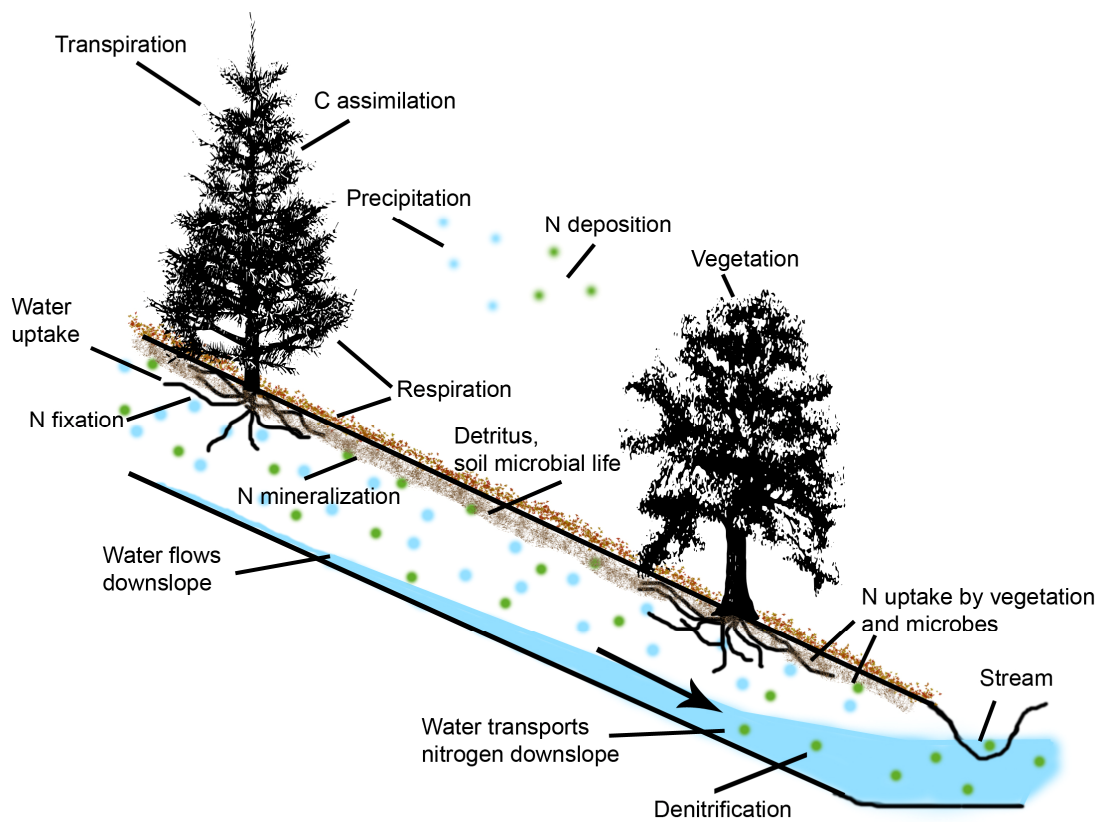


# Interaction between vegetation and lateral nutrient fluxes in a forested watershed A model study



MSc Thesis Hydrology

Sija Stofberg

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Sija F. Stofberg

3173925

28 February 2011

Supervisors:

Dr. K.T. (Karin) Rebel

Prof. dr. ir. M.F.P. (Marc) Bierkens

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## **Abstract**

In terrestrial forest systems, ecology is strongly influenced by hydrological and nutrient fluxes, but the ecosystem itself can control these fluxes as well. A model study was done on a watershed with a temperate forest to investigate if upslope vegetation can control downslope vegetation through the control of water and nutrient fluxes. The ecohydrological 'WALNUTS' (water, nutrients & succession) model was based on three existing models: Water and Tracer Balance (WTB) model (Rebel et al., 2007), Multiple Element Limitation (MEL) ecosystem model (Rastetter et al., 2001) and Brook90 hydrological model (Federer, 2002). The WALNUTS model was parameterized for watershed 3 of Hubbard Brook (NH, USA). A model experiment was done to assess the effects of upslope vegetation on nutrient fluxes and the effects of these fluxes on downslope vegetation at a time scale of several decades.

Result showed that nutrient fluxes downslope could be limited if the upslope ecosystem had limited N output. This should not be attributed to vegetation alone, but also to soil microbial processes and other controls on nutrient transport. Biomass accumulation rates of downslope vegetation were affected by nutrient fluxes; these rates were highest in areas with much inflow of nutrients. Furthermore, a buffering effect was noticed: if upslope areas would export very little nutrients, mid-slope areas would react with increased mineralization, therefore allowing downslope ecosystems to develop at the same rate as ecosystems that received more nutrients from the upslope system.

However, as the results on nutrient transport were not realistic (due to high net mineralization and no retention), the extent of these interactions could not be quantified in a realistic way. Furthermore, the results of the simulations can not be confirmed by observations. Further research is necessary to gain understanding of the interaction between vegetation and nutrient fluxes.

## **Acknowledgements**

I would like to thank the following persons for their ideas and comments when I was conducting my MSc research and writing my thesis. First of all, my supervisor Karin Rebel, who had the idea for building this ecohydrological model and invited me to work on it for my MSc research. Her comments and ideas were very helpful. We met regularly, and after such a meeting I would know how to proceed with problems that I had encountered.

I would like to thank my second supervisor, Marc Bierkens, for giving useful comments on my research and thesis. He provided practical ideas to improve the model and asked challenging questions, of which I regretfully can not answer all in this thesis.

Furthermore, I would like to thank Kevin McGuire, for providing helpful comments on my plans and model results, and especially for useful information about the watershed hydrology and how to model it.

I would like to thank Ed Rastetter, who helped with modelling denitrification and gave me helpful comments on my research progress.

Finally I would like to thank my fellow MSc students, who asked good questions and gave me fresh ideas in our lively discussions during breaks.

## 1. Introduction

Ecosystems, such as temperate forests, can be strongly influenced by the abiotic environment. Hydrological processes and associated nutrient transport can for example determine growth rates of plants and trees. On the other hand, the ecosystem can influence these abiotic processes as well, by taking up water and nutrients and mineralization of detritus. Although ecosystem and abiotic processes are often visualised unconnected, combining these processes provides a more complete view of reality.

Modelling studies of terrestrial nutrient cycles and transport are relevant in several areas of research. For example, it is of interest for climate research, because feedback processes that involve terrestrial vegetation can amplify or weaken the effects of climate change. Heimann & Reichstein (2008) observe in their study the importance of including N related processes in climate change feedback studies. In the review by Campbell et al. (2009) changes in biogeochemical cycles in forested ecosystems are projected, such as an increase of primary production and an increase of nitrate leaching due to changes in temperature. They point out that future research should focus on feedback mechanisms of biogeochemical processes and the climate system. Similar observations have been done by Chen & Coops (2009), who conclude that more research is needed into the coupling of terrestrial C, N and hydrological processes to be able to model realistic climate change feedbacks. On smaller scales, nutrient cycles and fluxes are of interest for nature management, agriculture and water quality management.

Model studies that couple hydrology and biogeochemistry can have several focus points. Catchment studies often focus on groundwater and subsequent nutrient concentrations in river discharge, to assess water contamination risks (e.g. Sebestyen, 2009). Rastetter et al. (2004) observe that many studies focus on stream solutes, rather than on hydrological hillslope processes and the associated effects on the hillslope ecosystems. Ecosystem processes are often simplified or not taken into account. However, the fluxes of water and nutrients are not separate from the ecosystem, as they continuously influence each other, by evapotranspiration of water, and transport and cycling of nutrients.

### *1.1 Hydroecological model studies of catchments*

Rastetter et al. (2004) used a combined hydrological and ecological model to study the effect of climate change on nutrient fluxes and ecology on Arctic hill slopes, with the hypothesis that ecosystems upslope and downslope interact through water and nutrient fluxes, thus making the downslope vegetation dependent on the upslope vegetation. The model they used is the GEM (General Ecosystem Model, Rastetter et al., 2004). They found a higher productivity downslope, not because N concentrations were higher there, but because more water containing N would flow through these plots, thus supplying water and nutrients to depleted soil near the roots. They ran simulations for a hypothetical hillslope and found that climate change would increase carbon biomass, and this increase would be larger downslope. In another simulation they removed 1% of the humus to investigate the time lag of the effects of water and N movement downslope. The results of this model experiment were a good example of an environmental change that triggered upslope processes to affect down slope vegetation through water and nutrient fluxes.

Another study that found interaction between upslope and downslope processes has been done by Cervarolo et al. (2010). They coupled a hydrological model of the unsaturated zone using cellular automata with vegetation models to explore energy and mass (C and water) fluxes in an ecosystem. Their observations show that evapotranspiration (compared to bare soil evaporation) can slow the

propagation of wet fronts in the unsaturated zone down due to water uptake and the reduction of the hydraulic conductivity associated with reduced water content. Their study shows the importance of modelling ecohydrological interactions in a spatially explicit way, as these processes can influence each other profoundly, and cause changes in spatial distribution of hydrological and ecosystem variables.

Govind et al. (2009) developed a model that simulated hydro-ecological and biogeochemical processes, and used it to study hydrological and ecosystem processes at the catchment scale. The ecosystem processes (including C cycles) are modelled in great detail and the hydrological processes included one-dimensional unsaturated zone processes, groundwater, overland and preferential flow in the upper layer. They found that it was necessary to also include N cycles in their model to be able to make valid simulations of vegetation growth. In their conclusions, the authors stress the importance of further research of hydro-ecological interactions on landscape scale, because these interacting processes may have significant effect on C-cycling and thus vegetation growth.

### *1.2 Research goal and question*

In this MSc research, the interaction of nutrient fluxes and ecosystem processes in a forested catchment is studied. It is expected that linking the feedbacks between vegetation and nutrients in a model will lead to different results compared to when these processes are handled separately. Not only do nutrient fluxes control vegetation (and thus C cycling) distribution in the catchment, there is also a feedback effect from vegetation on the distribution of nutrients. Changes in evapotranspiration affect water fluxes and nutrient uptake. This is not only important for short timescales, affecting ecosystem processes down slope, but also on the long term, because it affects future inputs of nutrients through litter, and thus the rate of succession.

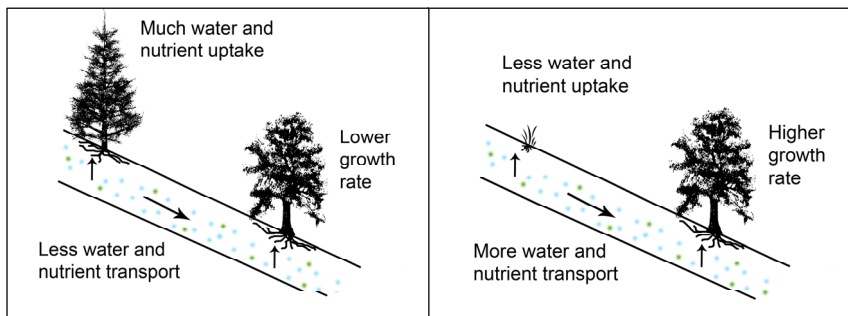
The following research question is formulated:

Does upslope vegetation influence downslope vegetation through the control of water and nutrient fluxes?

Sub questions:

- How does upslope vegetation influence water and nutrient fluxes?
- How do these fluxes influence succession down slope?

The hypothesis is that upslope vegetation can indeed influence downslope vegetation through the control of water and nutrient fluxes. If there is abundant upslope vegetation in the initial conditions, it would take up relatively much water and nutrients, therefore slowing down water and nutrient fluxes down slope. This would decrease biomass accumulation rates down slope compared to the response when no upslope vegetation is present. The hypothesis is illustrated in figures 1a and b.



**Figures 1a (left) and b (right): Hypothesis. a: if an upslope forest takes up relatively much water and nutrients, less water and nutrients will be available for the downslope forest, reducing its growth rate, and on a longer time scale, its succession rate. b: if there is no upslope forest, there will be relatively more water and nutrient movement downslope, positively affecting biomass increase downslope.**

The hypothesis can be weakly tested with a model study, simulating hydrological and nutrient fluxes on the catchment scale (provided that the model is properly validated). The unsaturated zone would be the focus of the study, as this is where the limitation would take place.

To do this, a computer model is used, consisting of the coupling of a spatially explicit hydrology and an ecosystem model. The original models are WTB (Water and Tracer Balance, Rebel et al., 2007) and MEL (Multiple Element Limitation, Rastetter, 2001). An initial coupling was made by van Osch (2009) in her MSc research project. Furthermore, parts of the Brook90 hydrological model (Federer, 2002) are used. The model is parameterized on a catchment of the Hubbard Brook Long Term Ecological Research site (LTER) (New Hampshire, USA), for which a large volume of data is available. As the Hubbard Brook catchments are fully forested, the model run with realistic initial conditions can be compared to a model run without uphill forests. Also, simulations are done with and without the incorporation of lateral nutrient fluxes, so that the effects of lateral flow can be assessed. The biomass accumulation of downslope vegetation of the model runs are compared, as well as nutrient cycling rates and vegetation characteristics (such as C:N ratio).



## 2. Methods

### 2.1 Hydrology and ecosystem models

The Multiple Element Limitation (MEL) model was first developed by Rastetter et al. in 1992 and has been adapted several times since then. The model simulates the way vegetation deals with limitation of growth by several resources in the environment. It is assumed that there is an optimal ratio of these elements that results in optimal growth. However, usually one or more of these elements will be limiting relative to the optimal ratio. To maintain optimal growth, plants have several strategies to gain more of the limiting resource, but the costs of the different strategies have to be taken into account. The model calculates the most efficient uptake strategy that can be used by the vegetation (Rastetter et al., 1992).

Rastetter et al. (2001) incorporated symbiotic N fixation in the MEL model. They assess the relative C costs of N uptake from the soil and N fixation, and limit N fixation to periods when its cost is lower than that of N uptake from the soil. In their assessment of N-uptake costs, they took into account the allocation of resources to the roots or canopy and the openness of the canopy. The model can simulate succession together with the availability of N over time. They found that during early succession species that rely on symbiotic N fixation are more efficient than species that take up N from the soil (Rastetter et al., 2001).

The MEL model is a one dimensional model. To simulate spatial variation explicitly, the interaction between grid cells must be modelled. Rebel and McGuire (2005) combined the MEL model with the hydrological model TOPMODEL. To do this, the yearly MEL model was adapted to have a daily time step. Rebel et al. (2009) consider the inability of TOPMODEL to simulate lateral flow in the unsaturated zone a drawback, because this flux may be an important process in nutrient transport.

Rebel et al. (2007) developed the Water and Tracer Balance model (WTB), a grid-based semi 3d model that simulates the flow of water and tritium activity. The model includes hydrological processes that are important on hill slope scale. It is able to simulate flow of any non-reactive solute vertically through the soil layers and laterally over the hill slope using a bucket approach. To do this, the assumption is made that the solute mixes instantaneously within a cell. Unlike TOPMODEL, lateral flow in the unsaturated zone is included in this model.

