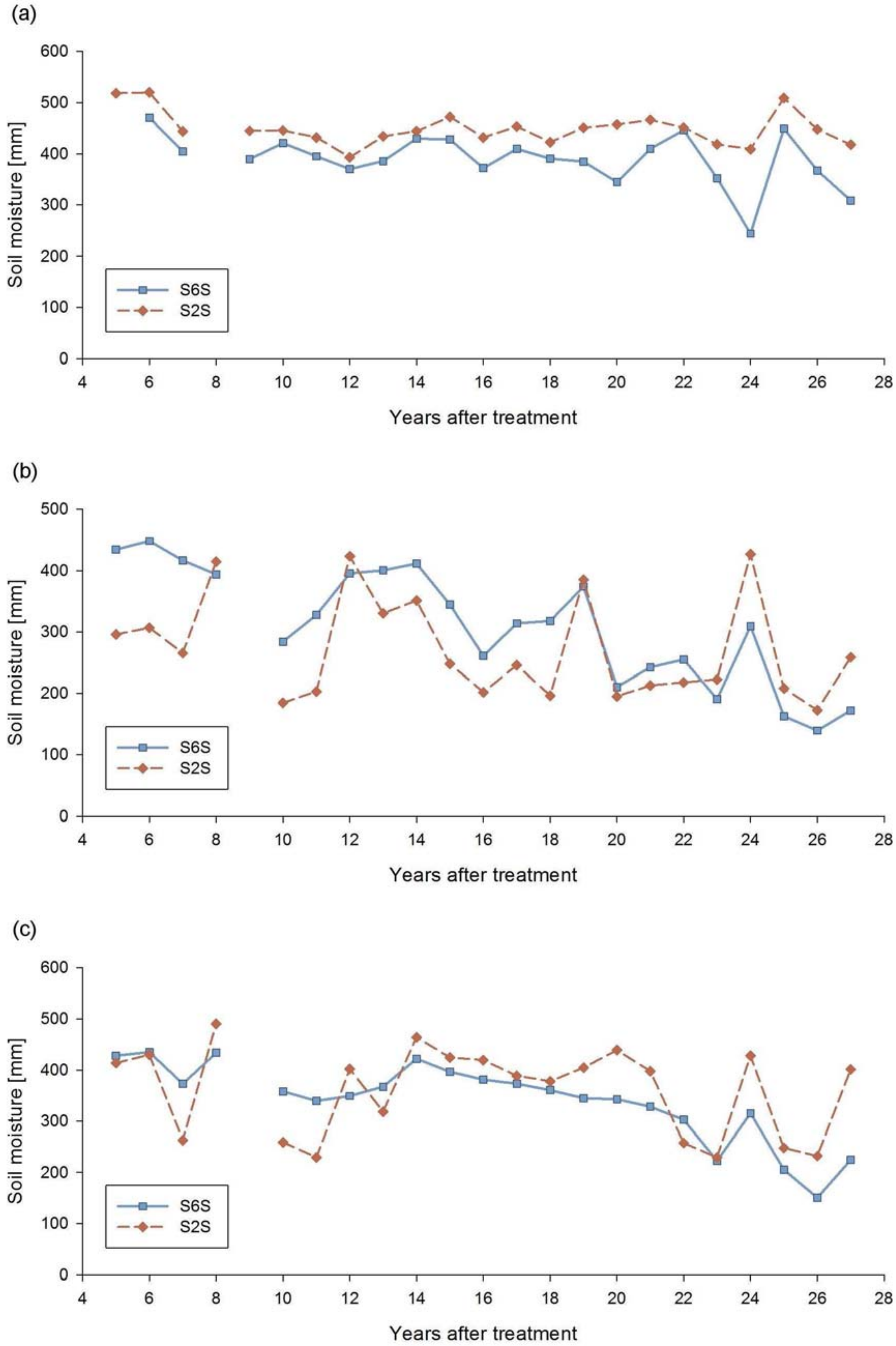



Figure 5.13.: Seasonal reactions of integrated soil moisture for (*a*) May, (*b*) September, and (*c*) November values.

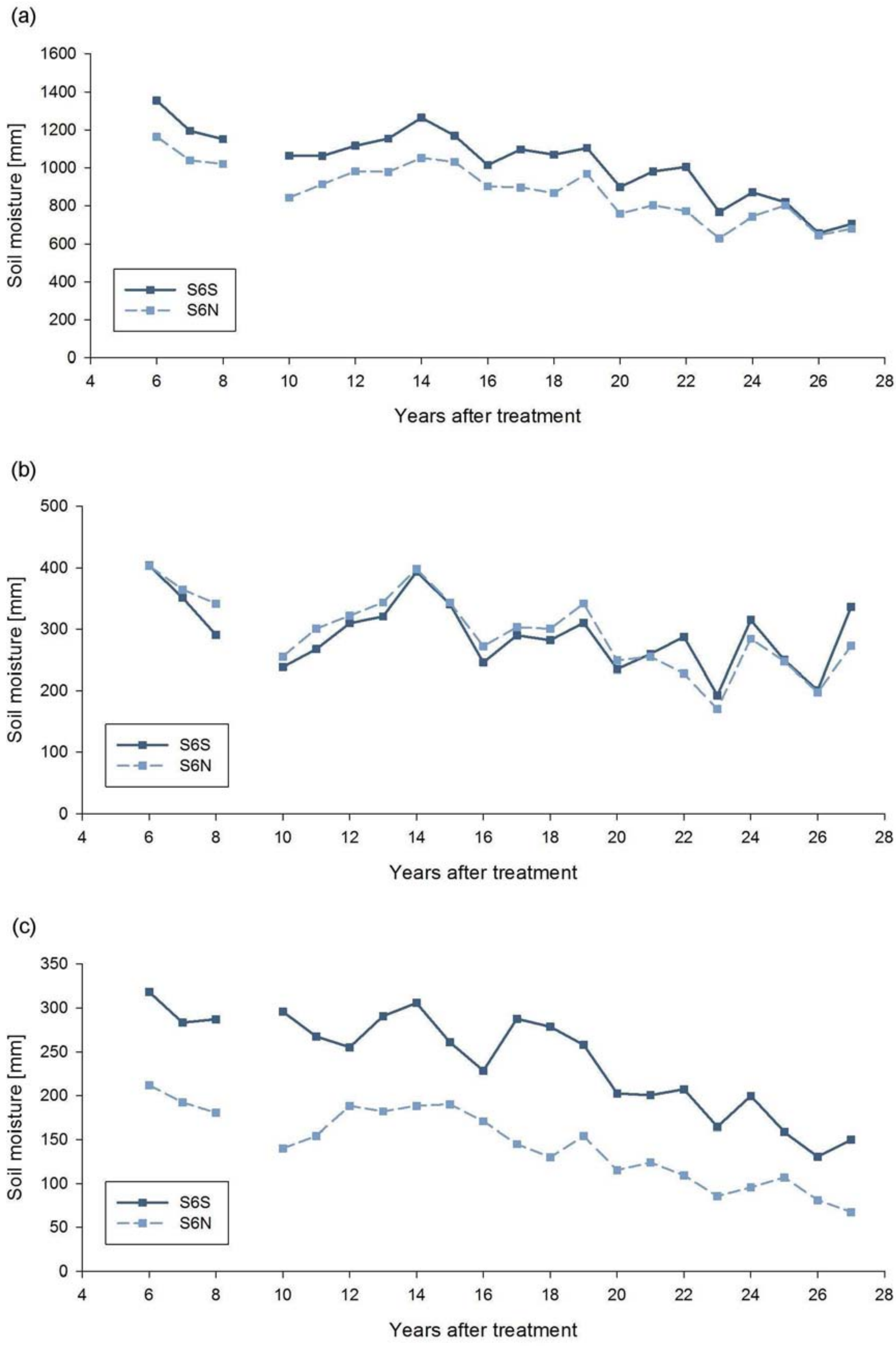



Figure 5.14.: Annual soil moisture reactions in the treated catchment for northern (S6S) and southern (S6N) aspects, for (*a*) the entire depth of observation, (*b*) 0 to 76 cm, and (*c*) 76 to 137 cm.

catchments than in May. S2S shows higher amplitudes compared to May but also shows no signs of a general up- or downward trend. Reactions in the November graph can be compared to those in the September graph, however S6S follows a much smoother curve and soil moisture means are a little above those of September for both sites. S6S standard deviation for May, September and November are 50, 95 and 77 mm, respectively.
The effects of opposing aspects could be studied, by comparing North and South plots of S6, as to see in figure 5.14($a$). Both, north and south aspect curves have a general downward gradient from 1164 and 1355 mm 5 YAT to 680 and 706 mm 27 YAT, respectively. The southern plot provides higher soil moisture values over the entire time of study. Striking is also the parallelism of both curves for about 20 years, before they converge 25 YAT. These uniform and almost parallel reactions could be observed for all horizons. Remarkable is the fact, that the highest mean difference of −96 mm between S6 North and South plot was found to be in H2, which is the most shallow horizon. Minimal mean differences of 4 mm on the other hand occured in H1 (see figures 5.14($b$) and ($c$)).

## 5.3. Subsurface and surface water flow reactions

In this section, results from the long-term monitoring of the eight runoff plots under investigation are presented. First, annual reactions and summarized volumes of the plots of each catchment are analyzed, then seasonal scales and single plots will be studied.
Figure 5.15($a$) shows the annual precipitation for the whole observation time. Figures 5.15($b$) and ($c$) display the annual summarized plot runoff (SPR) for catchment S6 and S2, respectively. Already one year after treatment, the values in S6 range at a level about 2.5 fold the level of the corresponding S2 value. A general downward trend for the first to the last year of observation is identifiable for S6, although scattering is high and jumps in subsequent values occur numerous times. Having some high annual volumes in between, the last decade of S6 is nonetheless characterized by very low total volumes. Proportionally low values occur in both catchments for the most part in the same years, namely 3, 10, 11, 20 and 23 YAT. Optically, no trends are identifiable for the course of the values in S2, although low volumes seem to occur a little more often in the last 8 years of observation. Mann-Kendall trend tests were performed for the annual SPR of the treated and control catchment. Runoff from S6 showed a statistically significant downward trend on the 0.1% significance level. The output for the equation of the computed linear function describing the trend was $y = 40650 - 1191x$. So the true slope was computed to be about −1190 L/year. Runoff from S2 didn't show any significant trends on the 5% level.
In figures 5.16 and 5.17 subsurface and surface plots are regarded separately (note that the scales are different). Relative differences between each catchments' summarized subsurface and surface runoffs are given. Positive values indicate a higher runoff in S6. Relative differences in subsurface runoff follow a general downward trend from 187% 1 YAT to −87% 27 YAT. Optically, the period of observation can be divided into two parts, with mostly higher values for S6 from 1 to 17 YAT and