Van Osch (2009) made an initial coupling of the WTB hydrological model with the MEL ecosystem model to simulate lateral N fluxes in a forest ecosystem. First the water and nutrient fluxes are simulated. After that, the output is used for a run of the MEL model. This means that the ecosystem processes are dependent on water and nutrient flow, but there is no feedback; the ecosystem does not influence water and nutrient availability. In her model experiment, the lateral fluxes played an important role in redistributing inorganic N down slope, causing less N availability for vegetation upslope. The combined model was not applied on a catchment for which data is available. She suggests a tighter coupling of the two models, by linking more state variables and fluxes such as the plant uptake of nutrients, which is modelled separately in both models.

## 2.2 The WALNUTS model

To study the effects of within watershed nutrient fluxes on succession, the WALNUTS (Water, Nutrients, Succession) model was developed. To be able to simulate possible effects of nutrient fluxes on the rate of succession of forests the model contains saturated and unsaturated water fluxes that transport nutrients vertically and laterally, and a simulation of succession that depends on the availability of nutrients.

The WALNUTS model is a coupling between the WTB (Water and Tracer Balance) model (Rebel et al., 2007) that simulates water fluxes and the MEL (Multiple Element Limitation) model (Rastetter et al, 2001) that simulates succession of ecosystems. Additionally, parts of the Brook90 model (Federer, 2002) have been included to simulate evapotranspiration and snow. In figure 2 a schematic overview of the model processes and their references is shown.

First all variables and parameters are initialized. Then all processes within the dynamic time loop are then run for every cell and this is repeated for all time steps. A time step is one day. Every 365 (or 366 for a leap year) time steps, data is saved, and after the last time loop graphs of all output are created. In the next section, the model processes are described.

## 2.3 WALNUTS model processes

### *Precipitation and snow layer*

Daily precipitation and air temperature data are used to distinguish between rain and snow. After the interception is subtracted, a function is started that calculates the depth of the snow layer, its temperature and the amount of water it can hold. The output of this function is the input of water in the soil, which consists of rain and snowmelt. This function is from the snow subroutine ('SNO') of the BROOK90 model (Federer 2002, see also Federer et al., 2003).

### *Interception*

The simulation of the evaporation of intercepted water is based on the assumption that the amount of water that is intercepted and evaporated in one time step is equal to:

$$\text{Evaporation of intercepted water} = \min(\text{OWE}, \text{PrecL}, \text{MaxInt}) \quad (\text{equation 1})$$

OWE = open water evaporation

PrecL = Precipitation that falls on leaves

MaxInt = LAI (m<sup>2</sup> m<sup>-2</sup>) \* max interception capacity (m m<sup>-2</sup>)

This method is found in Brolsma et al. (2010). Open water evaporation is calculated with the Penmann Monteith equation, using daily data of radiation, vapour pressure and temperature.

### *Potential evapotranspiration*

Potential evapotranspiration is also based on the BROOK90 model (Federer, 2002). It uses the Shuttleworth & Wallace (1985) method to calculate potential evapotranspiration by separating resistances for canopy, leaves and soil. Soil evaporation is not included in the WALNUTS model; it is assumed that soil evaporation is generally low due to a snow layer in winter and a full canopy in summer.

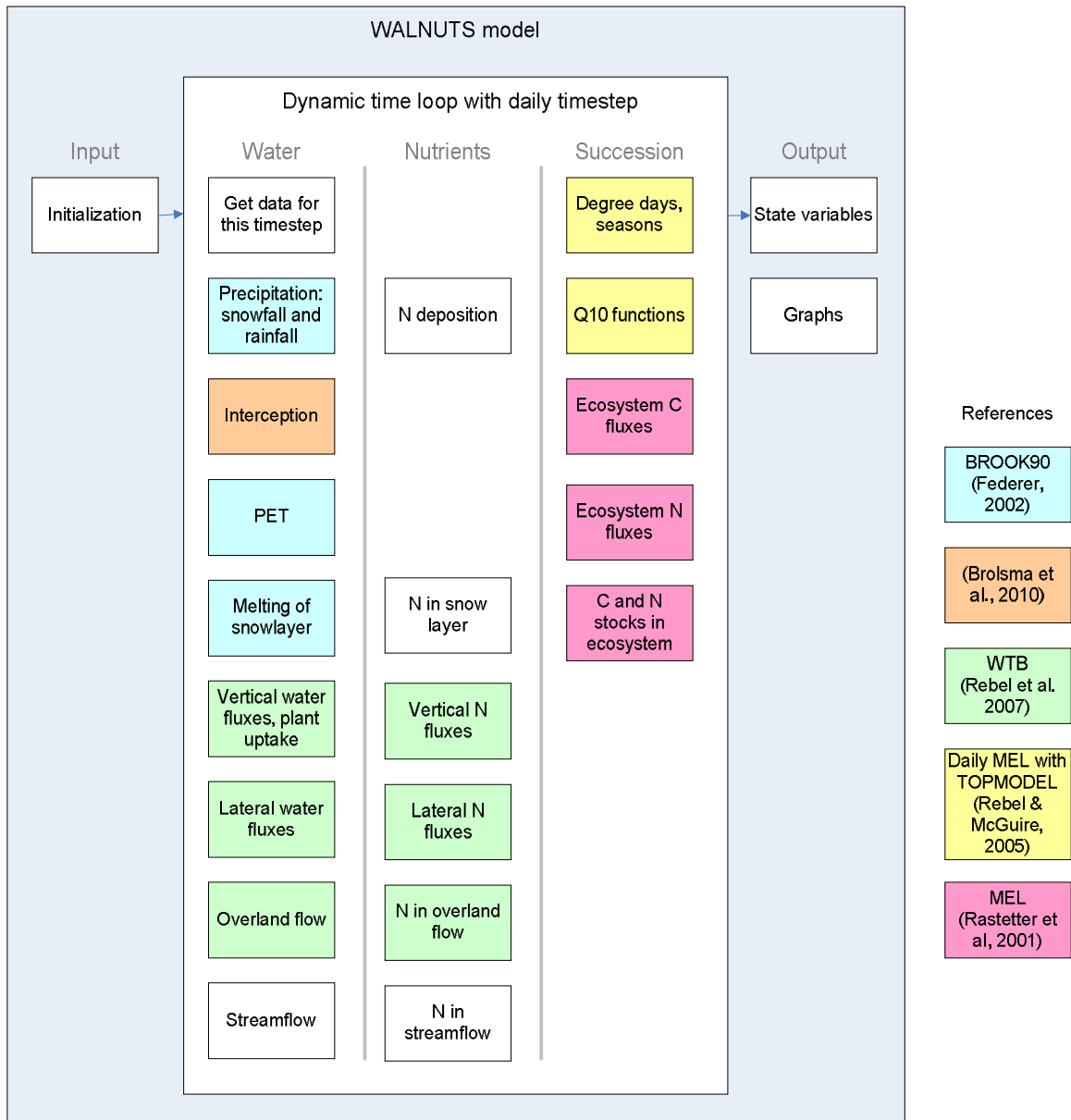


Figure 2: Overview of WALNUTS model processes. Coloured processes are based on models that are referred to at the right.

### *Water fluxes*

For water and nutrient fluxes in the soil, the WTB model by Rebel et al. (2007) is used. Every cell consists of 6 layers of soil for which vertical and lateral flow is calculated. Water uptake in a layer is potential transpiration, weighed with the root fraction and limited by the amount of plant available water (water content minus permanent wilting point). Demand of water that is not met in one layer is transferred to a lower layer.

Water content above field capacity flows to the layer below. If that layer is (or becomes) saturated, saturated flow will occur to the next layer. Unsaturated flow consists of all water content above field capacity flowing downwards at a rate that depends on a vertical drainage coefficient. It is assumed that all vertical flow occurs within one time step.

After calculating vertical flow, the results are used to calculate lateral flow. Lateral flow is simulated in a similar way; water content above field capacity is transported to the next cell according to the local drainage direction (LDD). Saturated and unsaturated flows are not separated: water content above field capacity is transported at a rate that depends on a multiplication of the drainage coefficient (derived from saturated conductivity) and the slope. To save calculation time, the LDD is not based on water table heights (for which the LDD needs to be updated every time step) but on the digital elevation map (DEM). After the simulation of lateral flow, all cells are checked for oversaturation, and surplus water is transferred to higher cells.

### *Overland and stream flow*

In case of oversaturation of the first soil layer, overland flow occurs. It is assumed that overland flow does not infiltrate and reaches the outlet of the watershed within one time step, so any amount of overland flow is added to the daily stream flow.

### *Nutrients in water fluxes*

For all water fluxes that are described above, N loads and concentrations are calculated. Monthly values of N content in precipitation are used to estimate daily N input into the snow layer and soil. When precipitation containing N is added to the snow layer, it is assumed that there is mixing. This means that the N concentration of snowmelt is equal to the average concentration within the snow layer. The same assumption of complete mixing is done for the soil layers. The nutrients are then distributed over the soil layers and to other cells according to water fluxes. However, the ecological part of the model does not distinguish between soil layers. The N content of all layers is summed, and then uptake (vegetation and microbial) and denitrification are subtracted and mineralization is added to the stock. Next, the nitrogen is again distributed over the soil layers in the same ratio it was distributed before.

### *Degree days and Q10 functions*

To be able to use the yearly MEL model with a daily time step, Rebel & McGuire (2005) used a parameterized degree day method to simulate seasonal processes such as the start of leaf growth in spring and when the leaves are fully grown. Start and end of fall (shedding of leaves) are set at a fixed date. Nitrogen fixation costs will only change in summer and litter losses are increased in fall. As some ecosystem processes depend on temperature, Q10 functions are used to estimate respiration rates, N fixation and uptake rates and decomposition rates.

### *Ecosystem fluxes and state variables*

The MEL model (Rastetter et al., 2001) is used to simulate ecosystem processes. It assumes that vegetation aims towards an optimal C:N ratio, and depending on the relative 'cost' of uptake, C assimilation, N uptake or N fixation takes place. The state variables are C and N contents of the different parts of the ecosystem: soil, vegetation and litter. Other state variables are the relative uptake efforts of C and N and the N uptake cost. The change in state variables is approximated by a differential equation solving function that uses a variable time step.

### *Denitrification*

As the MEL model did not include denitrification, this process is added to the model. Denitrification rate is limited by the availability of nitrate and influenced by temperature and soil moisture. The following equation is used:

$$DNtr = aDNtr * WCont * 2^{\frac{Ta}{10}} * \frac{SoilNitrate}{kDNtr + SoilNitrate} \quad (\text{equation 2})$$

(E.B. Rastetter, personal communication). DNtr is the denitrification rate ( $\text{g N m}^{-2} \text{d}^{-1}$ ), aDNtr is the denitrification rate at 0 °C and no nitrate limitation, WCont is the water content of the soil, Ta is the air temperature (°C), SoilNitrate is the nitrate content of the soil, and kDNtr is the half-saturation of soil nitrate.

## 2.4 Study area

The Hubbard Brook LTER site (New Hampshire, USA) has been an experimental area for hydrological and ecological research since 1955. Most of the following information on the area characteristics is based on Campbell et al. (2007). It is a hilly area, completely covered with temperate forest. Its climate is wet (about 1400 mm precipitation per year, with an estimated PET of about 800 (LTER, 2004) and AET of 500 mm) and monthly temperature averages vary from -9°C in winter to 18°C in summer. One third to one quarter of the precipitation is snow; the area is covered with a snowpack from late December to mid-April. The growing season for trees is thought to be from 15 May to 15 September.

The soils consist mainly of well drained spodosols with sandy loam textures that developed from glacial basal till. Soil depths vary with elevation, with an average of 2 meters and a thin organic layer on bedrock on hilltops.

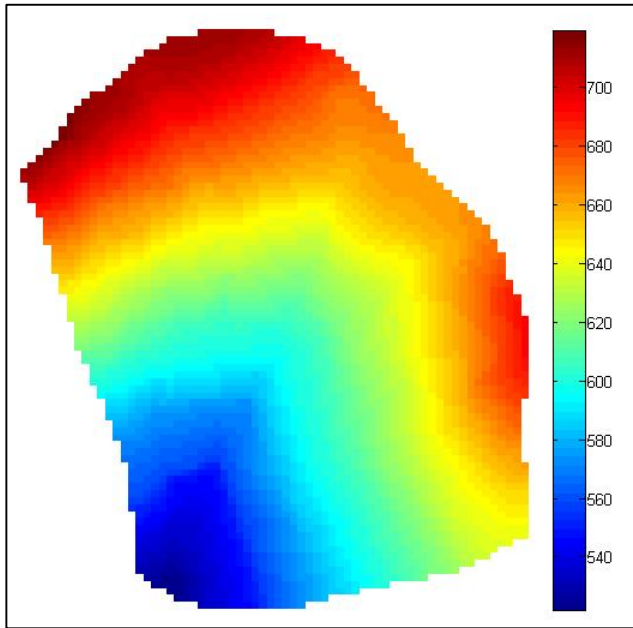
The vegetation varies with elevation. The main part consists of deciduous northern hardwoods, including sugar maple (*Acer saccharum*), beech (*Fagus grandifolia*), and yellow birch (*Betula allegheniensis*) and white ash (*Fraxinus Americana*) on lower and middle slopes. Mainly coniferous species are found on higher elevations and rock outcrops and include red spruce (*Picea rubens*), balsam fir (*Abies balsamea*) and mountain paper birch (*Betula papyrifera* var. *cordifolia*).

The selected study area is watershed 3, which is the hydrological reference watershed. Although hydrological measurements are available of all watersheds, for this watershed additional hydrological information was available.

## 2.5 Input data and parameterization

A 10x10 m digital elevation map (DEM) of 10x10 m of watershed 3 (<http://www.hubbardbrook.org/gis>) is shown in figure 3. From this map, slopes and flow accumulation maps were derived with ArcGIS.

Sets of meteorological data were found on the Hubbard Brook website as well (Bailey, 2010 and Campbell & Bailey, 2010). Data for the years 1966 – 2008 was used. For some of the meteorological data (wind and solar radiation) there were periods of missing data. In these cases, averages for day of year were used as an estimate of the missing data.



**Figure 3: Digital elevation map (DEM) of watershed 3 of Hubbard Brook**

Two of the models that were used, MEL and BROOK90, were already parameterized for Hubbard Brook; these values from literature were used in the WALNUTS model (Rastetter et al., 1997 and 2001; Federer et al., 2002). The parameters of MEL have been adapted by Rebel & McGuire (2005) to use MEL with daily timesteps. Lists of the parameters that were found in literature are shown in appendices A and B.