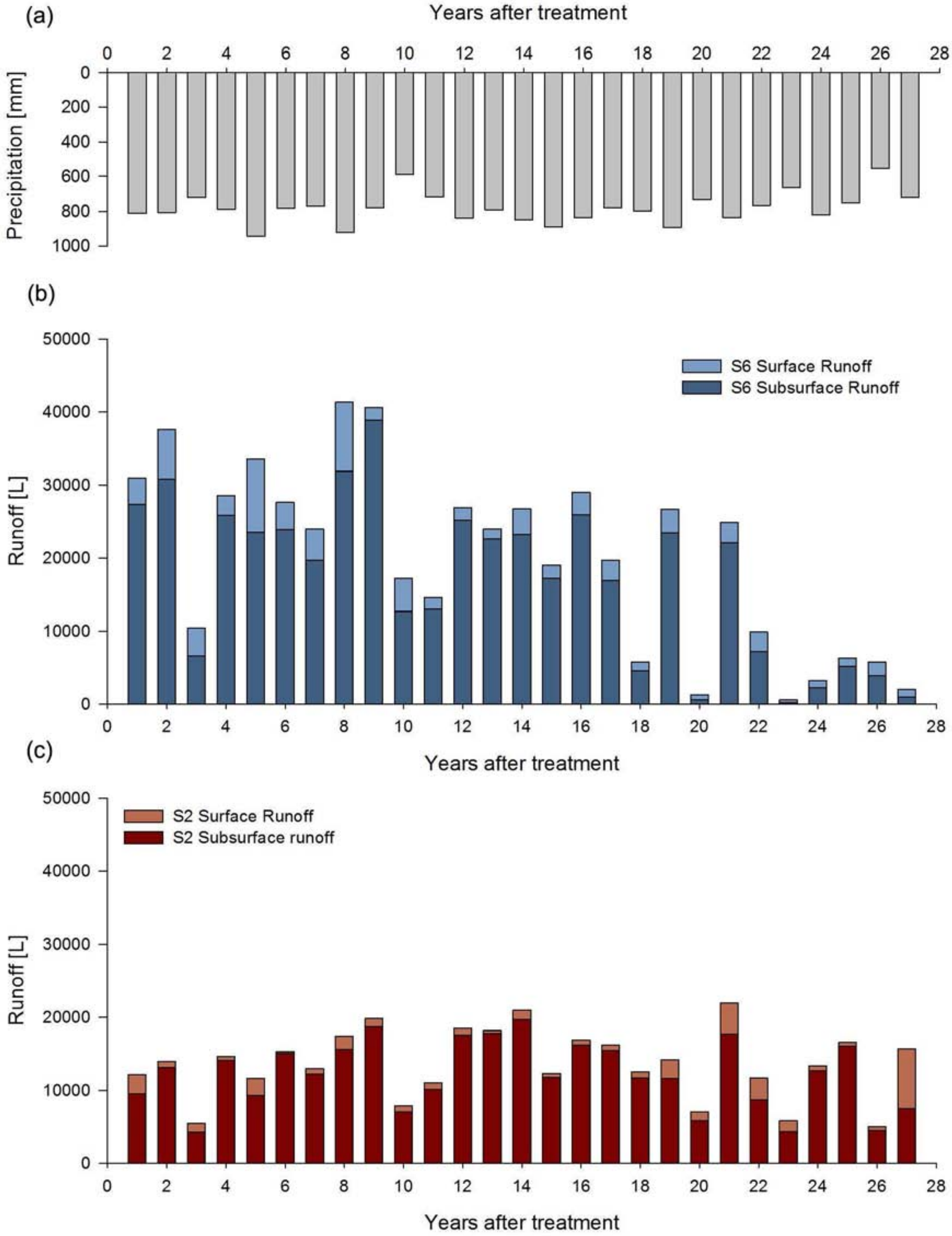



Figure 5.15.: Annual summarized plot runoff (SPR) for catchment (*b*) S6 and (*c*) S2 (The bar diagram has been chosen in non-conformity to the above presented total volumes for streamflow and soil moisture, because it is possible to display both sum and each part of the sum for one year). Annual precipitation is displayed in (*a*).

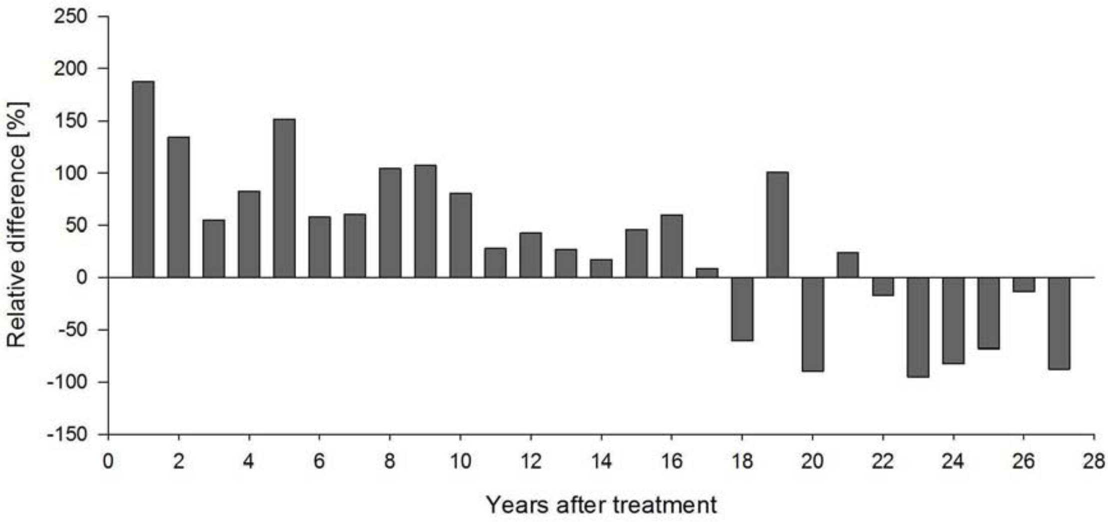



Figure 5.16.: Relative differences between each catchments' summarized annual subsurface runoff. Basic value for the relative difference is the respective S2 runoff.

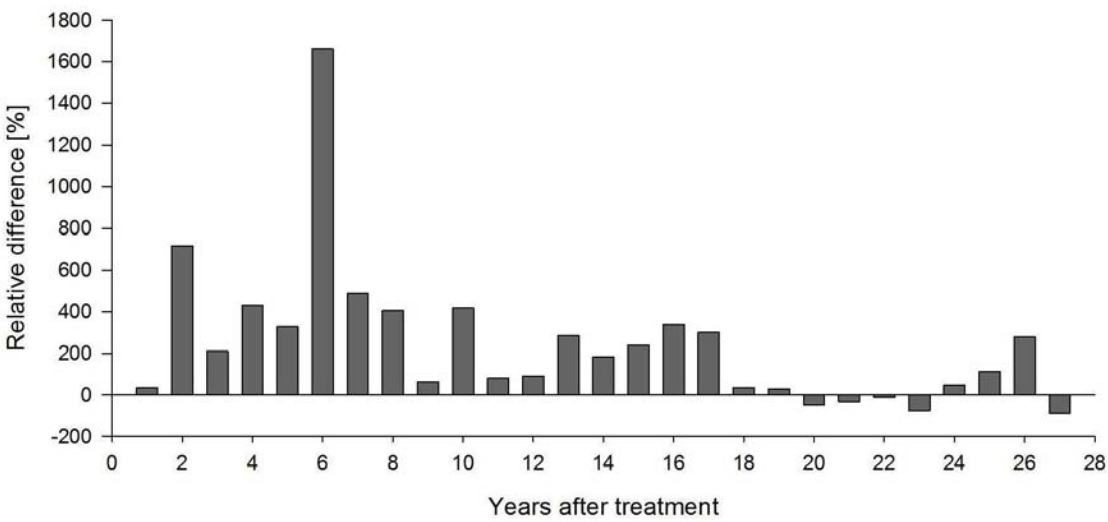



Figure 5.17.: Relative differences between each catchments' summarized annual surface runoff. Basic value for the relative difference is the respective S2 runoff.

with mostly higher values for S2 from 18 to 27 YAT. The same partitioning can be adopted for the relative differences in surface runoff. Still, positive relative differences in surface runoff are remarkably higher than for the same time period in subsurface runoff. Six YAT the surface runoff of S6 is about 1600% higher than the surface runoff of S2. Two YAT the second most high relative difference of about 800% occured. Negative relative differences for surface runoff reach about the same magnitude as for subsurface runoff.
Figure 5.18 displays each catchments' annual subsurface runoff as percentage of the annual SPR. S6 subsurface runoff generally seems to contribute less to the total plot runoff compared to S2. This behaviour is pronounced in particular for the time period 1 to 10 YAT and 20 to 27 YAT. In the latter period the decrease of the relation is more distinct, when subsurface contributions drop to less than 50% in 20, 23 and 27 YAT. The scattering of S6 values has also increased in the period from 20 to 27 YAT.

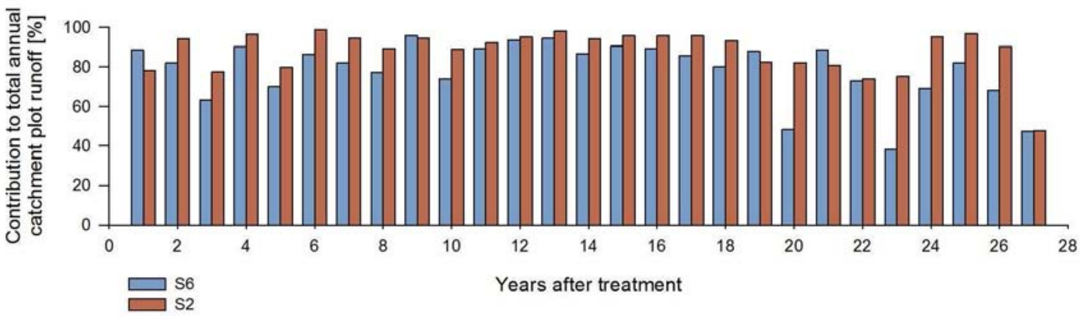



Figure 5.18.: Subsurface runoff as percentage of the total annual catchment plot runoff for both catchments.

After summarizing results by catchment and runoff form, in the following paragraph every runoff plot from the treated catchment is compared to its counterpart from the control catchment. The subsurface plot from the northern side of S6 is compared to the subsurface plot from the northern side of S2, the surface plot from the southern side of S6 is compared to the surface plot from the southern side of S2 and so on.
Figures 5.19 and 5.20 show the double mass curves for each pair of plots. Obviously, all curves follow a general long-term right hand bend. Since S6 runoff is displayed on the y-coordinate and S2 runoff on the x-coordinate a right hand bend is equivalent to a decreasing relationship of S6 runoff versus S2 runoff. Especially the curve for the southern subsurface runoff follows a smooth course, indicating that only slight changes in the relationship occur over the years. Both curves for the northern plots show the strongest change in slope. Roughly in the first 18 to 20 YAT both curves are characterized by a very steep slope, while in the last years of observation the curves seem to reach a plateau. The curve for the northern subsurface runoff plot seems to follow a rather linear relation, which is interrupted by a severe change in slope in the years 22 to 23 after treatment. The plateau can also be observed for the southern surface plots. Still, the change in slope seems less severe for both southern plots. As to see in figure 5.19 the highest total runoff for the time of observation with

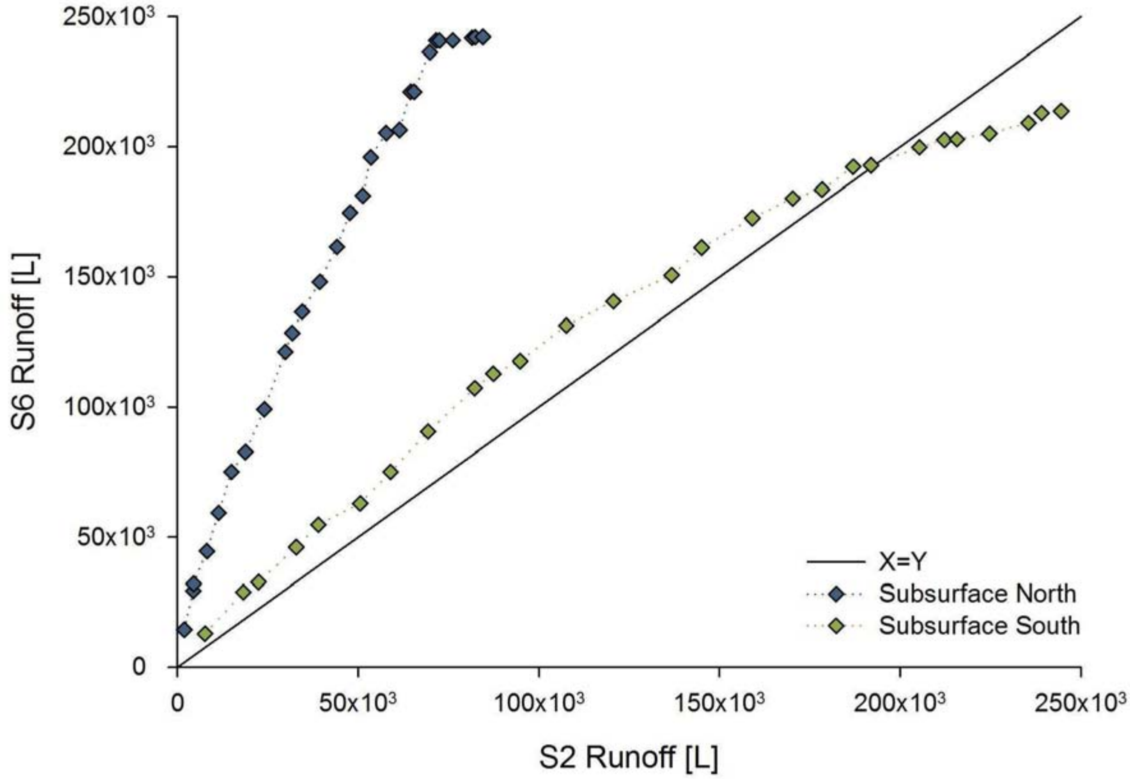



Figure 5.19.: Double mass curves for annual runoff volumes of the subsurface plots.

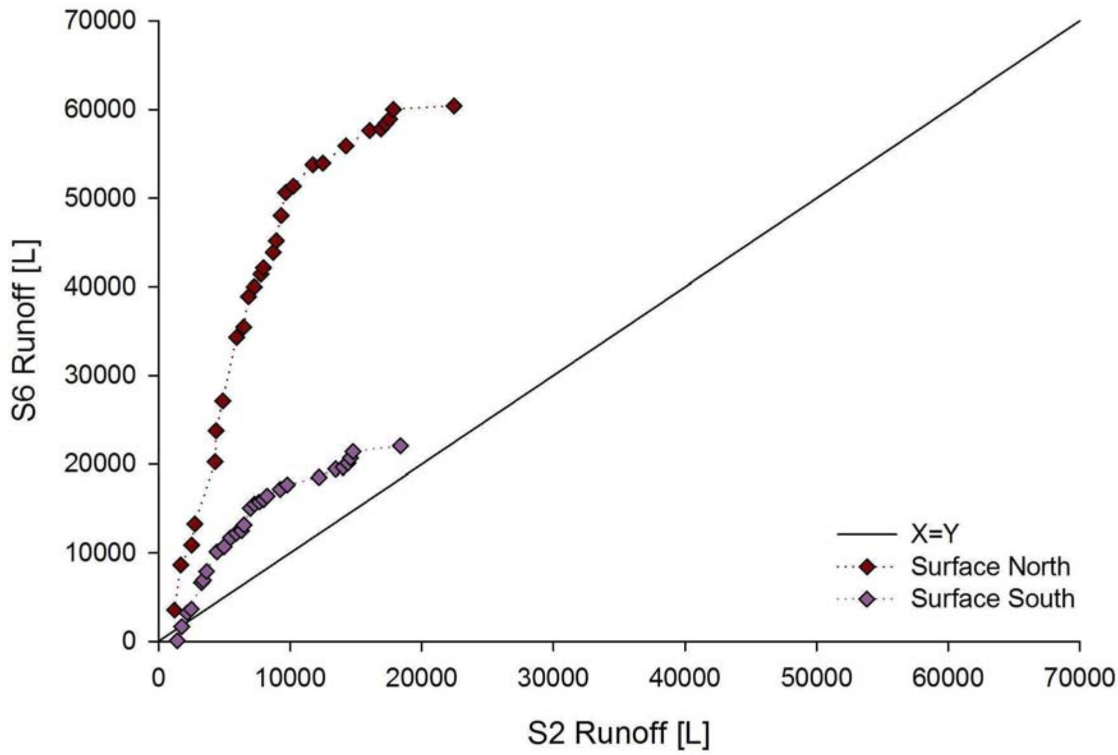



Figure 5.20.: Double mass curves for annual runoff volumes of the surface plots.

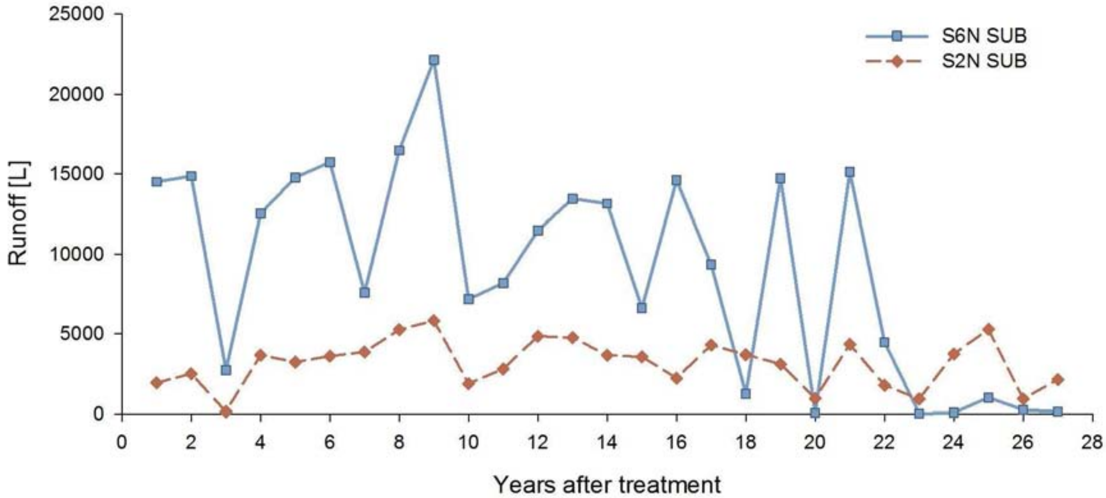



Figure 5.21.: Reactions of annual runoff from the northern subsurface plots of S6 and S2 for the observation period of 27 years.

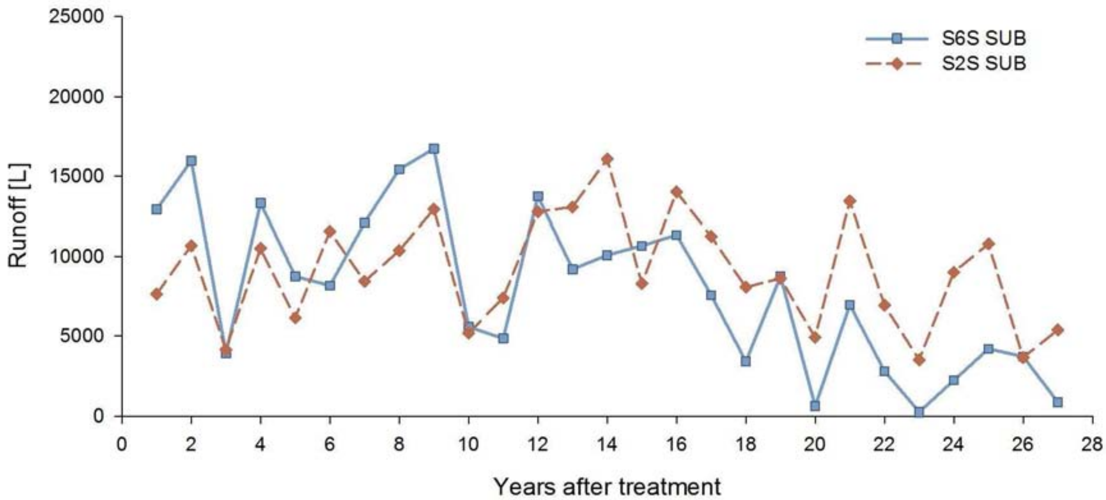



Figure 5.22.: Reactions of annual runoff from the southern subsurface plots of S6 and S2 for the observation period of 27 years.

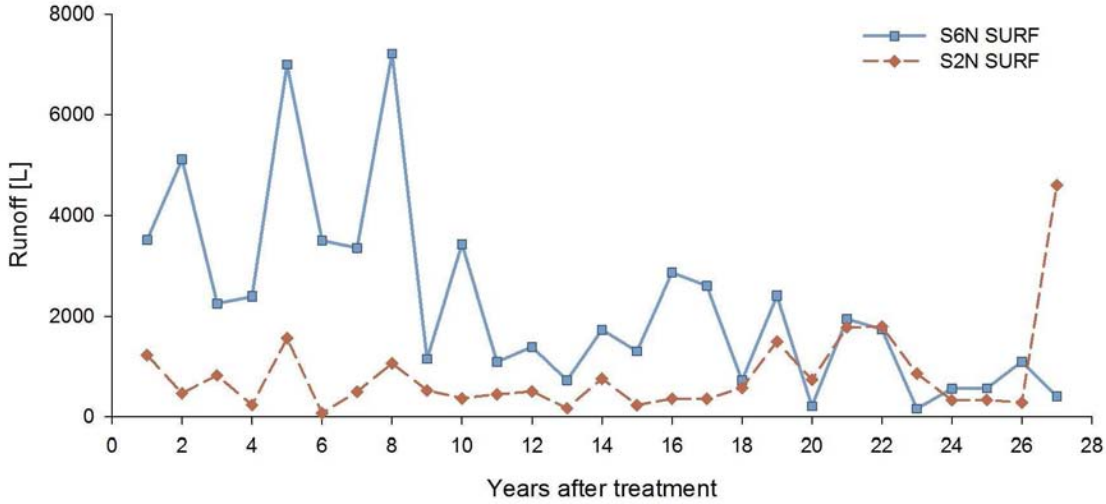



Figure 5.23.: Reactions of annual runoff from the northern surface plots of S6 and S2 for the observation period of 27 years.

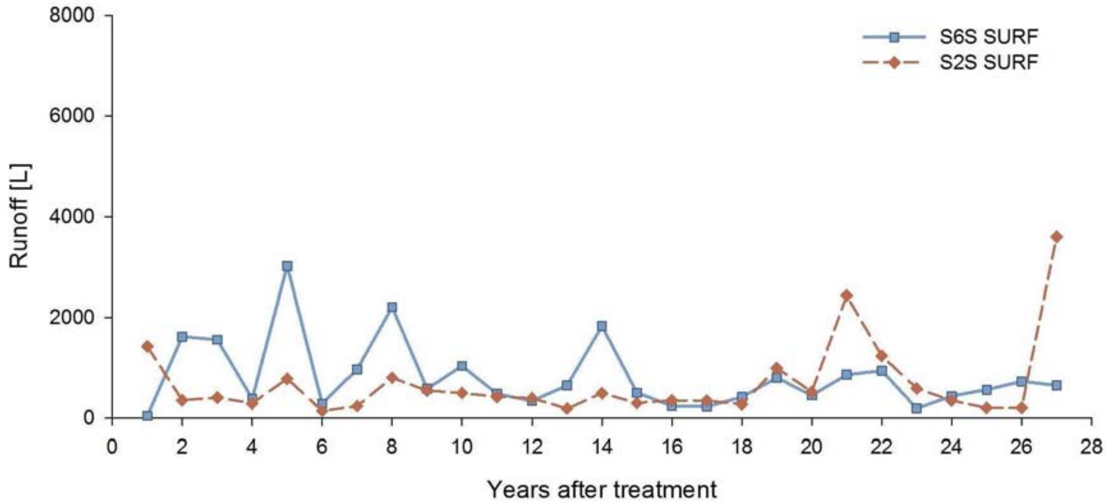



Figure 5.24.: Reactions of annual runoff from the southern surface plots of S6 and S2 for the observation period of 27 years.

about 250 $m^3$ occured in the southern subsurface plot of S2. In S6 both northern plots produced higher runoffs for the whole observation time than their southern counterparts.
In additon to the double mass curves, the developement of annual runoff for each plot is displayed in figures 5.21, 5.22, 5.23, and 5.24. For both subsurface plot pairs, as well as for the northern surface plot pair, the runoff relations have changed, with higher S6 runoff compared to S2 immediately after the clearcut and lower S6 runoffs compared to S2 in the last observation period. Remarkable is the almost complete stop of flow in the last five years of observation for the northern subsurface runoff of S6 (figure 5.21). Remarkable are also the rather high runoff volumes at the southern subsurface plot of S2. While the subsurface runoff of S6 South falls below its counterparts' runoff already 3 YAT, the subsurface runoff of S6 North does so 18 YAT.
Correlation analysis of annual plot runoff and annual streamflow of the respective catchment for 1 to 27 YAT showed, that Spearman correlation coefficients are generally higher for S6. Runoff from both subsurface plots in S6 showed the best correlation. Runoff from all S2 plots are only poorly correlated to streamflow runoff volumes. Table 5.2 shows the Spearman correlation coefficient for the correlation of each plots' runoff volume with the respective catchment streamflow.