Layer	Horizon	Depth	Thickness	Ksat	ThetaSat	ThetaFC	PWP	Rootfrac Forest
1	Oa	0.04	0.04	0.44	0.9	0.32	0.1	0.15
2	E	0.06	0.02	0.44	0.61	0.23	0.1	0.07
3	Bh	0.16	0.1	0.22	0.71	0.44	0.1	0.26
4	Bh	0.27	0.11	0.22	0.71	0.44	0.1	0.19
5	B	0.44	0.17	0.22	0.64	0.25	0.1	0.17
6	B	0.6	0.16	0.22	0.64	0.25	0.1	0.16

Table 1: Soil parameters. PWP is taken from (Campbell & Norman, 1998 as found in Hong et al., 2004), root fraction from Jackson et al. (1996), the rest is taken from Detty & McGuire (2010b).

#### Soil parameters and hydrology

Most of the soil parameters ( $k_{sat}$ ,  $\theta_{sat}$ ,  $\theta_{fc}$ ), were taken from literature (Detty & McGuire, 2010b). The value for  $\theta_{pwp}$  was taken from (Campbell & Norman, 1998 as found in Hong et al., 2004). The values are listed in table 1.

Soil depth was set at 60 centimeters, because around that depth a layer is found with a much lower hydraulic conductivity than the overlaying soil (K. McGuire, personal communication). Values for root fraction for a temperate forest have been taken from Jackson et al. (1996), and were adapted to account for a shallower root zone, which is illustrated in figure 4.

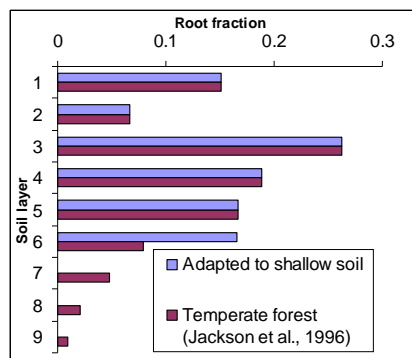


Figure 4: Root fraction per soil layer

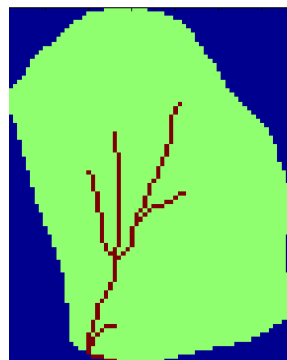


Figure 5: Stream location

Due to the low resolution of the DEM (10 meters) the stream characteristics are lost within the cells. To be able to account for quick stream dynamics, the stream cells are set 1 meter lower than the DEM and the soil depth is multiplied with 0.5. Using ArcGIS, flow accumulation has been determined from the DEM. Every cell that receives water from more than 200 cells (see figure 5) is considered stream in the model.

The resulting hydrograph of a model run of the years 1986 – 1990 was compared to observational data and a sensitivity analysis was done. As the values of the soil parameters are based on point measurements and a large range of values is observed between measurement methods (Detty & McGuire, 2010b), the soil parameters were multiplied with a calibration factor. The calibration factor is the same for all  $\theta$  parameters ( $\theta_{sat}$ ,  $\theta_{fc}$  and  $\theta_{pwp}$ ), as it is assumed that the ratio between the values of the soil parameters remains the same. The parameter  $k_{sat}$  is not used in the model. Instead, a dimensionless drainage coefficient (SWCon and SWConHor, see also Rebel et al., 2007) determines how much of the water flows to the next



layer or cell. To convert  $k_{\text{sat}}$  to the drainage coefficient, it is multiplied with a calibration factor as well.

For calibration, simulations of five years (1986 – 1990) with daily time steps were done. As a simulation of five years took about 15 hours on a quadcore PC, the simulations could not be longer than that. The simulated hydrograph was compared to observational data (Campbell & Bailey, 2010) by determining the Nash-Sutcliffe model efficiency coefficient. The natural logarithm of the discharge data is used to prevent peak data to become too important. The first 150 time steps were not taken into account, to remove the influence of the initial conditions. The calibration was done for combinations of values for the 2 calibration factors that ranged between 0 and 1 with steps of 0.25. Near the optimal values another run of combinations was done with steps of 0.1. Further calibration of the soil and snow related parameters could improve the performance, but this could not be done due to time limitations.

### Phenology

The growing season of the forest is determined by a degree day factor. Leaf area index data of several watersheds were available from the Hubbard Brook website, see figure 6 (Bailey, 2010). The degree day parameters have been fitted to match the average phenology of the measured tree species (American beech, sugar maple and yellow birch), using average temperatures for every day of the year (Campbell & Bailey, 2010). The resulting parameters can be found in table 2.

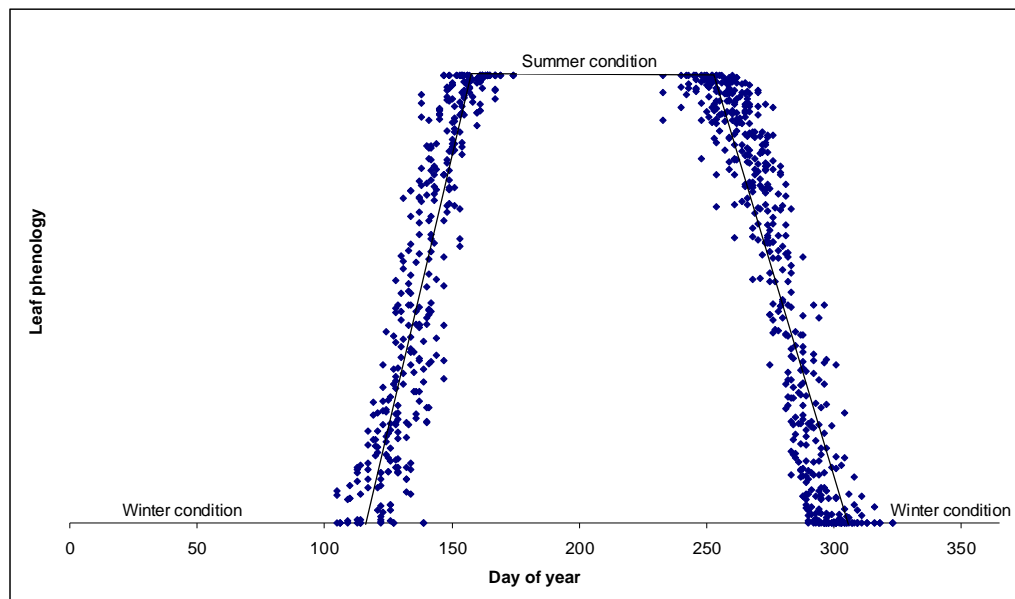


Figure 6: Phenology measurements for various species on various locations in Hubbard Brook (Bailey, 2010). The black line represents the assumed phenology for watershed 3.

Parameter	Value	
JDstart	108	Julian Day start (Start date of counting degree days)
Ddbud	150	Degree Day leaf buds
Ddfull	540	degree day full leaves
JDfallstart	252	Julian Day start of fall
JDfallend	302	Julian Day end of fall

Table 2: Phenology parameters

### Denitrification

Groffman et al. (2001) found denitrification rates of 0 to 0.65 g N m<sup>-2</sup> y<sup>-1</sup> for Hubbard Brook. As the simulated outflow of nutrients was very high, denitrification parameters were set to result in an average rate of 0.65 g N m<sup>-2</sup> y<sup>-1</sup>.

Soil chemistry data from the Hubbard Brook website (Driscoll, 2010) were used to determine the average *nitrate N: total N* ratio, which is used to estimate the nitrate content of the soil. The value for kDNtr, the half saturation parameter, is chosen by assuming that saturation would occur at the steady state N content of the soil (which is 2.6 g N m<sup>-2</sup> according to Rastetter et al. (2001)) and the value of aDNtr is fitted to result in the expected yearly denitrification rate.

Parameter	Value	
aDNtr	0.008 g N m <sup>-2</sup> y <sup>-1</sup>	Rate
kDNtr	0.0962 g N m <sup>-2</sup>	Half saturation
NitrateFraction	0.074	Nitrate N : Total N ratio

## 2.6 Model experiment

For the virtual experiment, three model simulations are conducted. The purpose is to identify the effects of upslope vegetation on lateral nutrient fluxes and the effects of lateral nutrient fluxes on downslope vegetation.

In simulation 1, the 'complete' simulation, the model is run with all the processes that were described. As the watershed is forested, initial conditions include a full forest cover. In simulation 2, lateral N flow will not occur. In the model, these fluxes will be set to zero. This means that N will not be transported by water through the soil. However, it can be transported out of the soil by overland flow, which occurs near the stream. Other parameters and initial conditions will be the same as in simulation 1. Comparing these two simulations can give insight in the effect of lateral N fluxes.

In simulation 3 the effect of uphill vegetation will be focused on. All parameters remain the same as simulation 1, but there is a difference in initial conditions: the watershed is not completely forested. Upslope areas will have a very low biomass, as if its vegetation is at an early stage of succession. Figure 7 is an illustration of the initial conditions. Table 3 shows an overview of the model experiment.

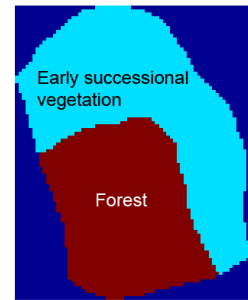


Figure 7: Initial conditions of simulation 3

Simulation	Initial vegetation	Lateral N fluxes	
1. Complete	Realistic vegetation	Yes	<p>Simulation 1</p>
2. No lateral N flux	Realistic vegetation	No	<p>Simulation 2</p>
3. No uphill forest	No forest on higher elevations	Yes	<p>Simulation 3</p>

Table 3: Simulations of the model experiment

The initial conditions that are not related to biomass are the same for all simulations, and are shown in table 4. The initial biomass values (table 5) are used to distinguish between forest and early successional vegetation. The values of all initial conditions (except for water content) are based on papers by Rastetter et al. (2001 and 1997).

Variable	Initial value
Water content	Field capacity
Soil nitrogen content	1 g N m <sup>-2</sup>
C uptake effort	0.5
N uptake cost	10 g C g <sup>-1</sup> N

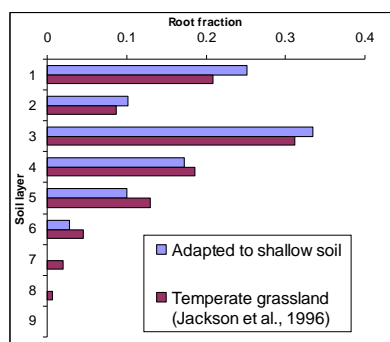
**Table 4: Initial conditions of all simulations (Rastetter et al, 1997 and 2001).**

Variable	Forest	No forest	Description
Y2	22000	22	C in plant biomass (g C m <sup>-2</sup> )
Y3	154	0.11	N in plant biomass (g N m <sup>-2</sup> )
Y4	13000	13	C in soil detritus (g C m <sup>-2</sup> )
Y5	521	0.04	N in soil detritus (g N m <sup>-2</sup> )

**Table 5: Ecosystem initial conditions for forested areas and early successional vegetation (Rastetter et al, 1997 and 2001).**

To run the model for an area with early successional vegetation, some parameters needed to be adapted. The chosen values are literature values based on small vegetation such as grassland, although in reality early successional vegetation may consist of other species. However, for the purpose of this simulation, rough parameter estimates should be sufficient.

For root fraction per soil layer (figure 8), the distribution for temperate grassland (Jackson et al, 1996) was used and adapted for shallow soil depth. For canopy height an estimated value of 0.3 meters was taken and albedo was set at 0.25. For ratio of leaf area to projection a value of 20 was used and a value of 0.5 cm for leaf width. Light extinction coefficient is set at 0.9 and aerodynamic resistance to 208/wind speed (value for grass, FAO, 2010).



**Figure 8: Assumed root distribution of early successional vegetation.**

### 3. Results

#### 3.1 Sensitivity analysis

After the model was made and parameterized, its performance was tested and compared to observational data of watershed 3 of Hubbard Brook. General model behaviour will be discussed in the next section, but first the results of the sensitivity analysis will be shown.

Soil parameters were considered uncertain because they were based on point measurements, and since the resulting hydrograph could be compared to observations (Campbell & Bailey, 2010), a sensitivity analysis was done to identify the most important parameters that influence performance.

The model was run for 5 years with soil parameter values that were changed +25% and -25% while the other parameter values remained the same. The resulting hydrograph was assessed using the Nash-Sutcliffe model efficiency coefficient. As the watershed is small, there are relatively large differences between peak values and baseflow, so the natural logarithm of the hydrograph was taken to limit the influence of these large differences.

The results of the sensitivity analysis are shown in figure 9. It shows that the model performs better with higher values for  $\theta_{fc}$  (field capacity), lower values of  $\theta_{sat}$  (saturation) and lower values of the horizontal drainage coefficient (which has the same value as saturated conductivity (m/d)) and soil depth. In other words, if the area through which the water can flow becomes smaller, the hydrograph becomes more realistic.

Although the stream location varies throughout the year (Kevin McGuire, personal communication), the stream location in the model is fixed to the cells that receive water from more than 200 cells as was explained in Methods. However, the results are not sensitive to this parameter.

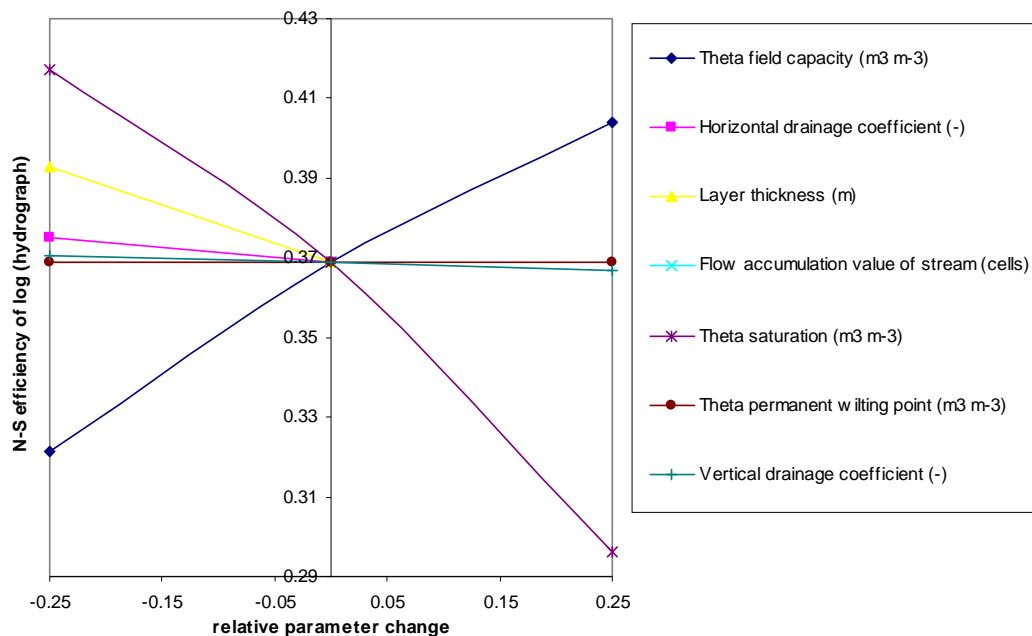


Figure 9: Nash-Sutcliffe efficiency of the hydrograph for simulations with soil parameter variations of -25% and +25%.

As was described in Methods, some of the soil parameters are multiplied with a calibration factor in order to account for uncertainties and to convert the parameter for saturated conductivity into a dimensionless drainage coefficient. From the sensitivity analysis it was clear that reducing the difference between  $\theta_{\text{sat}}$  and  $\theta_{\text{FC}}$  would result in a better performance, as well as reducing the value of the drainage coefficients. Calibration of soil  $\theta$  and drainage parameters resulted in the following values:

*Calibration factor of drainage coefficient = 0.75*

*Calibration factor of theta parameters = 0.5*

The upper calibration factor is multiplied with the drainage coefficient (which had the value of saturated conductivity). The second is multiplied with all soil moisture parameters:  $\theta_{\text{sat}}$  (saturation),  $\theta_{\text{FC}}$  (field capacity) and  $\theta_{\text{PWP}}$  (permanent wilting point). Multiplying the parameters with these calibration factors resulted in a better performance of the hydrograph.

### 3.2 Model behaviour

When running the model a stream pattern emerges in cells with high water contents, where often overland flow occurs, as is shown in figure 10. It can be seen that the LDD map does not function properly for all areas as water is retained in some of the upper cells. This is clarified by figure 11, in which the cells that do not receive water and nutrients from other cells are highlighted in yellow.

Figure 12 shows the distribution of N concentration within the soil solution over the catchment. As the lateral water flow transports nutrients, the cells near the stream have a higher nitrogen concentration.

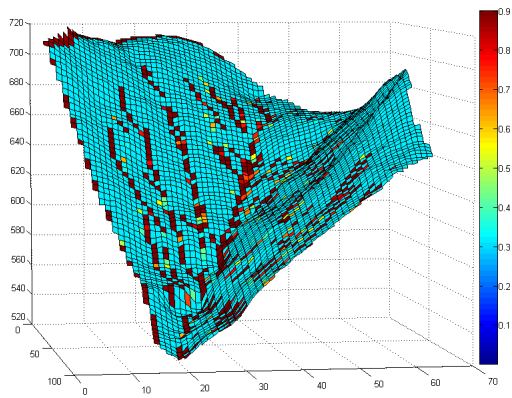


Figure 10: Average water content ( $\text{m}^3 \text{m}^{-3}$ ).

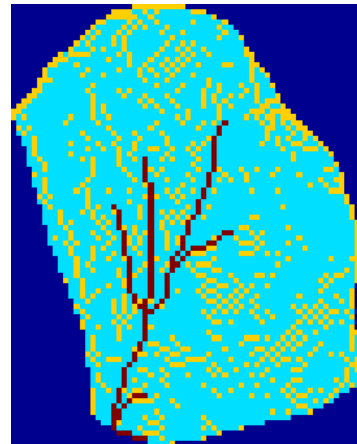


Figure 11: Cells that receive no lateral flow are highlighted in yellow. The stream cells are dark brown.

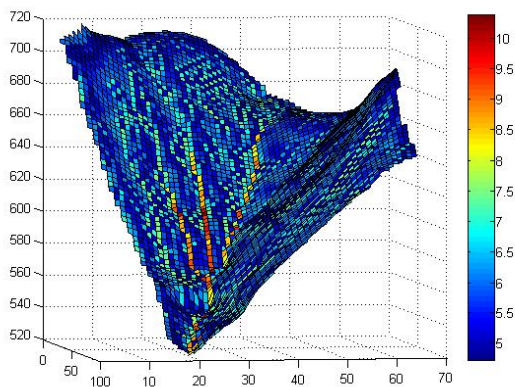
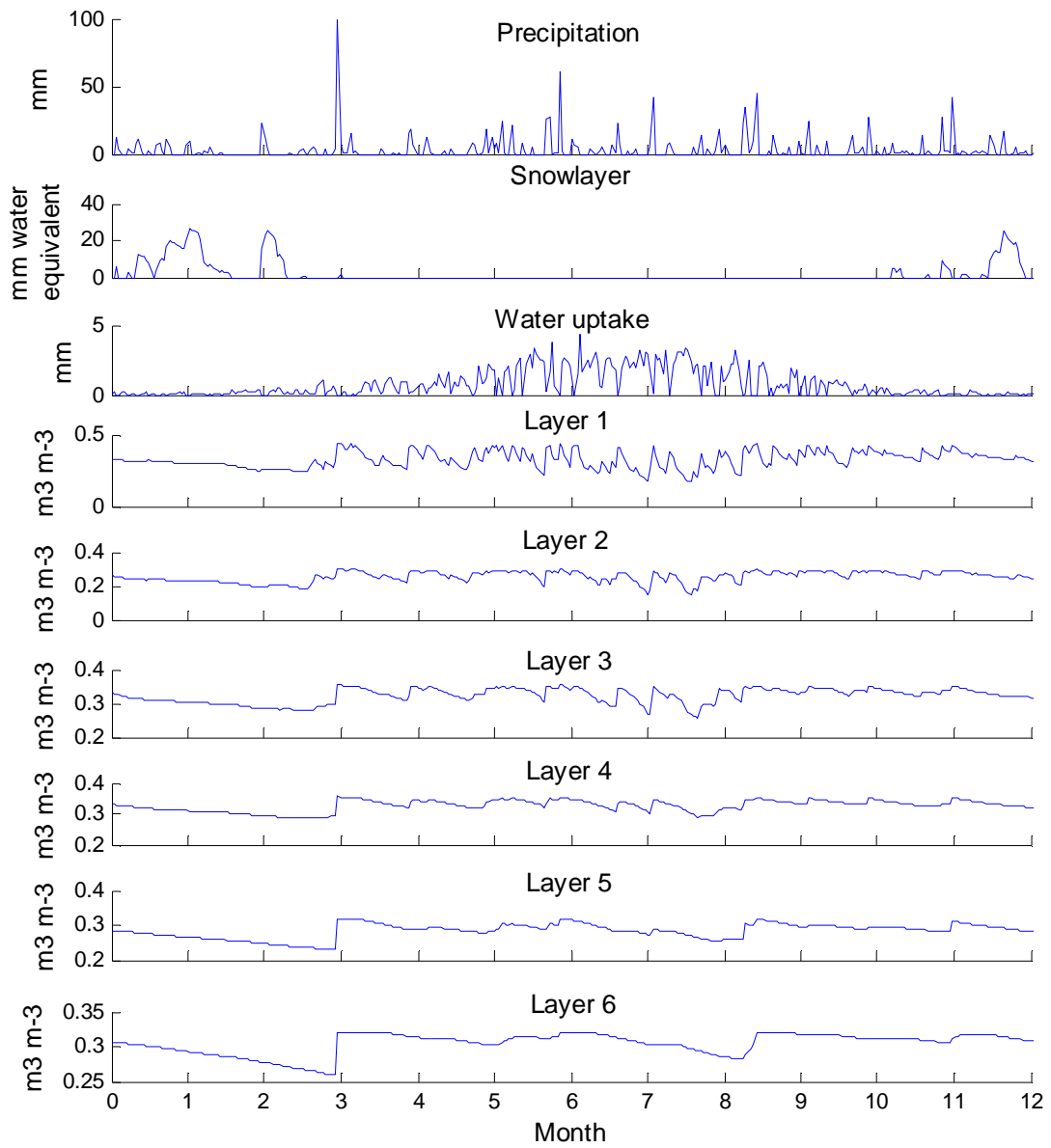


Figure 12: N concentration ( $\text{mg N l}^{-1}$ )

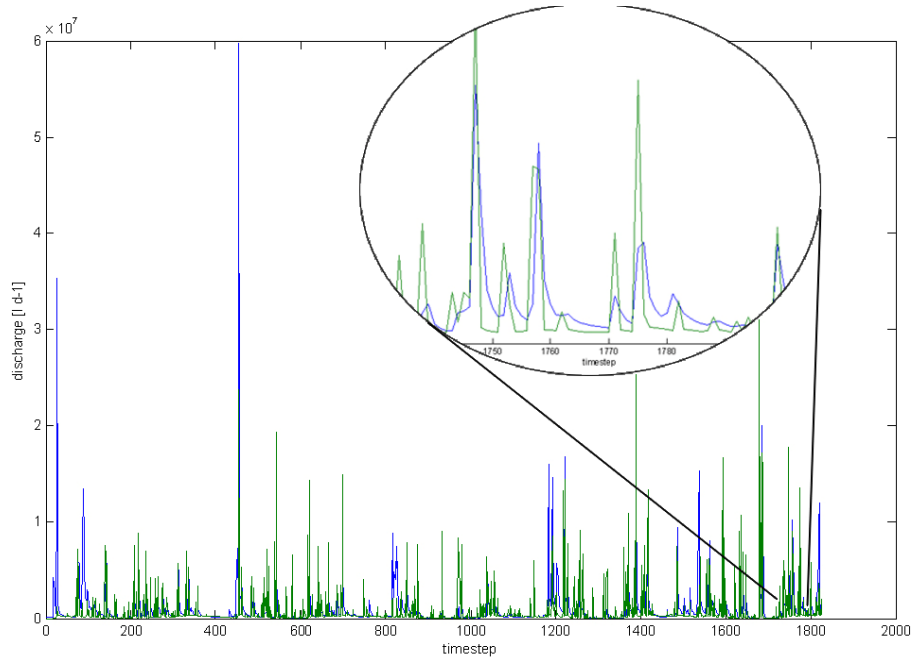
Figure 13 shows precipitation, average snow layer, average water uptake and water contents of the six soil layers over time for 1987. In the summer and autumn seasons, when irregular precipitation enters the soil immediately, the upper soil layers react much more quickly than the deeper soil layers.



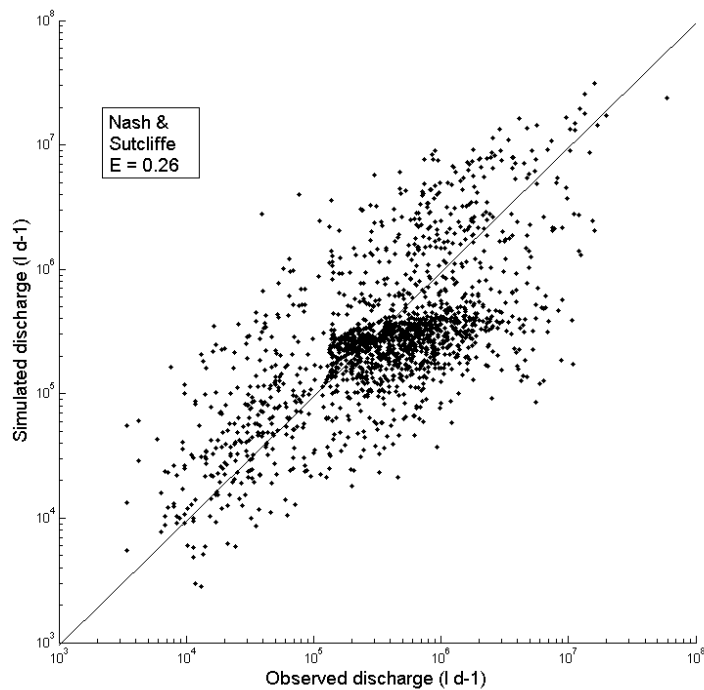
**Figure 13: Graphs of precipitation (Campbell & Bailey, 2010) and simulation results that are averaged over the watershed: snow layer (in mm water equivalent), water uptake (mm) and water content of soil layers (in  $\text{m}^3 \text{m}^{-3}$ ) in 1987.**



Figure 14 shows the observed and simulated hydrographs. The largest errors occur in early spring during snowmelt events due to an underestimation of snowmelt. The model performance of the simulated against the observed hydrograph is plotted in figure 15. The Nash-Sutcliffe model efficiency coefficient is 0.26.



**Figure 14:** Observed (blue, Campbell & Bailey, 2010) and simulated (green) hydrographs for 1986 – 1990.



**Figure 15:** Simulated vs. observed discharge (log scale) for a 5 year simulation (1986-1990). The black line is the 1:1 line.

Figures 16 and 17 show the most important ecosystem C and N fluxes over the year (in this case 1987), averaged over the watershed. Gross photosynthesis is the largest C flux and occurs during the growing season, as it depends on leaves. The process rate increases with air temperature and the amount of incoming radiation. Plant respiration occurs throughout the year and increases with air temperature as well. Microbial respiration depends on soil temperature, which is why there is a lag between the peaks of plant and microbial respiration.

N uptake by plants depends on temperature, fine root length and N availability. In the model, fine root length is an indicator of how much energy the plant 'invests' in taking up nutrients. N uptake by soil organisms depends on temperature and availability, but also on the C:N ratio, which is aimed towards an optimum value. Mineralization of N depends on the N content of the detritus, optimal C:N ratio and temperature. The smallest ecosystem N flux is denitrification. It depends on temperature, N availability and soil moisture. Note that although all fluxes are positive, mineralization is a process that adds N to the soil solution, while uptake and denitrification remove N from the soil.

For comparison, figure 18 shows the average N input in the soil from deposition. The flux of atmospheric deposition is relatively low compared to most of the ecosystem N fluxes.

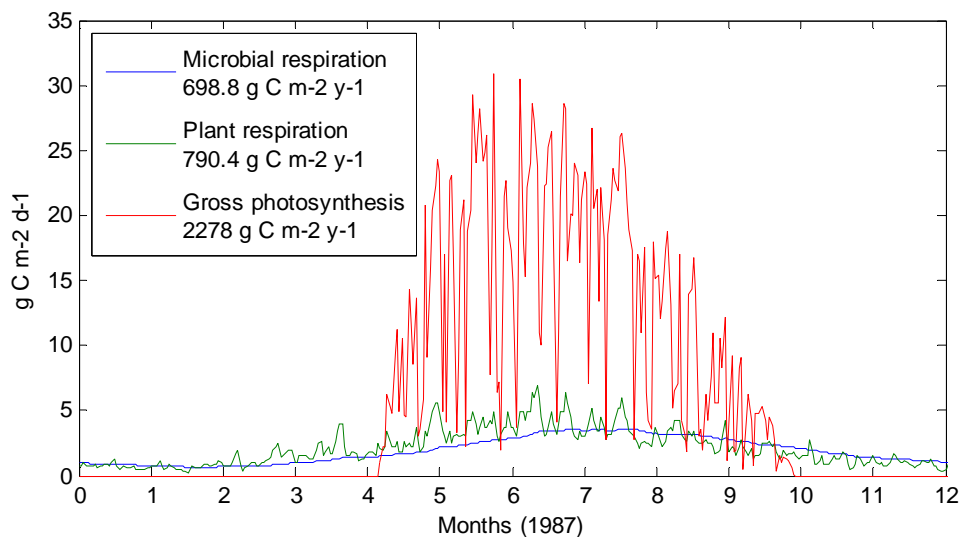


Figure 16: Ecosystem C fluxes per day. The legend shows yearly values for 1987.