Table 5.2.: Spearman correlation coefficient for the correlation of each plots' annual runoff with annual streamflow of the treated and the control catchment.

| | subsurface north | subsurface south | surface north | surface south |
|---|---|---|---|---|
| S6 | 0.87 | 0.80 | 0.72 | 0.30 |
| S2 | 0.50 | 0.52 | 0.34 | 0.36 |

Seasonal effects of clearcutting and forest conversion are given in the following paragraph. For this purpose, monthly runoff is summarized for snowmelt, growing and dormant season in the same manner as already presented in chapter 5.1. Seasonal runoff variations are analyzed for subsurface plots only. Figures 5.25 and 5.26 display the annual developement of the seasonal components of northern and southern subsurface runoff, respectively, for ($a$) snowmelt season, ($b$) growing season, and ($c$) dormant season. If looking at the volumes of each season, it becomes obvious, that for both aspects the highest and the lowest subsurface runoffs occur in the snowmelt and the dormant season, respectively. This is conform with the typical long-term behaviour of the watersheds as to see in figure 2.4. As already mentioned above, the southern S2 subsurface plot generally produces more runoff than its northern counterpart. This difference can also be observed in the seasonal analysis.
Snowmelt season runoffs for both northern and southern S6 subsurface plots exhibit a curve, very similar to the annual runoff curve of S6 subsurface plots, which are presented in figures 5.21 and 5.22. On average, snowmelt runoff contributes 57% to annual runoff for both southern and northern S6 subsurface plot. The curve of the northern S6 subsurface runoff in figure 5.25($a$) is characterized by a very high

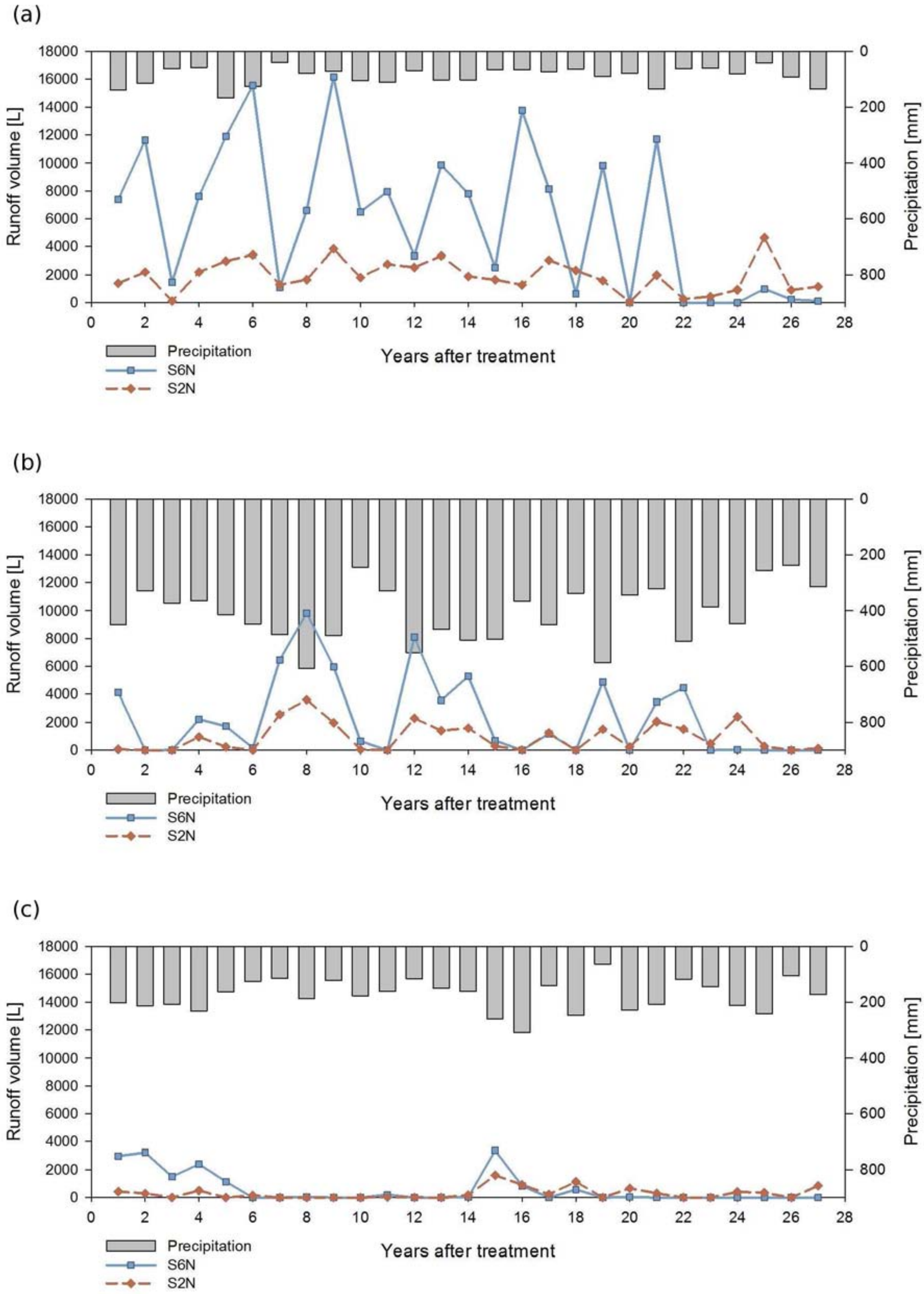



Figure 5.25.: (*a*) Snowmelt, (*b*) growing and (*c*) dormant season runoff reactions of the northern subsurface plots of treated and control catchment. Seasonal precipitation input is shown on the second y-coordinate.

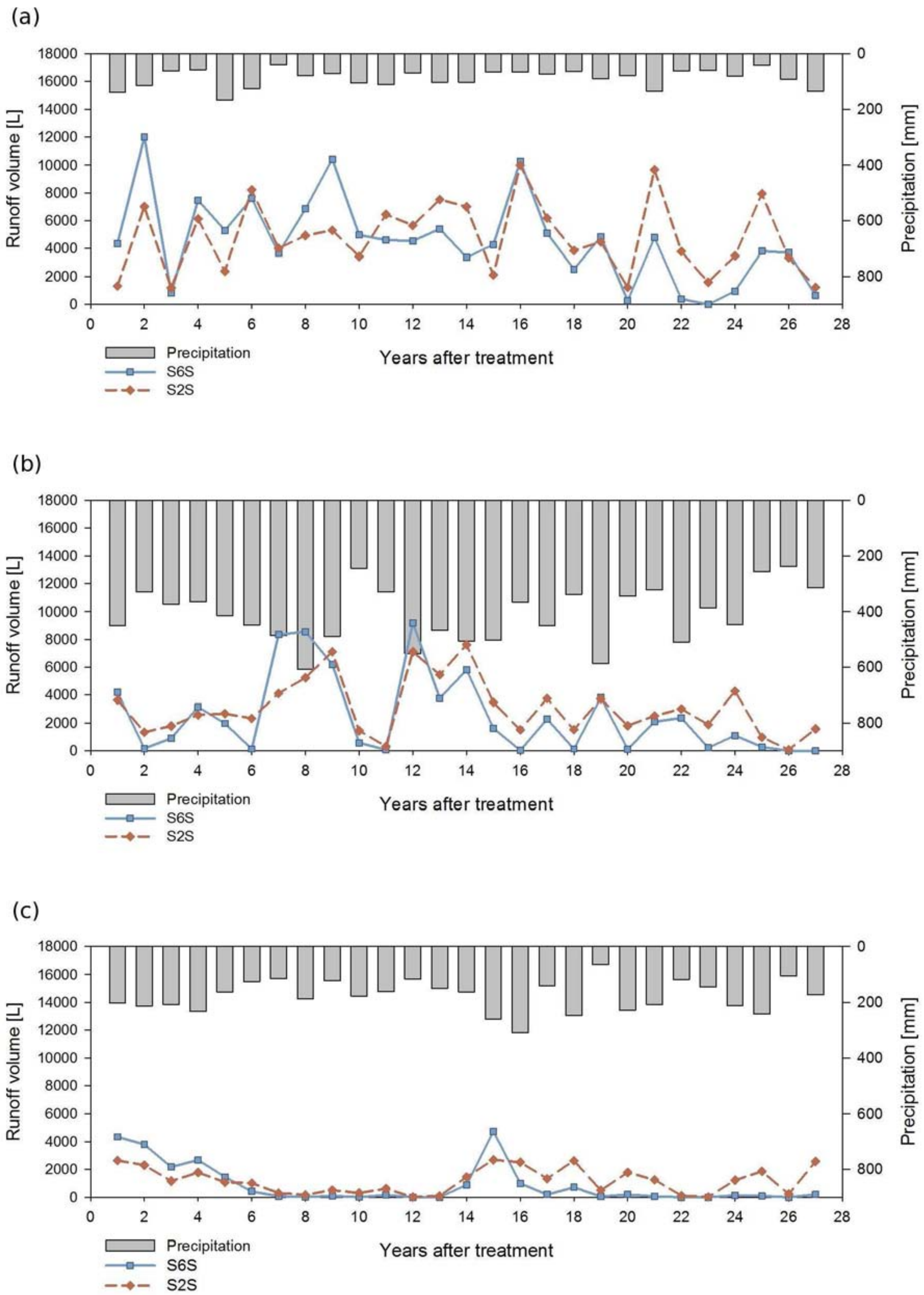



Figure 5.26.: (*a*) Snowmelt, (*b*) growing and (*c*) dormant season runoff reactions of the southern subsurface plots of treated and control catchment. Seasonal precipitation input is shown on the second y-coordinate.

scattering for the first 22 YAT, which does not seem to be controlled by precipitation amount. Once again, the nearly complete stop of flow can be observed for the period 23 to 27 YAT. The scattering in the southern subsurface plot of S6 is not that emphasized and a continuous ceasing of flow can neither be observed. Still, the general patterns of both S6 subsurface curves seem similar, when compared to their S2 counterparts.

The number of complete stops of flow in the growing season seems to increase in the course of time for both S6 subsurface plots. Still, growing season runoff seems much more controlled by the amount of precipitation than snowmelt season runoff. Highest flows occur for both aspects from 7 to 14 YAT. In later years, similar precipitation amounts are not able to produce runoff in the same magnitudes.
Both dormant season curves for the S6 plots show a rapid decline after treatment to very low levels, which causes complete stop of flow in the 6th and 12th YAT for respective northern and southern subsurface plot. Both curves stay on this low-flow level until the end of observation, with the exception of the time period 14 to 16 YAT, when the highest dormant season precipitation for the observation time was recorded. Except for the snowmelt season of the southern S6 subsurface plot, all seasons of both plots depict an almost complete stop of runoff for the last 4 to 5 years of observation.
In a final step, subsurface runoff was analyzed on an event basis. Events have been defined as presented in chapter 4.3. Figure 5.27 shows the histograms and cumulative distribution functions of different time periods for the event volumes monitored at the northern and southern subsurface plot of S6, respectively. The classification of the runfoff volumes and thus the classification of the x-coordinates of the histograms has been chosen to be a sequence of increasing intervals, since a sequence of unidistant intervals did not show any satisfying visualisation. The first class summarizes volumes from $> 0$ to 5 L, the second class from 5 to 10 L, the third class from 10 to 20 L and so on. The maximum event runoff for the northern and the southern S6 subsurface plot was 15660 and 8790 L, respectively, which occured in mid-April for intensive and prolonged snowmelt events. Thus, the upper limit of the last class was set to 20480 L.
Number of events, mean event length, mean event runoff, and summarized event runoff for the three periods unter investigation are presented in tables 5.3 and 5.4. While summarized event runoff is declining for both plots, number of events, mean event length and mean event runoff don't show uniform reactions. Nonetheless, number of events may be declining on the long-term view, since only slight changes occured from the first to the second period, but more severe declines from the second to the third.

The analysis of the histograms shows mostly uniform results for both plots. The highest and second highest frequencies are subsequently shifted to the left for increasing YAT, indicating that change to smaller events is taking place. The only exception is the period from 19 to 27 YAT of the northern subsurface plot, when the highest frequency occurs for both, rather smaller and rather larger event runoffs. The raised frequency of larger events also causes a higher mean event runoff of 1325 L for that period, although the summarized event runoff is the lowest of all three