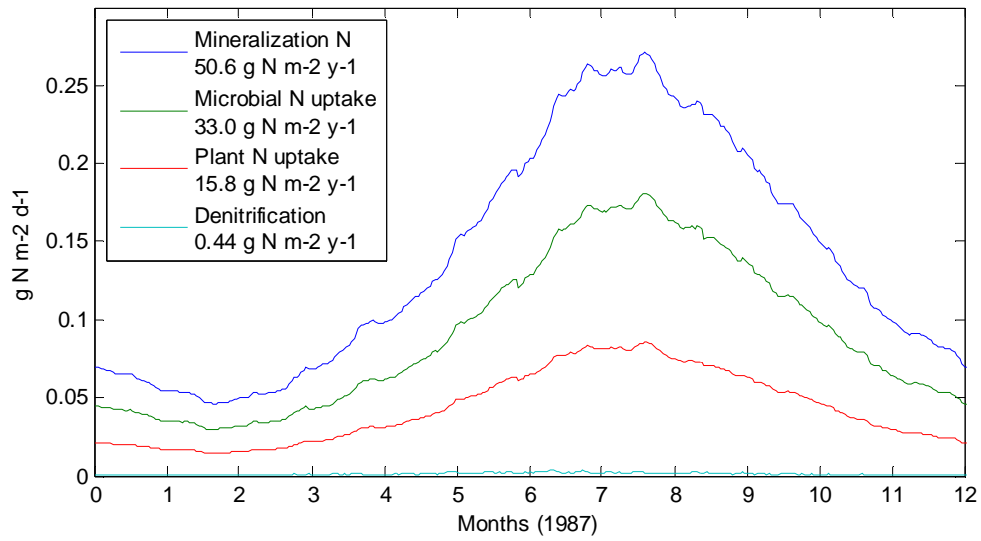


Figure 17: Ecosystem N fluxes per day. The legend shows yearly values for 1987.

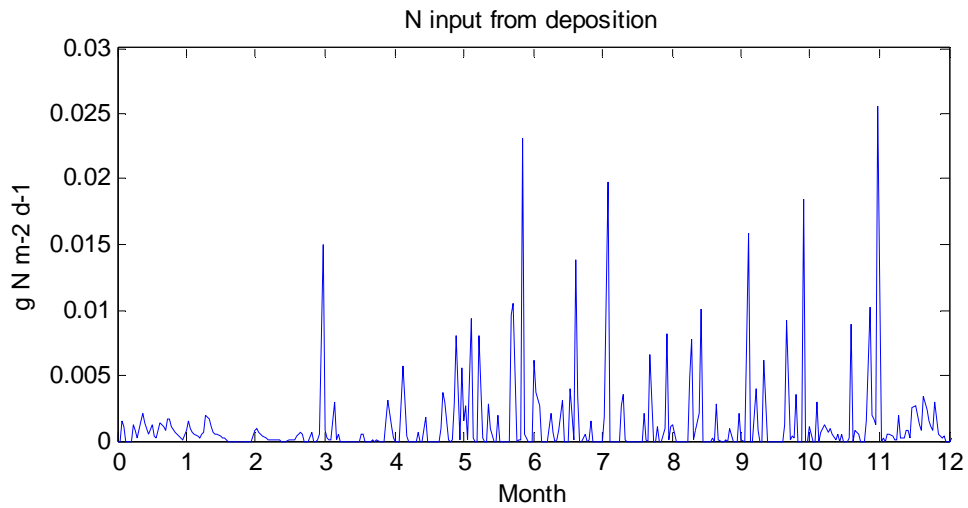


Figure 18: Soil N input from deposition in 1987. In winter, input is relatively low due to the snow cover. Total N input from deposition is 0.4593 g N m<sup>-2</sup> y<sup>-1</sup> in 1987, which is lower than most years (average is 0.59 g N m<sup>-2</sup> y<sup>-1</sup>).

The seasonal ecosystem processes and the lateral fluxes of nutrients result in an output concentration of nitrogen in the stream. It is clear from figure 19 that the simulated concentration is most of the time an order of magnitude higher than observed concentrations. The cause of this difference is that mineralization is more than uptake, as is shown in figure 20. The net mineralized nitrogen is then transported through the watershed into the stream. This imbalance is observed in all results of the 42 simulated years.

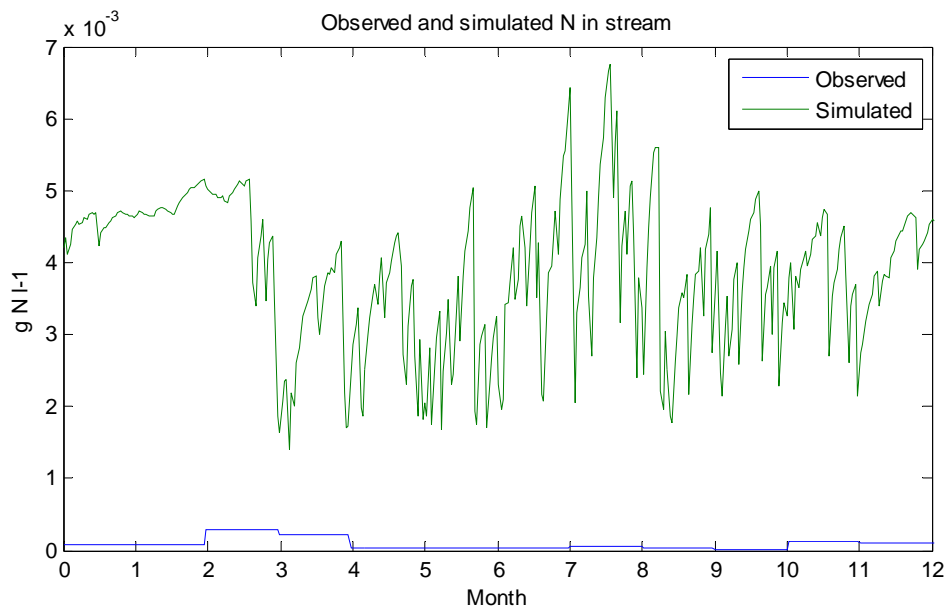


Figure 19: Observed (Likens, 2010) and simulated nitrogen concentration in the stream ( $\text{g l}^{-1}$ ) in 1987. Observational data consist of monthly averages based on weekly measurements.

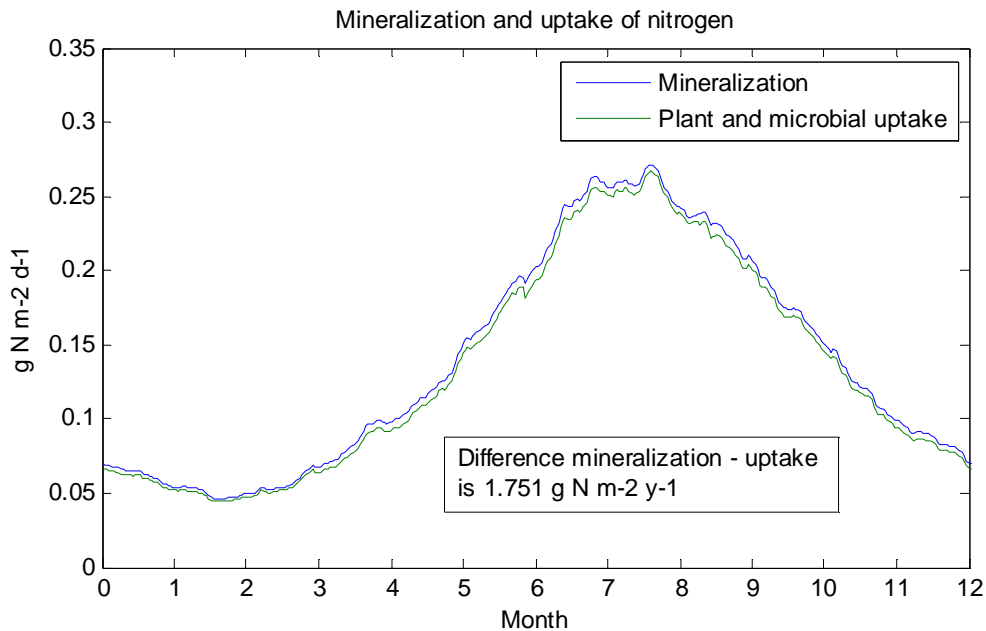
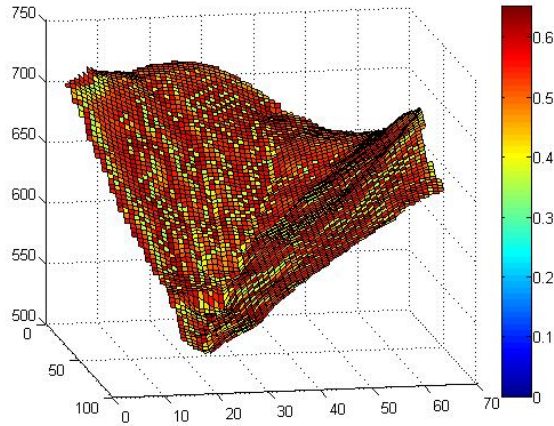
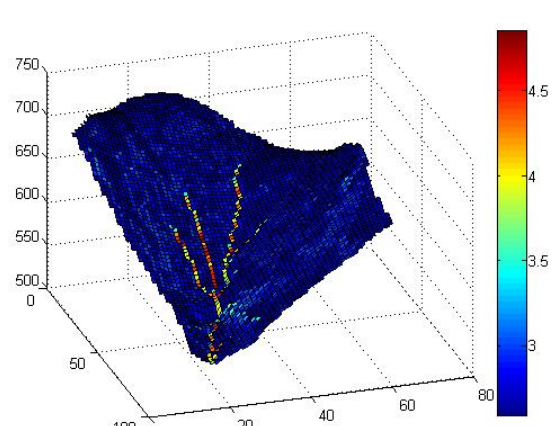


Figure 20: Mineralization and plant and microbial uptake in 1987

### 3.3 Simulation 1: Complete

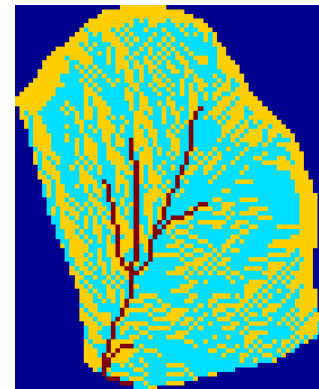


**Figure 21: Soil inorganic nitrogen content (g N m<sup>-2</sup>) after 42 years of simulation.**

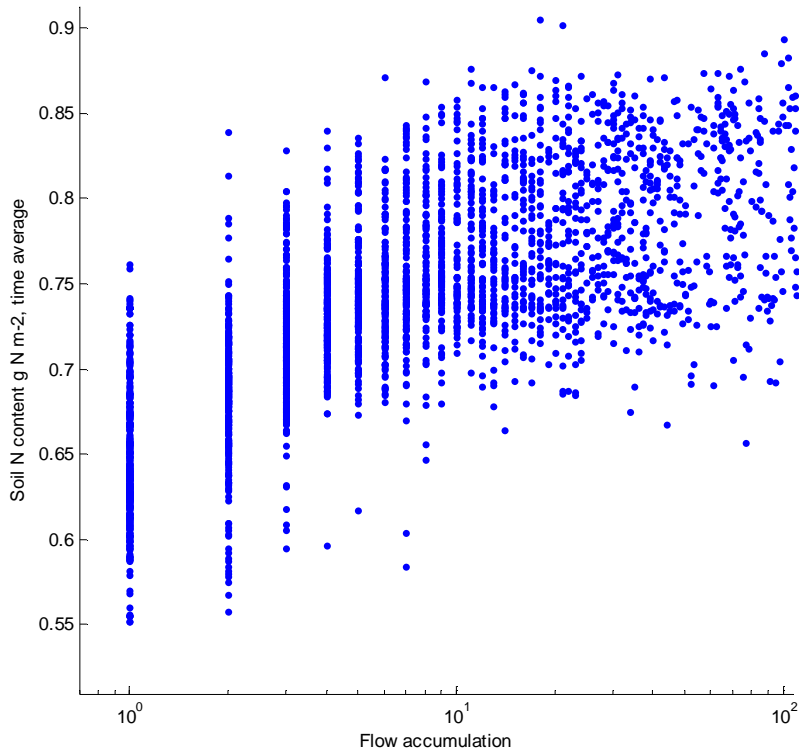


**Figure 22: Inorganic nitrogen concentration (mg l<sup>-1</sup>) in soil moisture after 42 years of simulation.**

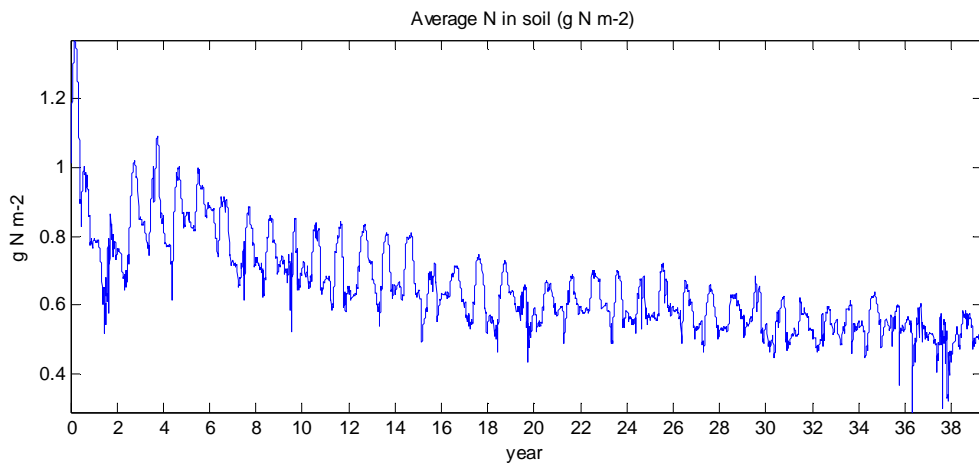
The simulation has been run for the available input data timeseries. Figures 21 and 22 show the soil inorganic N content and concentration after the complete simulation of 42 years (1966 – 2008). Inorganic nitrogen is distributed unevenly over the catchments due to lateral flow and ecosystem processes. Some cells in steep areas have a very low N content because they receive no lateral water and nutrient flow from cells above. There is no clear relation visible between altitude and inorganic N content, but the pattern seems more related to flow accumulation. For comparison, figure 23 shows the areas with a flow accumulation value of less than 4 cells. Its correlation with soil N content is plotted in figure 24. For cells that receive water from less than 10 cells, soil inorganic N content is lower.



**Figure 23: Flow accumulation of less than 4 cells (yellow).**



**Figure 24: Scatter plot of soil nitrogen content vs. flow accumulation (cells).**



**Figure 25: Average soil N content (g N m<sup>-2</sup>) for the whole watershed against time.**

The average N content for the whole watershed (figure 25) has decreased from 1 g N m<sup>-2</sup> (initial condition) to 0.5 g N m<sup>-2</sup>. The yearly variation shows a peak in summer and autumn, which is caused by a relatively high net mineralization rate. In winter and spring the soil N content becomes lower, as nutrients are transported away by snowmelt.

Figure 26 shows the sources of N input in the soil, and allows a comparison between them to see which processes determine input of nitrogen the most. Inputs from the ecosystem (net mineralization) is the largest source and accounts for 53% of the total N input (average for the whole simulation). The relative N input by lateral flow is 29% of the input, leaving deposition to be the smallest input flux.

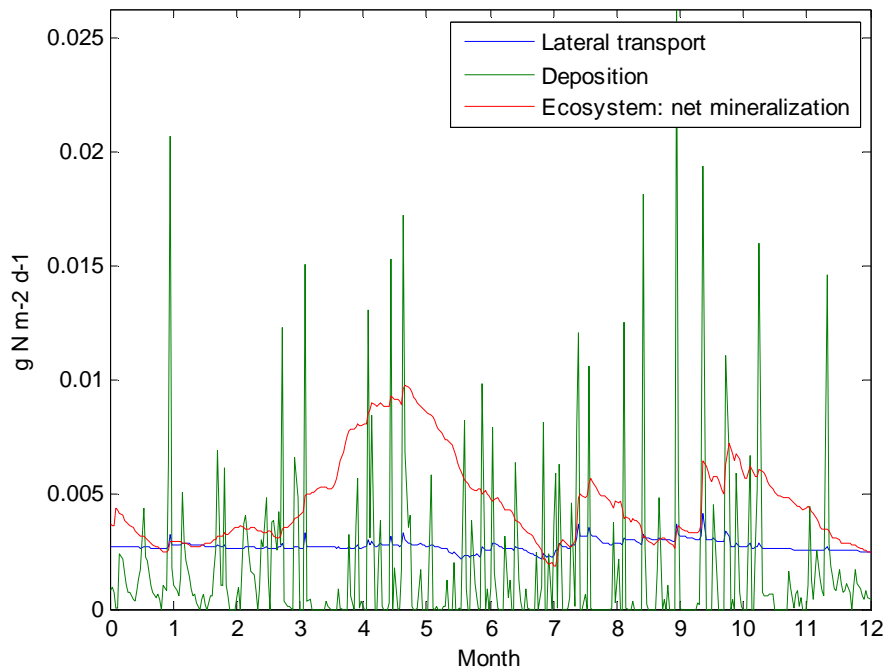


Figure 26: Soil N input sources ( $\text{g N m}^{-2} \text{d}^{-1}$ ), average for all cells for 1 year.

As net mineralization is such an important control of inorganic nitrogen input, a further look is taken at its spatial distribution. Net mineralization rates seem to be highest in areas that receive water and nutrients from very few cells (which are the cells with the lowest inorganic N content), and by that, they are correlated with soil water content (figure 27) and C: N ratios (which will be discussed next).

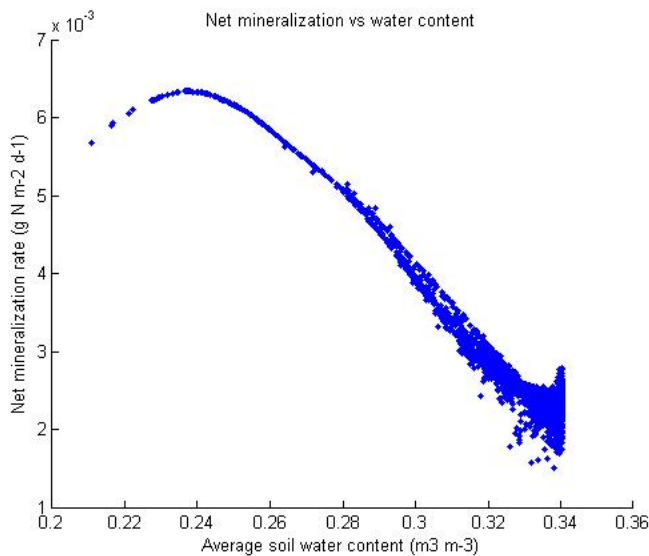


Figure 27: Net mineralization vs average water content.

The vegetation biomass (C and N in  $\text{g m}^{-2}$ ) has grown over the whole catchments, but not at the same rate in every cell. The biomass distribution (figure 28) shows the same pattern as soil N content; the more a cell receives water and nutrients from uphill cells, the more vegetation biomass has grown over the years. Vegetation C:N ratio average has decreased from its initial value of 200 and seems to be in equilibrium at a value of 159. Relative carbon uptake effort has decreased and shifts around a value of 0.3, which indicates more effort is put in the uptake of nitrogen.

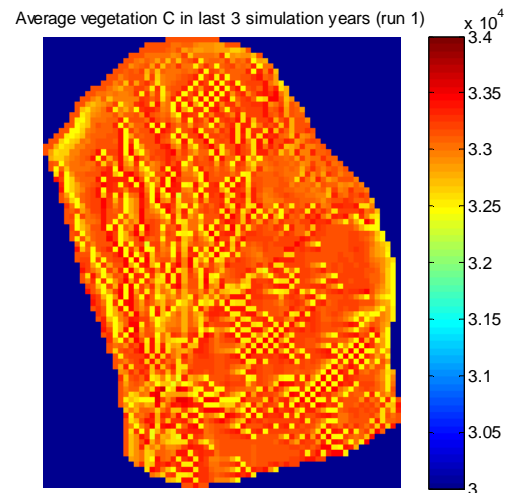


Figure 28: Vegetation C ( $\text{g C m}^{-2}$ ).

During the simulation years the detritus carbon mass has increased while the nitrogen mass has decreased which resulted in an increasing average C:N ratio of 34 that has not reached equilibrium within the simulation run. The detritus mass distribution over the catchment is similar to the soil N and vegetation biomass distribution. Figure 29 a - d shows the averages (over the watershed) for the ecosystem variables over time. There is very little difference between up and downslope development. In comparison, figure 30 a-d shows the same variables but the averages of areas with little flow accumulation ( $\leq 3$ ) are compared to areas that receive flow from more upslope cells. In this comparison, a significant difference is observed, which is consistent with the distribution patterns of soil nitrogen content.

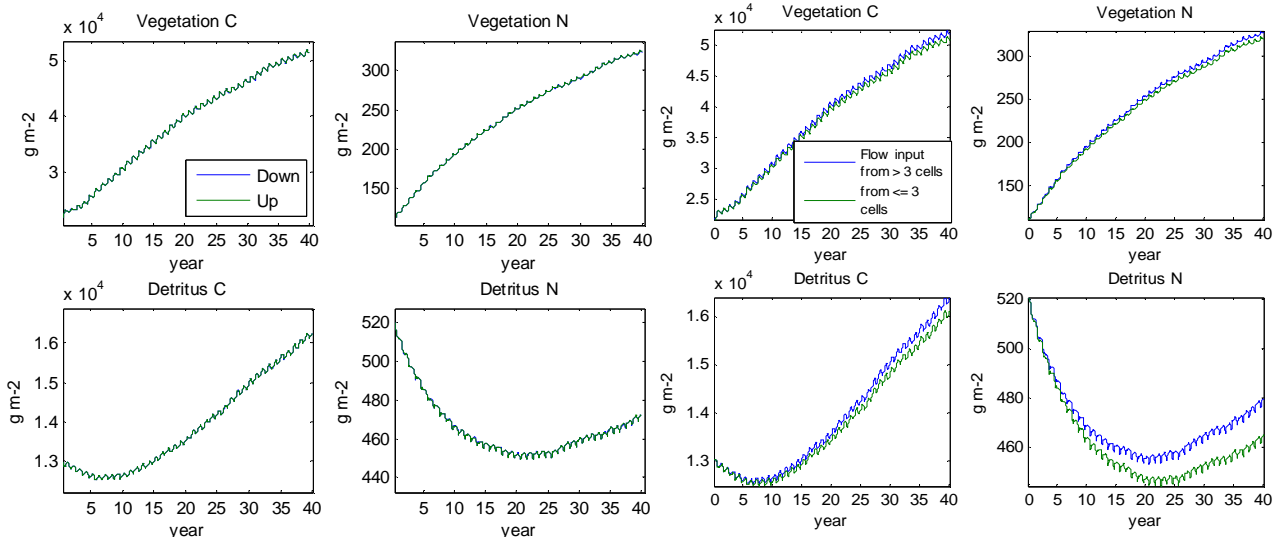


Figure 29 a-d. Ecosystem variables. Averages for the up ( $> 630$  m, green) and down slope (blue) areas of the watershed. As values for upslope and downslope are practically the same, no difference is observed.

Figure 30 a-d: Ecosystem variables. Averages for areas with inflow from less than 4 cells (green) and inflow from 4 or more cells (blue). When there is



### 3.4 Simulation 2: No lateral N fluxes

The results from the simulation with no lateral N fluxes show a different distribution of nitrogen in the watershed (see figure 31). Figure 32 shows the difference with the complete run (the map of simulation 2 is subtracted from the map of simulation 1). Lateral water fluxes do not transport nutrients to other cells, but nutrient outflow could still occur due to overland flow. This process explains the relatively high nitrogen content of the upper parts of the watershed and low nitrogen content in near-stream areas. Vegetation biomass and detritus are similarly distributed, as well as their differences with the results of simulation 1.

Figures 33 and 34 show the net mineralization rate (mineralization minus plant and microbial uptake) and the difference with the net mineralization of simulation 1. In the areas with a high soil N content, net mineralization is relatively low.

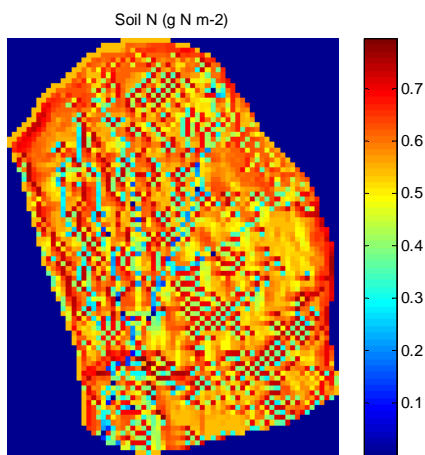


Figure 31: Soil nitrogen (g N m<sup>-2</sup>) after a 42 year run with no lateral N fluxes.

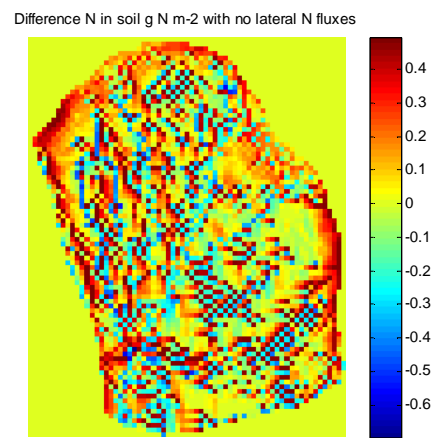


Figure 32: Difference in soil N content (g N m<sup>-2</sup>) between simulation 1 (with lateral N fluxes) and simulation 2 (no lateral N fluxes) .

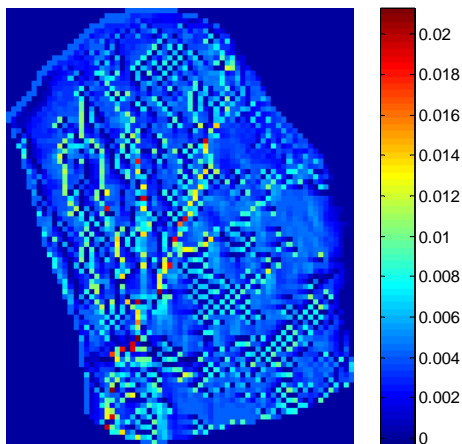


Figure 33: Net mineralization rate (g N m<sup>-2</sup> d<sup>-1</sup>). Net mineralization is relatively high in areas with low soil N content.

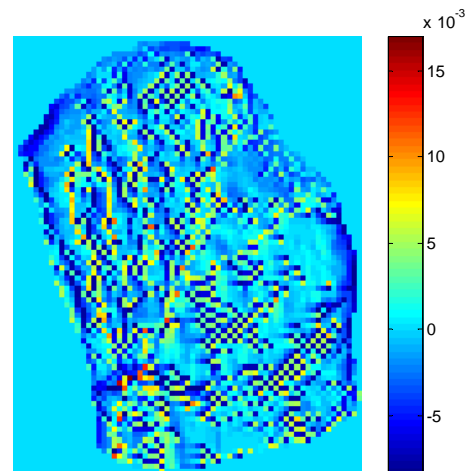
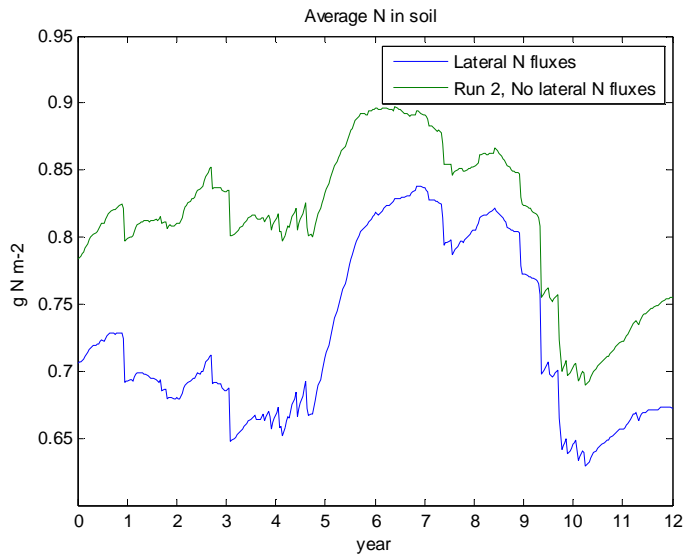


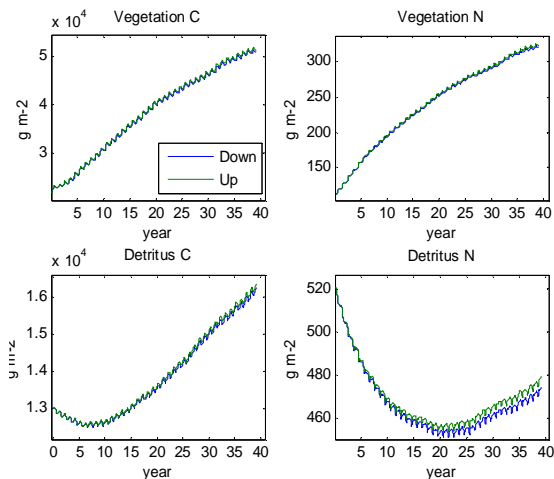
Figure 34: Difference of net mineralization rate between simulation 1 (complete) and 2 (no lateral nutrient flow).