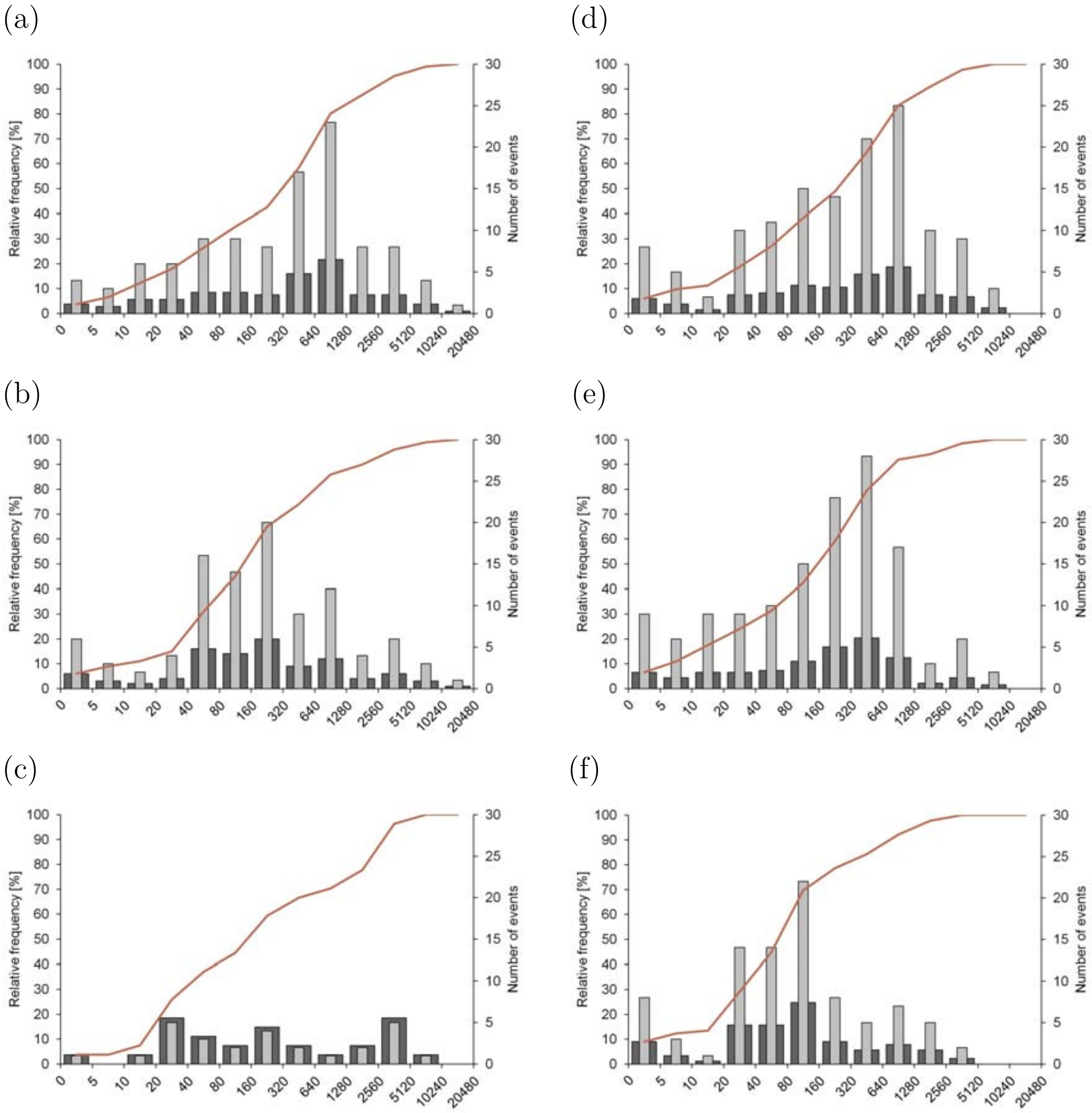



Figure 5.27.: Histogram of runoff volume frequencies. Dark bars represent relative frequency [%], gray bars represent the absolute frequency (number of events). The red line denotes the cummulated relative frequency. Histograms of the northern subsurface plot are displayed on the left side for (*a*) 1 to 9 YAT, (*b*) 10 to 18 YAT, (*c*) 19 to 27 YAT. Histograms of the southern subsurface plot are displayed on the right side for (*d*) 1 to 9 YAT, (*e*) 10 to 18 YAT, and (*f*) 19 to 27 YAT.

Table 5.3.: Statistical key data, gained by the event analysis of the northern subsurface plot of S6.

| | 1 to 9 YAT | 10 to 18 YAT | 19 to 27 YAT |
|---|---|---|---|
| Number of events | 106 | 100 | 27 |
| Mean event length [d] | 3.6 | 3.9 | $4,3$ |
| Mean event runoff [L] | 1144 | 851 | 1325 |
| Summarized event runoff [L] | $121 * 10^3$ | $85 * 10^3$ | $36 * 10^3$ |

Table 5.4.: Statistical key data, gained by the event analysis of the southern subsurface plot of S6.

| | 1 to 9 YAT | 10 to 18 YAT | 19 to 27 YAT |
|---|---|---|---|
| Number of events | 133 | 137 | 89 |
| Mean event length [d] | 3.1 | 3.4 | 2.8 |
| Mean event runoff [L] | 806 | 557 | 339 |
| Summarized event runoff [L] | $107 * 10^3$ | $76 * 10^3$ | $30 * 10^3$ |

periods. The overall very low number of events for that period may account for the redistribution of the histogram and the raised mean event length. Mean event runoff for the southern plot are declining as expected from 806 L in the first period to 339 L in the last period.

## 5.4. Summary

Results of long-term streamflow, soil-moisture and plot runoff monitoring have been presented in chapter 5. All three parameters revealed similar long-term reactions to the clearcut and reforestation of catchment S6 at the MEF. Streamflow data has been used to adopt a regression model, which revealed short-term increases in the treated catchment runoff, followed by a prolonged period of steady decreases under the expected runoff level. Soil moisture was analyzed for different aspects and depths and showed a general long-term decrease in the period after treatment. So did the summarized runoff from all plots (SPR) in the treated watershed. Runoff from the single plots showed somewhat less uniform reactions compared to the soil moisture. Seasonal reactions have been presented for all three parameters, focusing on the snowmelt and growing season. Subsurface runoff events have been defined and visualized in histograms. Regression and correlation analyses have been performed on several parameter combinations and trends have been statistically determined using the Mann-Kendall approach. The following table 5.5 summarizes the trend analyses, conducted in this study.

Table 5.5.: Mann-Kendall test results for streamflow, soil moisture and plot runoff. Every analysis was based on the time period 1 to 27 YAT.

| Parameter | site | trend | level of significance [%] | Theil-Sen slope [change/year] |
|---|---|---|---|---|
| Annual streamflow | S6 | down | 1 | −4.4 |
| Annual streamflow | S2 | — | — | — |
| Soil moisture | S6 South 0-290 cm | down | 0.1 | −25.1 |
| Soil moisture | S6 South 0-76 cm | — | — | — |
| Soil moisture | S6 South 76-137 cm | down | 0.1 | −7.7 |
| Soil moisture | S6 South 137-229 cm | down | 0.1 | −7.5 |
| Soil moisture | S6 South 229-290 cm | down | 0.1 | −3.5 |
| Soil moisture | S6 North 0-290 cm | down | 0.1 | −20.0 |
| Soil moisture | S6 North 0-76 cm | down | 0.1 | −6.8 |
| Soil moisture | S6 North 76-137 cm | down | 0.1 | −6.3 |
| Soil moisture | S6 North 137-229 cm | down | 0.1 | −5.4 |
| Soil moisture | S6 North 229-290 cm | down | 1 | −1.1 |
| Soil moisture | S2 South 0-290 cm | — | — | — |
| Soil moisture | S2 South 0-76 cm | — | — | — |
| Soil moisture | S2 South 76-137 cm | — | — | — |
| Soil moisture | S2 South 137-229 cm | — | — | — |
| Soil moisture | S2 South 229-290 cm | — | — | — |
| Plot runoff | S6 (sum) | down | 0.1 | −1190.6 |
| Plot runoff | S2 (sum) | — | — | — |
| Subsurface runoff | S6 North | down | 1 | −539.6 |
| Surface runoff | S6 North | down | 0.1 | −120.0 |
| Subsurface runoff | S6 South | down | 0.1 | −456.8 |
| Surface runoff | S6 South | — | — | — |

# 6. Discussion

SPR from the treated watershed showed a highly significant downward trend for the 27-year after treatment period. If one would apply the linear equation provided by the Mann-Kendall test, starting at the year of treatment, the calculated runoff at year 27 after treatment would be about 8500 L. Of course the natural conditions observed in this study can't be described by one linear function, since many factors affect the runoff reaction of the slopes. The long-term downward trend is nonetheless plausible, if one assumes a regular growing of the conifer forest, which started with the plantings of three year old seedlings 3 YAT. With the developement of the young conifer forest, its capacity to intercept precipitation water and to transpire soil water increases with its increasing LAI, so the amount of water that is able to enter the ground, assuming equal annual precipitation, decreases and the water stored in the ground, might be depleted earlier and affect increasing depths. As it can be seen in figure 5.15 the annual precipitation naturally changes from year to year, so the monitored plot runoff for the treated watershed is the outcome of at least the combined effect of precipitation amount and stage of forest growth. In the third YAT below average precipitation amounts cause very low plot runoff volumes in both catchments, still the declines in S6 are relatively more pronounced. That may be also caused by the fact, that the low precipitation amounts are quickly consumed by the newly planted young conifer seedlings, whose roots are probably arranged in the layer, where subsurface flow usually occurs. Thus subsurface flow amounts are reduced in a stronger way than surface flow amounts for year 3 after treatment. The aspen stand of the S2 catchment seems to be in a stable condition, since its reactions to precipitation are more pronounced compared to S6 and the course over time doesn't show a significant trend. It is assumed that stationary conditions will appear for the conifer forest as well, however from the underlying data a conclusion concerning the moment when stationarity is reached can not be made. It is true that the last five to six years of observation lie within a close range of values, still, the variation of precipitation input is too high and the time period too short, to make a valuable statement. A possible future scenario of SPR in S6 could be a complete stop of flow for several consecutive years, which would be an indicator, that the coniferous forest has not reached maturity yet.

Observation of the subsurface runoff as percentage of the total annual plot runoff revealed that subsurface runoff in S2 contributes more to total flow than in S6 for all but 4 years. Furthermore the subsurface contributions in S6 even declined percentally to a mean of 64% in the last 7 years of observation, whereas the period before had a mean contribution to total plot runoff of 84%. This reaction is unexpected, since the increasing LAI of the coniferous stand was believed to have a stronger retentional impact on large precipitation events and thus reduce surface runoff contributions. On the other hand, the largest events for surface and subsurface runoff

occur in the snowmelt period, so changes in the behaviour of snowmelt season would be more easily spotted in the hydrograph than changes in the behaviour of precipitation events. It could be neither quantified nor qualified, whether changes in high precipitation events or snowmelt events were responsible for the change in relations. Subsurface and surface runoff sums from S6 have been compared to their counterparts in S2 and relative differences have been displayed in figures 5.16 and 5.17. Negative differences in the subsurface plots occur 2 years earlier than they do in the surface plots. This earlier reaction might indicate, that interflow in forested soils is more sensitive to alterations in vegetation cover than surface runoff. The very high relative differences in surface runoff, that occur in the years 2 to 17 after treatment are probably caused by the generally low volumes of S2 surface runoff. For example, surface runoffs in S6 for year 6 after treatment were not extraordinarily high, more in the region of the annual mean. On the other hand S2 values for the same year were the lowest on record and thus were responsible for the high relative difference. Nonetheless the high scatter from 34% to 1660% may be a sign of rapid changes in forest cover for that time period. In the period from 18 to 27 YAT relative differences still range between about −100% and 100% for both subsurface and surface plots, so even in recent years it seems, that stationarity of the coniferous forest has not been achieved yet, which is in accordance to the statement above.
When *Timmons et al.* (1977) analyzed nutrient transport in surface runoff and interflow at the S2 watershed of the MEF, they found out that 'more interflow was consistently collected from the northerly aspect than the southerly aspect during snowmelt'. This is in accordance to results presented in this study, and can be followed, looking at the subsurface double mass curves (figure 5.19). While the southern subsurface plot in S2 collected about $250m^3$ of water in the period of 27 years, the northern subsurface plot collected only about $90m^3$. Nonetheless, double mass curves also reveal, that the northern plots in S6 collect more water than the southern plots in S6. Those results are rather unexpected, since aspects of the plots would suggest higher runoff for the southern plots, assuming uniform growth of the coniferous forest. Solar energy input may influence evaporation and transpiration from steep slopes essentially and cause intesified runoff volumes for northerly aspect slopes. There might be crucial differences in hours of sunshine and slope area influenced by sunshine for different aspects of mountain slopes. In the rather flat topography of northern Minnesota, it can be possible, that aspect might not play an emphasized role on surface and subsurface runoffs, but as already presented in chapter 5.2 it does so on soil moisture, which will be discussed later. The differences between the northern and southern runoff volumes in S6 are probably also a consequence of slight differences in runoff plot configuration, like length of slope or distinctiveness of the less permeable soil layer or general permeability differences within the slope. The true length of the S6 slopes are not known, but it is assumed, that the northern plots collect water from a longer slope. The reactions of the double mass curves furthermore reveal, that each single plot in S6 seems to react the same way in a long-term view as the SPR in S6. But when optically comparing the curve of the summarized runoff of S6 (figure 5.15) with the reactions of each single plot (figures 5.21 to 5.24), a general downward trend can only be observed for three of

the four S6 plots. The southern surface plot of S6 neither optically nor statistically showed a significant trend at all and thus is the only plot that didn't show considerable changes in runoff volumes. The reason, why a right hand bend is displayed on the double mass curve nonetheless, must be the outcome of the natural variation of both plots (southern surface plot of S6 and southern surface plot of S2). The most severe changes occur at the northern subsurface plot of S6 with very high runoff volumes in the first decade of measurement and almost a complete stop of flow in the last five years. The sharp cut in the runoff volumes can also be observed in the double mass curve, but seems unnatural. Precipitation input is considerably below average in the $23^{rd}$ year after treatment and all plots show outstanding low runoff volumes. Still, the following year is characterized by above average precipitation amounts and all three other plots show higher reactions than the northern subsurface plot. One could assume changes in monitoring equipment or alterations in the configuration, but no anthropogenic and unnatural changes have been reported. The more realistic course, reflecting the developement of the conifer forest cover seems to be the developement of the southern subsurface plot of S6 with a more smoothened downward trend. Nonetheless, both subsurface curves show, that a critical point in the stage of observation is reached, since stop of flow and nearly no-flow conditions seem to happen more often in the last decade of observation.