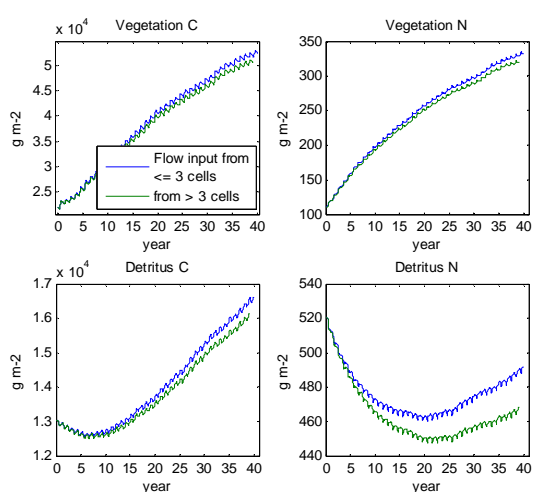
**Figure 35: Average soil inorganic N for simulation 1 (blue) and simulation 2 (green) (g N m<sup>-2</sup>).**

From figure 35 it is visible that the temporal patterns are quite similar in summer and autumn (uptake and mineralization are not flow related), but differ in winter, when there is much input (and also much transport in simulation 1, but not in simulation 2) due to snowmelt.

Compared to the complete run with lateral fluxes (simulation 1), the watershed of simulation 2 has on average more soil nitrogen, and consequently more vegetation biomass, detritus and slightly lower C:N ratios. Differences between up and downslope areas are much more clear than in simulation 1 (figure 36). There is more biomass on high altitudes, due to a higher nutrient availability, as more downslope cells have saturation overland flow and associated nutrient loss. The same is true for areas that receive water from few upslope cells (figure 37); nutrients are not transported away, causing biomass to accumulate at a higher rate than in areas that receive more water, and have thus more overland flow.



**Figure 36: Ecosystem variables in simulation 2. Green lines are upslope variables, blue is downslope.**



**Figure 37: Ecosystem variables in simulation 2. Blue lines represent input from less than 4 cells, green lines from 4 or more.**

### 3.5 Simulation 3: No upslope forest

The ecosystem mass fluxes of the early successional vegetation in the upper area of the watershed are much smaller than in the forest. Not only are the nutrient uptake rates lower, the mineralization is lower as well. As explained for simulation 1, mineralization is the largest source of inorganic nitrogen in the soil layers, thus the availability of inorganic nitrogen in the soil is considerably lower in the upper part of the catchment. Figure 38 shows the soil N content of the watershed and 39 shows the difference with simulation 1. As there is less inorganic N input from the upper part of the watershed, the sum of lateral N fluxes has decreased by about 40% compared to simulation 1. However, the effect of reduced lateral N flow on the downslope forested area is only visible at the border with the upper part.

Average soil N in last 3 simulation years (run 3)

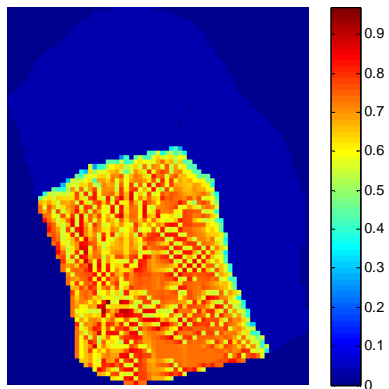


Figure 38: Average soil N (g N m<sup>-2</sup>), with no upslope forest.

Difference soil N content between simulation 1 and 3

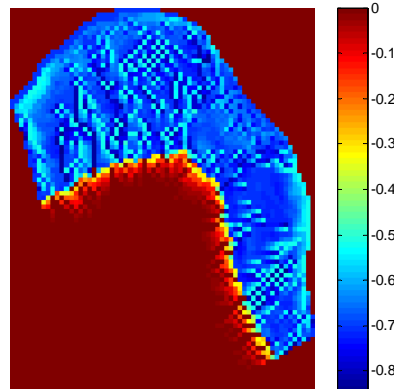


Figure 39: Difference in soil N content between the complete simulation (1) and the simulation with no upslope forest (3).

The fact that there are virtually no differences between the downslope areas of simulation 1 and 3 suggests that there is additional input of N from the upper edge of the downslope area. Figures 40 and 41 confirm this: the difference between mineralization and uptake is much higher in the upper edge of the forested area. When comparing this balance with simulation 1, the difference becomes very clear.

Difference between mineralization and uptake rate of N (g N m<sup>-2</sup> d<sup>-1</sup>) x 10<sup>-3</sup>

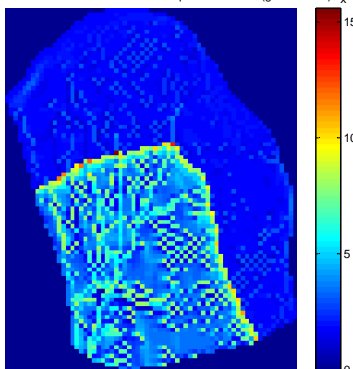


Figure 40: Average mineralization – N uptake balance (g N m<sup>-2</sup> d<sup>-1</sup>) in simulation 3.

Difference between mineralization-uptake balance in simulation 1 and 3 x 10<sup>-3</sup>

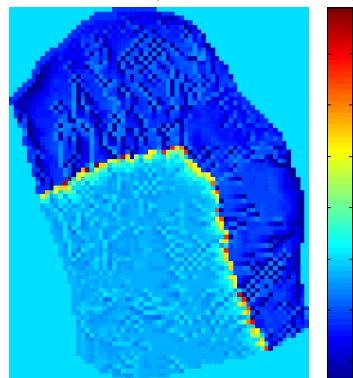


Figure 41: Difference of mineralization-uptake balance (g N m<sup>-2</sup> d<sup>-1</sup>) between simulation 1 and 3.

Figures 42 and 43 show the patterns of vegetation biomass and the differences between simulation 1 and 3. The downslope biomass is very similar to simulation 1, except for the border with the upslope area, where biomass is less than the rest of the area. This border area stretches to a width of about 9 to 10 cells, which is 90 to 100 meters.

The development of the ecosystem state variables is shown in figure 44 a-d and figure 45 a-d compares the downslope ecosystem development of simulation 3 with simulation 1. The main difference between these simulations is the detritus N content, which is lower in the downslope area of simulation 3 due to the relatively high net mineralization.

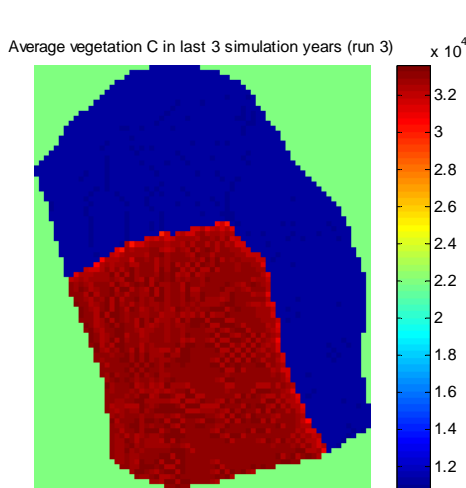


Figure 42: Vegetation C content ( $\text{g C m}^{-2}$ ) at the end of simulation 3.

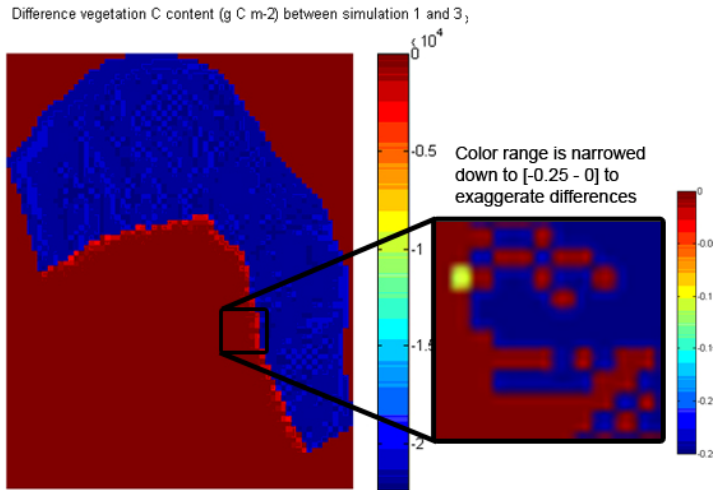


Figure 43: Difference between vegetation C content ( $\text{g C m}^{-2}$ ) between simulation 1 and 3. The small square zooms in on the border area, which is about 10 cells wide.

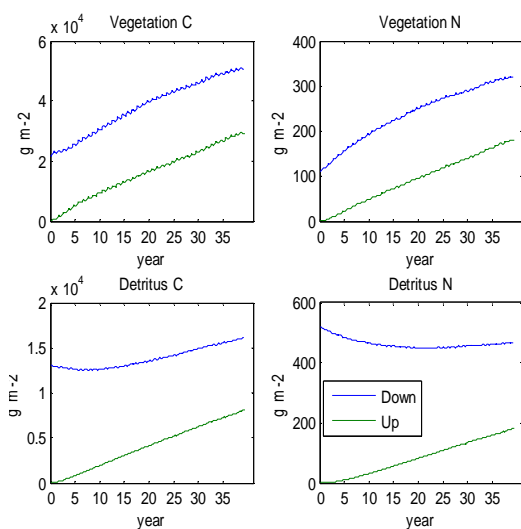


Figure 44: Up (green) and downslope (blue) ecosystem state variables of simulation 3.

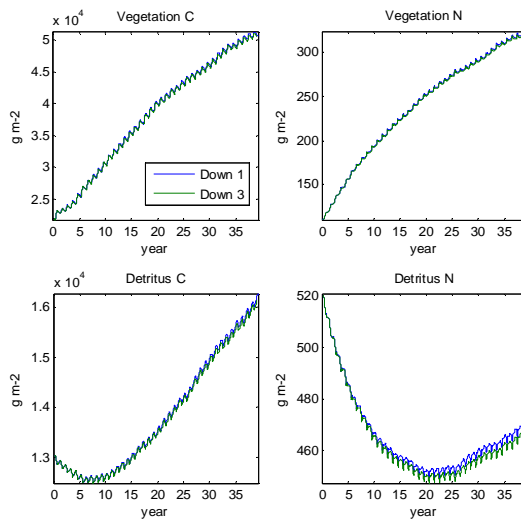


Figure 45: Downslope ecosystem state variables of simulation 1 (blue) and 3 (green).

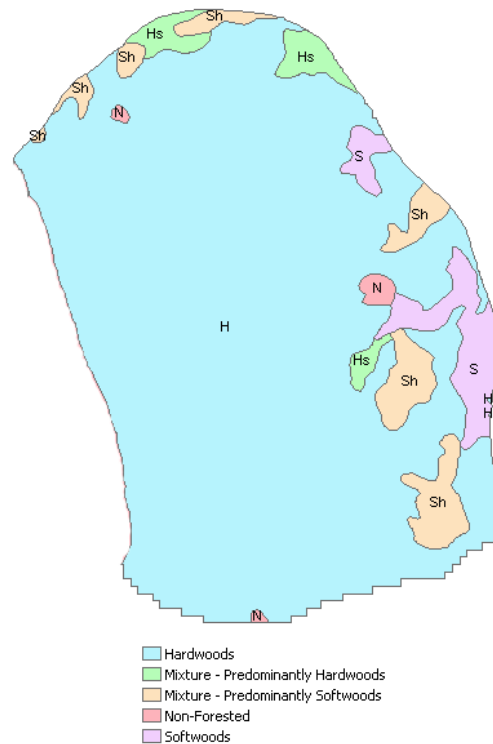
## 4. Discussion

### 4.1 Model experiment

The effects of nutrient fluxes in the watershed cause differences in nutrient cycling rates and biomass accumulation rates in the model study. In the long term, these differences may lead to a distinct spatial distribution of vegetation types. According to available GIS data (<http://www.hubbardbrook.org>), watershed 3 of Hubbard Brook the vegetation consists of more softwood (or mixture with softwood) on the higher areas near the edge of the watershed, compared to hardwood in the lower parts, see figure 46. Softwood stands have typically a lower biomass and carbon content per area (Brown, 2002). Although the results of the complete model simulation do not show this particular pattern, it is consistent with the observation that areas that receive input from less uphill cells will result in less biomass accumulation over time. Also, the second simulation shows that the absence of lateral transport of nutrients results in other patterns. Although the observed landscape patterns could also be caused by water limitation in the upper parts, it is not likely in a wet climate. However, a stronger conclusion could be drawn if water limitation would be included in the model. These simulation results are also consistent with observations and simulations by Rastetter et al. (2004), who studied biomass patterns in an arctic environment.

In contrast to the hypothesis, the absence of an upslope forest does not result in an increased biomass accumulation rate downslope. The effect of an early successional vegetation upslope was not a net increase of N output (due to lower plant uptake rates) but a decrease, because of lower net mineralization rates since there is less litter input and therefore less soil organic matter. Although these rates are not considered realistic, it does show that vegetation uptake is not the only control on N export. The whole ecosystem of vegetation and soil has to be taken into account, and other processes, such as (abiotic) retention (which will be discussed in the next section) may be important as well.

The model results also show that the effect of nutrient transport on ecosystem state variables is only visible up to a certain distance. The absence of an upslope forest results in a gradient of up to 10 cells (100 m). After that, the effect of the reduced nitrogen transport from the upslope ecosystem is buffered by the increased net mineralization rate of gradient cells. No literature is found on such patterns in reality, as natural gradients develop gradually. However, the opposite process, a forested patch that buffers increased nitrogen input from an upslope clearcut, has been reported by Laurén et al. (2005). In their study, 76% of the increased nitrogen transport was buffered by a forested patch that extended over less than 100 m between the clearcut and the stream. According to the authors, the



**Figure 46: Vegetation types in watershed 3 of Hubbard Brook. Source: <http://www.hubbardbrook.org>**

main processes responsible for this buffering were microbial and plant uptake and sorption.

Furthermore, time scale may be an important factor in this buffering process. Low inorganic N input can not be compensated by increased mineralization indefinitely, as organic soil N will be depleted. This means that eventually the border area's N export will decrease. It can be hypothesized that the border area would extend or shift in the downslope direction over time. On the other hand, on such timescales, the upslope vegetation would become a forest, thereby changing inorganic nitrogen input rates for the downslope area. Longer model runs (centuries instead of decades) could clarify what the effects of such processes are.

#### 4.2 Model behaviour and model improvement

There are two striking deviations between model results and observations. In the complete simulation, soil N content stabilizes around  $0.5 \text{ g N m}^{-2}$ . For the MEL model, Rastetter et al. (2001) assumed a value of  $2.6 \text{ g N m}^{-2}$  for a near steady state forest like Hubbard Brook. The simulated N concentration in the stream is more than an order of magnitude larger than observed values as was described earlier. Based on the observed concentration in the stream, the expected output for every square meter in the watershed is  $0.17 \text{ g N m}^{-2} \text{ y}^{-1}$  (average amount of inorganic nitrogen that is transported out of the cell that will eventually reach the stream).

Rastetter et al. (2001) assumed a that the rates of mineralization and uptake of nitrogen are the same. As their value for output ( $0.6 \text{ g N m}^{-2} \text{ y}^{-1}$  'leaching' out of the rootzone) is the same as input (deposition), equilibrium is simulated. The order of magnitude of this leaching value is consistent with expectations, as it includes stream output ( $0.17 \text{ g N m}^{-2} \text{ y}^{-1}$ ) and denitrification ( $0 - 0.65 \text{ g N m}^{-2} \text{ y}^{-1}$ , Groffman et al., 2001). The mass balance could then be similar to the values of table 6.

However, in the model simulations described in this thesis, there is more mineralization than uptake. The low inorganic nitrogen content of the soil seems to be limiting the uptake, while there is more mineralization in cells with low soil nitrogen content at this timescale of several decades. At longer timescales (hundreds of years, depending on parameters), this process should change, as resources (N) will be depleted. Such feedback relationships are discussed by Rastetter et al. (1997). Eventually, the model should tend towards equilibrium of equal uptake and mineralization.

In the original MEL model, soil inorganic nitrogen content would probably reach a higher equilibrium than was found in this model study, due to the fact that N leaching is constant in time ( $0.6 \text{ g N m}^{-2} \text{ y}^{-1}$ , Rastetter et al., 2001). In this model study, it is assumed that the inorganic soil N is fully mobile, so the mineralized N is rapidly flushed away, and the N content in the soil stays low, continuing the process of the imbalance between mineralization and uptake. The model performance may be improved by taking into account the lower mobility of ammonium. As the soils in Hubbard Brook are acidic (Campbell et al., 2007), nitrification may be relatively slow. The soil chemistry dataset (Driscoll, 2010) of O and B horizons in watershed 6 of Hubbard Brook shows an average ammonium N: nitrate N ratio of 7:1. Furthermore, observations of Judd et al. (2007) indicate an additional process: they found that nitrate production in winter was much more than the output in the stream. According to them, the  $\text{NO}_3$  retention in the soil is caused by an abiotic retention mechanism that is still unknown. Furthermore, Brooks et al. (2009) showed that the assumption that soil water mixes with rain water that enters the soil is not always valid. In their study of a forested watershed in a Mediterranean climate they found that soil water can be separated in a tightly bound and a mobile pool. However, no information was found on whether this process is found in other climates and if the bound soil water could retain nitrate.

Other processes may be involved as well, such as infiltration through preferential flow paths, which could reduce leaching of inorganic N from near-surface layers. Such improvements of the model would make it necessary that some kind of vertical distribution of ecosystem processes in the soil is included. These processes are now lumped for all soil layers, while mineralization is especially strong in the

Nitrogen flux	$\text{g N m}^{-2} \text{ y}^{-1}$
Atmospheric input	+ 0.6
Mineralization - uptake	0
Denitrification	- 0.43
Stream output	- 0.17

**Table 6: Possible nitrogen mass balance if mineralization and uptake of nitrogen would be the same.**

upper layers and plant nutrient uptake from a certain layer depends on its root fraction. Furthermore, spatial and temporal variability of (de)nitrification could be taken into account. The rates of these processes are much higher in certain areas (hot spots) and at certain times (hot moments) (McClain et al., 2003). Although implementing this variability could give additional explanation, it would further complicate the model.

Although a retention mechanism could improve model performance and provide more insight in the interaction between vegetation and nutrient fluxes, it still provides no complete explanation why soil nitrogen contents are much lower than expected. In the second simulation, without lateral nutrient fluxes, initial soil N content decreases and it is lower than would be expected from literature. It may be a 'temporary effect', as the system is still reaching equilibrium. Model runs for longer timescales would provide more insight. If retention mechanisms and reaching equilibrium do not explain stream N concentrations, it could be possible that recalibration of the ecosystem parameters is necessary. In short, to improve model behaviour regarding soil N uptake and mineralization, further research is needed.

Although a model is always a simplification of reality and much input data are estimates and do not consider spatial and temporal variation and disturbances, there are some ways in which the model performance can be improved (besides the above discussed nitrogen retention).

As discussed in model behaviour, the LDD could be improved by using a better resolution DEM. Although such a DEM (5 x 5 m) was available, it has not been used due to time limitations, because it would increase (the already long) run time significantly. However, it may improve the hydrograph performance, and it would make it possible to assess whether the model results show differences between landforms, as would be expected from a study by Detty & McGuire (2010) of the same watershed. Furthermore, the LDD that is used only provides one export pathway per cell. Including multiple pathways may be more realistic as the cells are rather large and it would smoothen the spatial patterns of the results.

The hydrograph could be further improved; as the largest errors occur during periods of snowmelt, recalibrating the snow model may improve the timing of snowmelt events. Although the snow subroutine from BROOK90 (Federer, 2002) was already calibrated for Hubbard Brook, it was designed for a 1-dimensional model. Implementing slope orientation and temperature differences with height may further improve snowmelt simulation, although there will always be uncertainties such as spatial variation in precipitation and snow displacement by wind.

Another snow-related uncertainty is the N content of the snow layer and N concentration of melt water. The model assumes that N concentration is the same for the whole snow layer and subsequent melt water. It is not clear if there would be concentration differences in reality, because N concentration of precipitation measurement data contained only monthly averages. These averages, as well as the modelled process of N concentration in melt water, introduce uncertainties in amount and timing of N input in the soil.

Since the implemented ecosystem model (MEL) is one dimensional, the N fluxes within the soil are not distributed over the soil layers in a realistic way. N uptake and input per layer are relative to the amount of N that is in the layer. In this model it means that the layer with the highest water content (usually the deepest layer) also has the highest N content. However, in reality N content is often highest in the upper soil layers (soil chemistry dataset: Driscoll, 2010). The model could be improved by distributing uptake and input processes realistically over the soil layers and by taking relevant transport and retention processes into account.



A further improvement could be done by linking vegetation more tightly with hydrology. Vegetation growth rate could be limited by water availability. To do this, it could be linked with actual transpiration rate. Although the effect is probably not very large in a wet area like Hubbard Brook (dry periods are usually limited to a few weeks in summer), this adaptation would be more important if the model was used for dryer areas. Another link between vegetation and soil moisture is oxygen availability. In areas near the stream, that often have water tables, oxygen limitation may limit vegetation growth.

A remark should be made about time scale. Since the run time of the model can take very long (the total model run of 42 years took about a week), it would be difficult to run the model for longer periods, to observe full succession series. However, such simulations would allow for a better understanding of spatial interactions on succession, as equilibrium values could be compared, instead of just biomass accumulation rates. Such simulations would require a stronger coupling of the hydrological and ecosystem models: parameters to estimate potential evapotranspiration rates (such as canopy height) would need to be dependent on ecosystem variables such as biomass C content.

## 5. Conclusion

From the simulation results it can be concluded that the upslope ecosystem can indeed influence N fluxes downslope and that these fluxes influence the ecosystem downhill.

Concerning the effect of the upslope ecosystem on nitrogen transport, it should be noted that the influence from uphill should not be attributed to vegetation alone, but also to soil microbial processes and other possible controls on nitrogen transport that have been discussed before.

In the simulation, an increased input of nitrogen resulted in an increased rate of biomass accumulation. As the simulated amount of nutrient transport was not realistic (due to high net mineralization and no retention), the extent of the effect can not be quantified in a realistic way. For the same reason, the effect of upslope ecosystem cannot be quantified.

Furthermore, a buffering effect was noticed in the simulation with no upslope forest; areas that received very little N input from upslope areas reacted with increased mineralization, thereby limiting the effect on areas further downslope.

As the results of the simulations cannot be confirmed by observations and the model behaviour produced unrealistic values of soil nitrogen content and transport, further research is necessary to gain a good understanding of the interaction between vegetation and nutrient fluxes.

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## Appendices

**Appendix A: Parameters for Hubbard Brook for potential evapotranspiration and snowmodules of BROOK90.**

Source: Federer et al., 2002 and Federer, 2010.

RStemp	-0,5 C	Base temperature for rain snow transition [degrees C]
CCFac	0.3 [MJ m-2 d-1 K-1]	degree day factor for accumulation of cold content for a day with daylength of 0.5 d.
MelFac	1.5	degree day melt factor for open land [MJ m-2 d-1 K-1] (Advised value is 1.5)
Grdmlt	0.35	groundmelt 0.35 mm/d
Maxlqf	0.05	maximum liquid water fraction of SNOW
SlfDay	1	ratio of potential insolation on slope to horizontal, for the moment a horizontal plane is assumed, but can be replaced with a map.
LaiMlt	0.2	dependence of snowmelt on LAI, dimensionless. Value taken from Brook90 HB data
CS	0.035	ratio of projected SAI to canopy height [m-1]
CHeight	15	Canopy height (in original model it varied through the year and snowdepth was substracted) [m] Could be replaced with a map, or made dependent on Biomass.
DenseF	1	Density factor. Canopy density multiplier between 0.05 and 1, dimensionless. DENSEF is normally 1; it should be reduced below this ONLY to simulate thinning of a the canopy by cutting.
SaiMlt	0.5	snowmelt dependence on SAI. dimensionless
LPC	4	LAI closed canopy [m2 m-2]
CR	0.5	extinction coefficient for photosynthetically-active radiation in the canopy
NN	2.5	wind/diffusivity extinction coefficient [-]
CZS	0.13	ratio of roughness to height for smooth closed canopies
CZR	0.05	ratio of roughness to height for rough closed canopies
HS	1	height below which CZS applies, m
HR	10	height above which CZR applies, m
Z0g	0.02	Ground surface roughness [m]
Z0s	0.001	Snow surface roughness [m]
Ksnvp	0.3	Multiplier to reduce snow evaporation [-] This parameter is rather arbitrary
Zminh	2	reference height for weather data above canopy [m]
RhoTP	2	ratio of total leaf area to projected area, is 2 for broadleaf

Lwidth	0.1	average leaf width [m]
TL	0	temperature below which stomates are closed
T1	10	lowest temp. at which stomates not temp. limited
T2	30	highest temp. at which stomates not temp. limited
Th	40	temperature above which stomates are closed
GLmax	0.48	maximum leaf conductance, open stomates, all sides, [s/m]
GLmin	0.3	minimum leaf conductance, closed stomates, all sides, [s/m]
R5	100	solar radiation at which conductance is halved (must be converted to MJ m <sup>-2</sup> )
Cvpd	2	pd at which leaf conductance is halved [kPa]
Rm	1000	maximum solar radiation, at which FR = 1, W m <sup>-2</sup>
Rssa	500	soil evaporation resistance at field capacity, s m <sup>-1</sup>
Rssb	1	exponent in relation of soil evap res to water potential
	0.2 * LAI	Maximum interception capacity, 1-2 mm for LAI = 6.



## Appendix B: Parameters of daily MEL for Hubbard Brook.

Source: Rebel & McGuire, 2005, made to fit yearly MEL (Rastetter et al., 1997 and 2001).

a	0.01369863	acclimation rate (day-1).
Ba_max	371	maximum Ba active tissue C [g C m-2]
c1	0.53	allometric parameter
q_min	17	minimum plant C:N ratio (g C g-1 N)
q_max	163	maximum plant C:N ratio (g C g-1 N)
bc	0.0455	leaf area per unit C (m <sup>2</sup> g-1 C)
bn	58	root length per unit C (m g-1 C)
kc	350	half saturation for CO <sub>2</sub> (ml m-3)
kn	0.462	half saturation for N (g N m-2)
ks	0.0000126	soil resource extinction (m <sup>2</sup> m-1)
rNfix	9.12	N fixation cost (gC g-1 N)
kNfix	50	1/2-saturation fixation cost (gC g-1N)
ma	0.001483	active tissue - litter loss rate (day-1)
mw	0.00003936	woody tissue - litter loss rate (day-1)
qa	24	active tissue litter C:N (gC g-1 N)
qw	123	woody tissue litter C:N (gC g-1 N)
h	1095	acclimation damping (day)
etha_N	0.24	max microbial N efficiency
etha_C	0.6	max microbial C efficiency
phi	8	C:N microbial byproducts (gC g-1 N)
alpha_N	0.0126	microbial-N-uptake (gN g-1 C)
kNm	1	microbial N half-saturation (gN m-2)
tau	0.00125	tau as damping for rNup to Rbar (y(7))
pgn	1.38*0.1477	
pgc	635*0.00183	
pra	1.25*0.00231	
prw	1.25*0.000001688	
ppsi	13.25*0.00000685	
pgNfix	7.5E-7	

## Appendix C: Description of model files and model structure.

The model consists of the following function files:

Files:	Description:
walnuts.m	Main model file. This file gets input from the initialization function, runs the model, saves data and shows graphs and images.
initialization.m	Initialization. In this file all site-specific parameters are entered and locations of input data are set. Hydrology and soil parameters speak for themselves. Explanation on snow and PET parameters can be found here: <a href="http://home.roadrunner.com/~stfederer/brook/b90doc.html">http://home.roadrunner.com/~stfederer/brook/b90doc.html</a> . Explanation on ecosystem parameters can be found in Rastetter et al, 2001.
petsnow.m	Potential evapotranspiration and snow. This function calculates the snowlayer and snowmelt and also calculates the amount of potential evapotranspiration.
jday.m	This function determines year, month, date and day of year from YYYYMMDD format.
daylength.m	This file calculates daylength based on day of year and latitude. Based on the CBM model by Forsythe et al 1995.
soiltemp.m	Estimates soil temperature from air temperature with a calibrated lag.
MELodesolver.m	Ordinary differential equation function. The functions in this file are solved with Matlab's ode45 function, using a variable timestep.
gof.m	Goodness of fit functions, used to calculate Nash & Sutcliffe efficiency for hydrograph performance.
drain1.m	This function calculates the local drainage direction (LDD) using the DEM.

Folder:	Description:
WALNUTS model\	Contains the model function files
\input\	Contains the input data files
\input\ini\	At the end of a simulation, state variables are stored to be used as initial conditions for a following run. This can be switched on in 'initialization.m' by changing: UsePrevious = 1;
\output\	Output is stored here. Output includes: <ul style="list-style-type: none"> <li>- Saved images of output graphs and maps (to get a quick view of results)</li> <li>- All variables are stored at the end of a simulation in 'all_variables_x'</li> <li>- After every simulated year state variables are stored for every day of the year: 'StatevariablesWxxx' (water) and 'StatevariablesYxxxx' (ecosystem). LAI and ecosystem fluxes are stored as well.</li> </ul>

All input is entered in the file initialization.m. The following input files are needed in the /input/ folder:

Input files:	
DEM	Excel formats are used, but many formats are possible.
Slope map	Can be derived from DEM using GIS
Flow accumulation	Can be derived from DEM using GIS
Soil data	Table of soil parameters
Meteo data	Table of daily meteo input