Correlation analysis was conducted for the combination of annual plot runoff data with annual catchment streamflow. It has been found that values of each plot of S2 showed only poor correlation with S2 streamflow data. In S6, subsurface runoff from both plots showed good correlation with streamflow. Keeping the importance of interflow on runoff generation, as presented in chapter 3.3 in mind, it makes perfect sense, that interflow volumes and streamflow volumes have a high degree of association. Nonetheless the question arises, why the runoff plots in S2 obviously show poor correlation. It has been speculated that differences in the shallow root system might be responsible for the difference in correlation. Coniferous trees might show a more horizontal spread of roots in the uppermost part of the soil, while deciduous trees spread their roots more vertically and influence deeper soil water reservoirs. Interflow occurs at both watersheds in rather shallow soil horizons and consequently a different root system could exert variable influence on the interflow patterns of each watershed.

The developement of seasonal runoff has been studied for both subsurface plots of the treated catchment within the 27-year period after clearcut. The apparent discrepancy of higher runoffs occuring in the northern plots, that has been mentioned in the paragraph above will be put into new perspective, when looking at the subsurface runoffs in the snowmelt season and keeping in mind that subsurface flow is a rather fast reacting runoff component. By comparing snowmelt runoff, presented in figures 5.25($a$) and 5.26($a$) with the respective total annual runoff, presented in figures 5.21 and 5.22, it becomes clear, that the curve of total annual runoff resembles strongly the curve of snowmelt season runoffs. Thus the snowmelt season contributes the largest part to total annual plot runoff, and aspect induced runoff differences in the snowmelt season are 'stamped' into the annual runoff curve of each plot. Now, transpiration losses in the snowmelt season are probably only marginal, so that aspect induced transpiration differences may not alter subsurface and surface runoff volumes between northerly and southerly aspects. In fact, it is assumed that snowmelt and sublimation processes and their differences between northerly and southerly aspects play the key role in the observed aspect induced differences in the snowmelt season runoff. The higher solar energy input on the southerly aspect may lead to a faster and intensified melting of the snowcover at the northern site of the catchment and thus to faster and higher subsurface runoff. On the other hand, parts of the southern site may experience longer shadow periods and overall less energy input and thus produce less pronounced but longer snowmelt runoff events. In the second case losses to percolation and sublimation are more likely, so the total volume of runoff measured at the southern site might be less than the total volume of runoff measured at the northern site. The high variability of snowmelt runoff may be explained partially by the character and the amount of energy input of each snowmelt season. Still, the magnitude of the amplitude at the northern subsurface runoff plot seems unnatural and may be caused by additional external impacts. When comparing the two S6 snowmelt curves, one can see that several times, especially in the 5 last years of observation runoff from the northern subsurface plot was considerably below runoff from the southern subsurface plot. Those reactions could not be explained by the considerations stated above. Furthermore, the question persists, why subsurface reactions in S2 show generally higher subsurface runoff for the southern plot than for the northern plot. Differences in the distinct configuration of each plot might cause the ambiguous results. Different tank sizes as well as the number of annual overflows per tank might contribute to the discordance.

Growing season subsurface runoff showed surprisingly uniform reactions for both sites in S6, in timing as well as in magnitude. The transpiration rates of the vegetation in the growing season are maximal and so slight differences induced by aspect caused the southern site to produce a slightly higher runoff than the northern site for the 27 years of observation. This reaction has been observed more severely for the deciduous trees of the control catchment. Ceasing of subsurface flow in S6 occurs regularly and mainly for the same years for both sites, so it is assumed that transpiration rates are not the same, but on an equally high level. Only intense precipitation volumes are able to produce considerable amounts of subsurface flow in the growing season and it seems, that over the years the same precipitation amounts cause decreasing volumes in subsurface runoff. The more distinct differences between the subsurface runoff of different aspects in S2 may be caused by the generally higher transpiration rates of deciduous trees during the summer months. Consequently the aspect induced differences get more pronounced due to the generally higher transpiration rates.

Dormant season runoffs at the S6 subsurface plots are characterized by volumes close to zero. The influence of the growing forest can be seen in the first years after clearcut and after that time dormant season runoff nearly stopped. Only the two highest dormant season precipitation amounts on record, which occured 15 and 16 YAT were able to produce a considerable rise in the hydrograph. Subsurface runoff amounts in S2 are generally higher, which is attributed to the leaf fall and complete stop of transpiration of the deciduous trees.

The definition of events and subsequent order by event volume has revealed a sequence of histograms, which show that medium event volumes, event number as well as summarized event volume decrease in the long-term view of the observation. This is plausible, because increasing interception capacity of the growing conifer forest reduces the amount of precipitation that reaches the surface of the forest soil. Thus for the same amount of precipitation, less amount of water is available in and on the forest soil to produce runoff. Still it can't be said with certainty how event volumes in the snowmelt season are affected. It seems that the largest events, which exclusively occur in the snowmelt season, also decline in the long-term view, but the rarity of those events make it difficult to proof that assumption. The general decrease in snowmelt volume in the last 5 years of observation, as presented in figure 5.25($a$) and 5.26($a$) seem to support this assumption. Still, figure 5.27($c$) shows, how a scenario could lool like, if the number of events is decreasing on a level where almost exclusively snowmelt events occur. In the northern subsurface plot of S6 this becomes noticeable in a flattening of the histogram and an increased frequency of larger events in relation to the total number of events.

Although only three soil moisture samples per year and site have been taken to calculate annual soil moisture sums, the results seem to represent very well the true annual developement of the soil moisture in S6 and S2. The soil moisture developement at the southern site of S2 does neither optically nor statistically show any significant trends in soil moisture for each soil horizon (table 5.5), signalizing stationarity on an annual basis. On the other hand, almost every horizon at the southern site of S6 seems to be influenced sooner or later by the growing of the coniferous forest. The integrated soil moisture at S6 South is characterized by an even downward trend and the relative difference between the values of the first and the last year of observation is $-48\%$. No stop of the trend is identifiable, indicating that the forest water consumption is still increasing. The time period between clearcut harvest and planting of the conifer seedlings unfortunately has not been monitored but a general rise of the soil moisture is assumed. The individual inspection of different soil horizons brought to light, that the fastest reaction to the planting of the conifer seedlings can be observed in the uppermost part of the soil. Three year old seedlings were planted 3 YAT, so the root system of the plants should have already been developed for several tens of centimeters and be able to alter the soil moisture conditions in the uppermost horizon. The decreasing trend beginning 6 YAT stops at about 10 YAT (7 years after planting of the seedlings), and in the subsequent years soil moisture monitored at the southern site of S6 shows a more or less constant distance to the soil moisture of the southern site of S2. It is assumed that the water consumption of the conifers in the first 76 cm of observation since about 10 YAT stayed on a constant level and root growth influenced more and more the deeper sectors of the soil. And indeed both medium horizons H2 and H3 display a curve with more or less equally high soil moisture values, before a drop in soil moisture occurs at about 15 to 19 YAT. The timing of the decline is not as distinct, but definitely occurs several years after the beginning of decline in H1. The downward trend for both medium horizons is undeniable and most severe for H3 ($-68\%$). Soil

moisture obviously is higher in S6 South than in S2 South for the lowest soil horizon throughout the whole time of observation. Only values of about the last 6 years of observation show a decrease and thus a possible influence of the conifer roots. As it can be seen in table 3.2 root depths of 290 cm are not unrealistic for white spruce species, and soil characteristics of the glacial deposits in northern Minnesota seem not very hindering. The higher soil moisture in S6 may be traced back on slight changes in soil characeteristics between S6 and S2, but could also be a result of old aspen root channels, passing soil water from the upper levels into deeper horizons. This assumption could not be validated, but according to table 3.2 aspen roots could have reached the lowest soil horizon. Assuming, that the timing of soil moisture decline in each horizon is in accordance with the time when coniferous roots reach the middle of the respective horizon, the mean root growth rate for coniferous trees in S6 South would be about 15 cm/year. Consequences of the decreasing soil moisture in S6 might not only be decreasing catchment runoff, which could be observed in chapter 5.1, but also decreasing groundwater recharge since the percolation of soil water down to the regional water table is hindered by a generally lower soil moisture.
For the analysis of seasonal changes in soil moisture contents only one sample per season was available (integrated over the total depth of observation). Nonetheless, the results show plausible reactions. The most constant course of soil moisture without any statistically or optically significant trends occurs for the May values, at the end of the snowmelt season. Except for year 24 all values for S6 South range at a similar level. This may be caused the filling of the soil moisture reservoir during the snowmelt season, before any evaporation and transpiration in a considerable amount can take place. Thus the May values probably show the maximum soil moisture level throughout the whole year and may possibly represent saturated conditions. Growing season soil moisture measured in early September differs considerably from the May values. The consequence of lower and higher summer precipitation (high scatter), as well as the increasing water demand of the growing conifers (general downward trend) can be easily observed in the graph, e.g. the years 16 and 20 were both characterized by below mean growing season precipitation, whereas the years 19 and 24 showed above mean growing season precipitation. It is plausible, that the growing season is affected most by the growing conifer forest, since increasing transpiration and interception capabilities are most severe in the summer months. The increasing water demand by the forest can also be observed in the dormant season course, but fall precipitation had a balancing impact on the downward trend and diminished the variability, that could be observed in the September curve. S2 curves in each season show analog reactions, just without the downward trend.
In a last step soil moisture from the northern site of the treated watershed was compared to soil moisture from the southern site, to identify aspect induced differences. The low SD of the difference between 'S6S' and 'S6N' of about 37 mm for the first 24 years shows that the mean difference of about 166 mm for the first 24 years only varies very low (see figure 5.14($a$)). Thus the mean difference is quite representative for the true difference in the first 24 years. It is assumed that the main differences between the northern and the southern site are contributed by the growing season, because energy input differences have the highest impact on transpiration rates and

interception losses in the summer months. It could not be explained why the difference in the last 3 years almost diminished to zero. It is rather implausible, that the energy input in three consecutive years is on such low level, that differences between aspect do not appear. Remarkable is, that the main differences between the total soil moisture values derive from deeper horizons. Differences in H1 are insignificantly low. A scenario could be that the understory of the forest, which is assumed to have rather shallow roots, is situated mostly covered by the overstory and is not able to produce considerable differences in the soil mositure of the uppermost soil horizon. The overstory on the other hand, which has deeper roots and is exposed directly to solar radiation is using high amounts of soil water in the lower horizons, for the northern site even more than for the southern site. This could explain general differences in soil water between the soil horizons. Still, it is not totally plausible because the roots of the young conifer forest did not reach very far in the early years of measurement and understory probably wasn't even developed. The difference between northern and southern soil moisture in the early years could also be a result of the former aspen forest, which probably also caused differences in soil moisture for different aspects. It is assumed, that the short time between clearcut and reforestation, when soil moisture had the possibility to increase, probably was not enough to compensate the differences of the two sites that were already there, caused by the former aspen forest.

Analysis of correlation between the catchment runoff of each catchment and precipitation revealed that both relationships can be fairly good described by a monotonic function, still, the correlation coefficient is slightly higher for S2 streamflow. The little difference in the coefficients might be caused by a second main influence next to precipitation, which in this case is the influence of the growing conifer forest in S6. Streamflow generally showed a similar course to SPR and the summarized soil moisture in S6. But since both streamflow curves (S6 and S2) follow the same general pattern, the differences are not that obvious as they are for the other two parameters. Therefore a regression model has been developed with the purpose to show the differences between the actual S6 streamflow developement and a simulated one. In chapter 3.1.1 it has been discussed that for the developement of a regression model a long calibration period would be advantageous. In this study only four years of calibration were available. Why those four years of calibration might provide good results nonetheless is justified by the fact, that the calibration period covers a wide range of precipitation inputs. The two consecutive years 1976 (-4 YAT) and 1977 (-3 YAT) were characterized by the lowest and highest precipitation amounts on record. The MAP for the period 1976-1979 was only slightly below the MAP for the period 1961-2006. Both facts support the application of the four-year regression model to get a simulation for the catchment runoff that would have occured, if there had not been a clearcut and reforestation in S6. The streamflow output of the catchment is the cummulative result of the effects of increasing transpiration and interception capacity, the alteration of the soil moisture as well as the change in surface and subsurface flow patterns. The developement of the measured streamflow volumes are compared to the simulated streamflow curve and differences between those two have been presented in figure 5.4. The curve shows the typical and expected reaction to the forest conversion, as it has been presented numerous times in literature (see figure 3.4). With the disappearance of the old forest interception and transpiration losses diminish and the excess of water is used to refill the soil water reservoir, but mainly to contribute to streamflow. Those positive differences increase until the point is reached, when the young conifer trees start to transpire more than the old aspen trees, which is guessed to happen at about 10 YAT. From that point on, annual water consumption by the conifer trees is so high, that streamflow continually decreases. In this study the period from 12 to 18 YAT is characterized by actual streamflow values that are not considerably different from the simulated streamflow values. This periods marks the transition from positive to negative differences. The maximum negative difference finally is reached 24 YAT. It is assumed, that the actual streamflow will swing into a level, lower than the predicted streamflow, gained by the regression model. But from the present dataset it can't be said where that level is.

Equal reactions have been observed by applying regression analysis between S6 and S2 streamflow for different time periods. Those have been outlined in chapter 5.1. The four regression lines presented in figure 5.2 show roughly parrallel behaviour for the range of the representing volumes. Thus the uppermost curve has the highest S6 runoff relative to S2 runoff. The uppermost curve is the regression line for the period 1981 to 1991 (1 to 11 YAT) which is, as already shown, the period with the highest differences between measured and simulated S6 streamflow. The two medium regression lines represent the time before clearcut respective the time from 1992 to 1998 (12 to 18 YAT), which are both characterized by little differences in measured and simulated S6 streamflow. Finally the lowest regression line represents the last period of observation (19 to 27 YAT) that has been characterized by negative differences between measured and simulated S6 streamflow.

Growing season in percentage of total annual streamflow has been presented separately and showed that it is highly dependent on the respective precipitation input for both catchments. High precipitation years cause proportions of up to 80%, dry years may minimize the proportion down to 5%. It is surprising, that S6 values generally lie below S2 values in the time immediately after treatment. Especially in the growing season it is assumed that the removal of forest cover will not only increase the total amount of growing season streamflow, but also its proportion to total annual streamflow due to the generally higher precipitation in summer. The expected graph would feature distinctly increased values of S6 relative to S2 immediately after the clearcut and a continuous decrease in differences as the forest grows. Further would the curve of S6 stay above the curve of S2, since the deciduous forest is expected to have higher transpiration rates during summer than the coniferous forest (although at the annual scale the coniferous forest is expected to have an overall higher water consumption). Now, the curve in figure 5.6 displays a completely different scenario. This might be caused by an above-average water consumption of young conifers in the growing season, with slight decreases in the course of time, causing an assimilation of both curves in the last part of observation. Nonetheless, the values are already decreased in the years before treatment, which could be an indicator for different general reactions of each catchment. Additional, actual evaporation data might have been useful to interpret those ambiguous results. Possibly the evaporation of soil water would have shown a significant change due to the forest clearcut.

A regression model has been applied on the parameter DOF. Figure 5.7 reveals that from year 12 on expected and actually measured DOF suddenly begin to diverge. Considerably more days of flow could actually be observed, than would have been expected under the old aspen forest. This behaviour prevails to the last year of measurement. Obviously the coniferous forest has not only the capacity to decrease catchment runoff but also to increase days of flow. Thus less water gets redistributed on more days of flow for catchment S6. When keeping in mind that the deciduous forest has its highest transpiration rates during the summer months, it seems plausible that the outflow of the catchment may stop for several times in the growing season. As already mentioned it is most likely that the coniferous forest shows generally higher transpiration rates on the annual scale, but in the growing season probably transpires less than the deciduous forest. Thus the runoff from the treated catchment may produce more balanced runoff and less severe downfalls of runoff in the summer months and thus the total amount of DOF increase.

Although interflow and surface runoff from the uplands are considerably negativ influenced by the forest treatments, and soil moisture has a continuous downward trend, streamflow only showed negative changes of maximal 41% (figure 5.5). This might be attributed to the important role of the peatland on the streamflow. As already presented in chapter 2.6, *Verry & Kolka* (2003) analyzed the importance of wetlands to streamflow generation and showed that normally more than 50% of the streamflow emerges form the bog. If it is assumed that roughly 50% of the streamflow emerge from the bog and the other 50% from the upland, and the streamflow in the year 24 after treatment had negative difference of about 40%, than the total change of the upland contribution to the streamflow would be as high as −80%, if no changes in the peatland contribution are assumed. This is an impressive change if looking at the upland contributions only and demonstrates very well the severe changes that forest conversion can exert on the water budget of a catchment.

# 7. Conclusions

The previous chapters show that forest management practices, namely clearcutting of a deciduous forest and forest conversion to a coniferous forest, had severe impacts on the water budget of a small upland-peatland catchment in northern Minnesota. The three parameters under investigation, which were subsurface flow, soil moisture content, and streamflow, showed significant long-term downward trends for the time of 24 years after the planting of young conifer seedlings in 1983. The storage and movement of water in the upland soil of the catchment was affected by distinct characteristics of the new forest and alterations in its specific parameters, due to the growing of the trees. Increases in LAI, rooting depth and overall water consumption with age were assumed to be the main driving forces behind the alterations of the water budget.

The aim of this study was to identify responses of subsurface flow and soil moisture to the forest treatment. Therefore, long-term datasets of up to 31 years have been analyzed. Soil moisture content, measured at two sites of the upland of the treated catchment showed decreasing trends at both sites and for the entire depth of observation. It was also shown that the soil water content is highly affected by season or more precisely that only in the growing and dormant season changes in soil moisture due to the forest conversion are visible. Soil moisture in the snowmelt season seems yet to be unaffected by the new forest cover, since the recharge of the soil water reservoir during the snowmelt season is high enough to keep the soil moisture on a constant level. Annual soil moisture showed a stepwise decrease for the consecutive sequence of soil horizons and it was assumed that this might be the effect of consecutive vertical root growth. On the basis of this assumption, a rough calculation of the mean root growth rate was conducted. Furthermore, differences in the northern and southern sample site of the treated watershed were assigned to the differences in solar energy input due to northerly and southerly aspects.

Subsurface runoff was measured at opposing sites at the uplands of both catchments. It was shown that subsurface flow in the treated catchment diminished dramatically, especially in the last 5 to 10 years. The growing forest caused a complete stop of flow at both subsurface collectors in the 23rd YAT. Furthermore it is assumed, that if the coniferous forest keeps on growing at a comparable rate, subsurface flow, measured at the runoff plots will stop for several consecutive years. Although the SPR in the treated catchment showed a constant decrease, the southern surface runoff plot did not show any sign of being affected by the forest conversion. As a result of this, the amount of subsurface flow as percentage of SPR was reduced in the last years of observation. Correlation of plot runoff with the respective streamflow of each catchment showed the best values for the subsurface plots of S6. Poor correlations in S2 were traced back to different root systems of the deciduous trees. Differences in northern and southern runoff plots revealed uniform reactions within

the treated catchment but the reactions of each catchment did not correspond with each other. It is probable that uncertainties in the measurement equipment as presented in chapter 4.1.4 outweighted the influence of aspect and thus were responsible for the ambiguity of the results. Snowmelt season revealed the most severe changes in terms of volume when comparing the values immediately after planting of the conifers and values in the last 5 years of observation. Snowmelt season also contributes the largest part to annual runoff and thus significantly forms its course over time. The high variability in the course of the snowmelt season runoff especially at the northern subsurface plot was assumed to be partially influenced by the amount of energy input of the snowmelt season. Nonetheless, it seems highly inconsistent. Growing season runoff showed the highest sensitivity regarding precipitation and the general downward trend raises the chance that in the course of time no flow might occur in the growing season at all. The differences caused by aspect in the growing season were only marginal at the treated watershed, the deciduous trees at the control catchment obviously revealed higher sensitivity concerning aspect. Dormant season runoff declined to a very low level soon after the forest operations and showed considerable reactions only to the highest precipitation inputs on record. Definition and analysis of subsurface runoff events revealed, that number of events, mean event volume and summarized event volume decline in a long-term view. Still, if the number of events declines to a level where almost exclusively snowmelt events occur, it is possible that the frequency of larger events increases again.
Streamflow has been analyzed to gain additional information to the other two parameters. A paired catchment approach has been applied on streamflow from the treated catchment, and showed reactions similar to other reforestation experiments, with raised streamflow volumes in about the first 11 YAT and reduced streamflow volumes for the time period 19 to 27 YAT, relative to the simulated streamflow. Those results were confirmed by the construction of regression lines, which were developed to describe the relation of treated and control catchment runoff for different periods. Results gained by the separate analysis of growing season streamflow showed irritating results. It was speculated that distinct evaporation changes after the clearcut had something to do with the unexpected reaction. Still, no additional arguments could be found to strengthen the assumption. Combining the results of the streamflow analysis and analysis of DOF, it can be concluded that the effect of the growing conifer forest is to diminish streamflow, but to distribute the diminished runoff on more days per year.
Although both catchments that were part of this study reveal many similarities, slight differences in some characteristics of the catchments are natural and may produce effects that couldn't be separated from the effect of forest regrowth. It is unfortunate, that impacts of obvious differences in the configuration of the runoff plots can not be quantified. Furthermore, the amount of overflows was not equal for both catchments (see Appendix) and may add up underestimations in the runoff volumes over the course of time. Thus, the data from the runoff plots seems to be afflicted with high uncertainties.
Further additional data concerning forest characteristics could have considerably strengthened some of the statements, mentioned above. Correlation of LAI with

SPR/streamflow or correlation of root growth data with affected soil horizon could have provided useful argumentation. Additional climatic data like SWE, evaporation data, and short- and longwave energy input may have brought new light into some of the controversies presented above. Maybe results from ongoing projects might contribute valuable additional data concerning transpiration and interception capacities of the conifer forest and might bring new aspects into the topic. Nonetheless, albeit additional data would have been useful, the long-term monitoring at the Marcell Experimental Research Forest, in particular the observation of subsurface and surface runoff, which provided the base for this study, established a unique dataset to determine long-term relations between forest cover changes and subsurface water reactions.

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# Appendix

## A. Additional information

The following tables contain additional information to chapter 2.4.1.

Table A.1.: Menahga soil classification after *Nyberg* (1987).

| Horizon | Depth (cm) | Description |
|---|---|---|
| *Oi* | 2.5 to 0 | Organic litter, mainly pine needles and twigs. |
| *A* | 0 to 2.5 | Very dark gray (10YR 3/1) and black (10YR 2/1) loamy coarse sand; single grain; loose; uncoated light gray (10YR 7/1) sand grains in the matrix; strongly acid; abrupt smooth boundary. |
| *E* | 2.5 to 7.6 | Grayish brown (10YR 5/2) loamy coarse sand; single grain; loose; strongly acid; abrupt smooth boundary. |
| *Bw*1 | 7.6 to 30 | Yellowish brown (10YR 5/4) sand; single grain; loose; strongly acid; gradual wavy boundary. |
| *Bw*2 | 30 to 71 | Yellowish brown (10YR 5/4) sand; single grain; loose; medium acid; clear wavy boundary. |
| *BC* | 71 to 96 | Brown (10YR 5/3) and yellowish brown (10YR 5/4) sand; single grain; loose; slightly acid; gradual wavy boundary. |
| *C* | 96 to 177 | Brown (10YR 5/3) coarse sand; single grain; loose; slightly acid. |

Table A.2.: Warba soil classification after *Nyberg* (1987).

| Horizon | Depth (cm) | Description |
|---|---|---|
| $Oi$ | 2.5 to 0 | Organic litter, mainly leaves and twigs. |
| $A$ | 0 to 2.5 | Very dark gray (10YR 3/1) fine sandy loam; weak very fine granular structure; friable; medium acid; abrupt smooth boundary. |
| $E1$ | 2.5 to 10 | Grayish brown (10YR 5/2) fine sandy loam; moderate thin platy structure; friable, slightly hard; many roots; strongly acid; clear smooth boundary. |
| $E2$ | 10 to 18 | Light brownish gray (10YR 6/2) fine sandy loam; moderate medium platy structure; friable, slightly hard; many roots; strongly acid; clear smooth boundary. |
| $E/B$ | 18 to 30 | Light brownish gray (10YR 6/2) fine sandy loam (E); massive; friable; E material surrounding and tonguing into dark brown (10YR 4/3) clay loam (Bt); weak medium subangular blocky structure; firm, hard; many roots; strongly acid; clear wavy boundary. |
| $Bt1$ | 30 to 40 | Light olive brown (2.5Y 5/4) clay loam; moderate fine and medium angular blocky structure; firm, hard; few roots; continuous thin and moderately thick dark brown (10YR 4/3) clay films on faces of peds; patchy light brownish gray (10YR 6/2) sand coatings on vertical faces of peds in the upper part; strongly acid; gradual smooth boundary. |
| $Bt2$ | 40 to 76 | Light olive brown (2.5Y 5/4) clay loam; moderate coarse prismatic structure parting to strong fine and medium angular blocky; firm, hard; few roots; continuous thin and moderately thick dark brown (10YR 4/3) clay films on faces of peds; many very dark brwon (10YR 2/2) organic stains on faces of peds; medium acid; gradual smooth boundary. |
| $Bt3$ | 76 to 121 | Light olive brown (2.5Y 5/4) clay loam; moderate coarse subangular blocky structure; firm, hard; few roots; continuous thin and few moderately thick brown (10YR 5/3) clay films on faces of peds; many very dark grayish brown (10YR 3/2) organic stains on faces of peds; neutral; clear wavy boundary. |
| $C$ | 121 to 152 | Light olive brown (2.5Y 5/4) sandy clay loam; massive; friable, slightly hard; few roots; about 3 percent coarse shale fragments; slight effervescence; mildly alkaline. |

The following figures contain additional information to chapter 4.1.4.

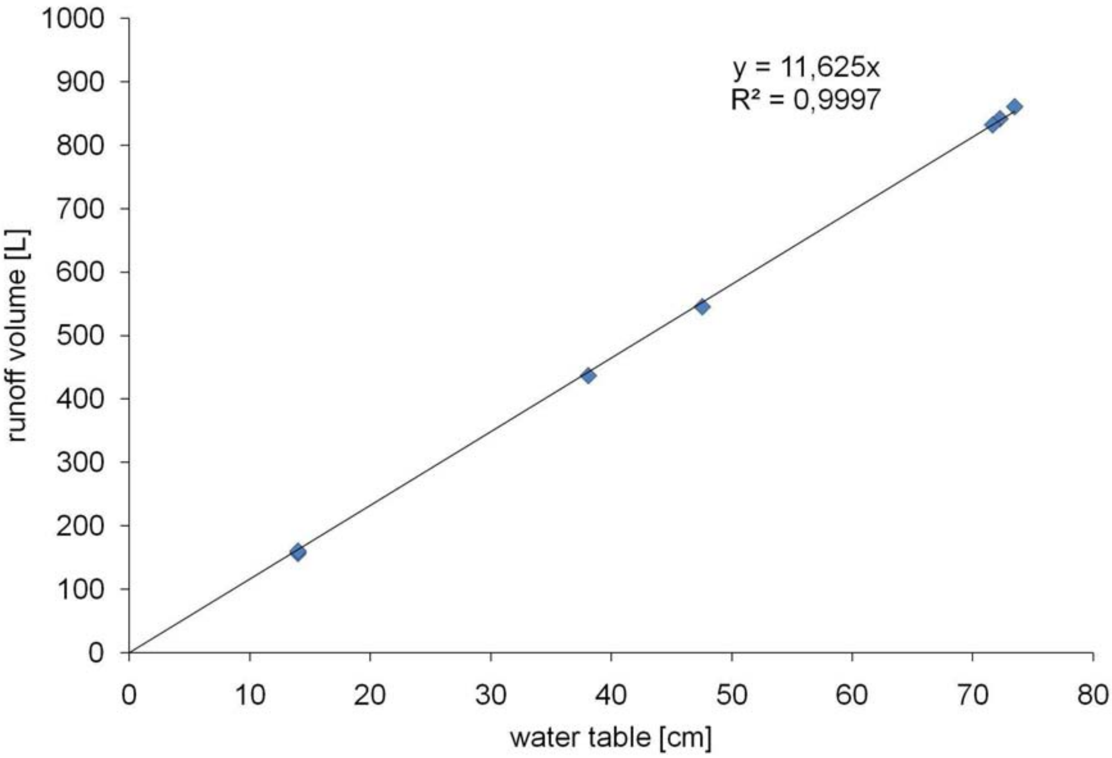


Figure A.1.: Regression line for the water-level-volume relationship of the metal tanks, which were used prior to 1984.

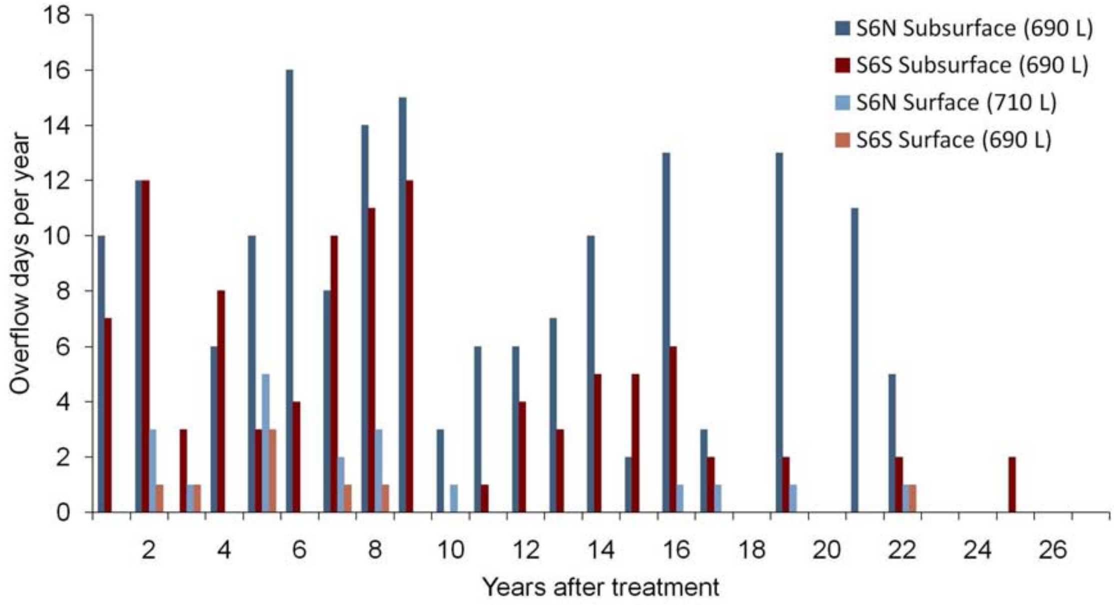


Figure A.2.: Days of overflow per year for each runoff plot at S6. The maximal overflow volumes for each tank are given in the parentheses.

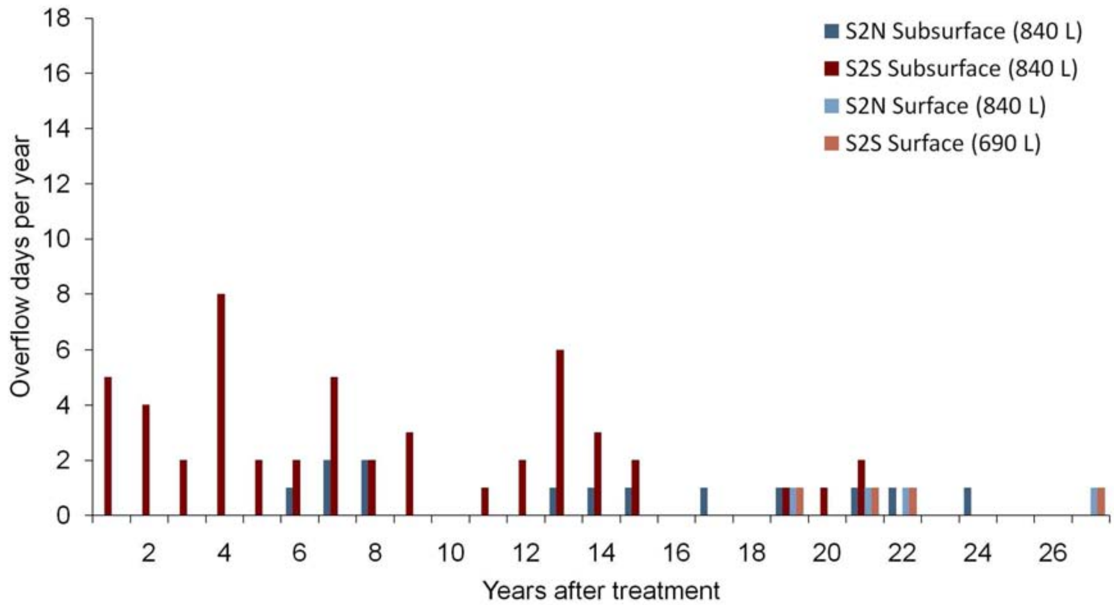


Figure A.3.: Days of overflow per year for each runoff plot at S2. The maximal overflow volumes for each tank are given in the parentheses.

# B. Pictures

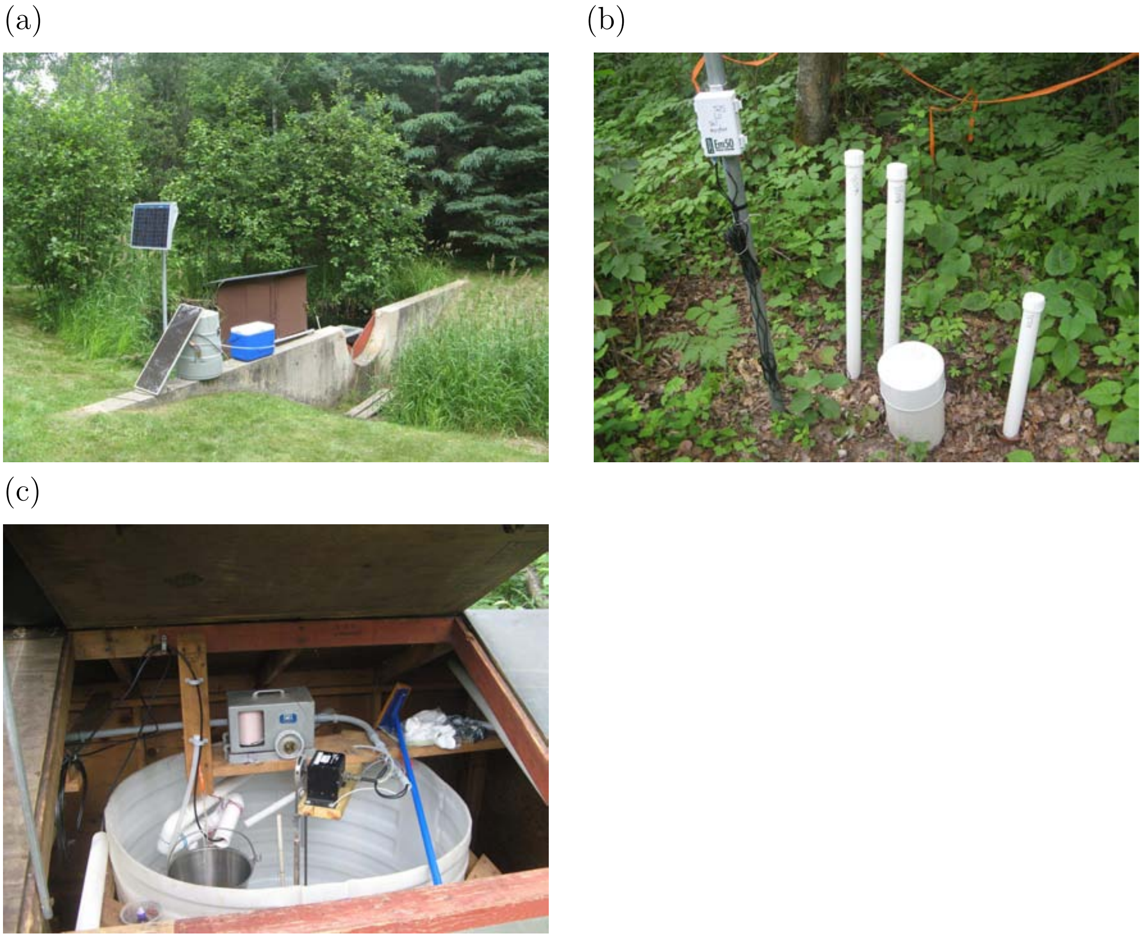


Figure B.1.: Measurements and installations at the MEF: (*a*) V-notch weir at S6, (*b*) Soil moisture measurements at S2, (*c*) subsurface runoff tank at S2 South (*own photographs*).

(a) (b)

Figure B.2.: Measurements and installations at the MEF: (*a*) funnel of the surface runoff collector, (*b*) steel well point to collect subsurface runoff (*source: USDA*).

Figure B.3.: Catchment S6 after harvesting of the upland in 1980 (*source: USDA*).

# Ehrenwörtliche Erklärung

Hiermit erkläre ich, dass die Arbeit selbständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Ort, Datum

Unterschrift