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The hydrological effects of changes in forest area and species composition in the federal state of Brandenburg, Germany

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“I may not have gone where I intended to go, but I think I have ended up where I needed to be.”

Douglas Adams

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List of Abbreviations

CAP - common agricultural policy
CREAMS - chemicals, runoff and erosion from agricultural management systems
DBH - diameter at breast height
DPSIR - driving forces pressure state impacts responses
EC - European Commission
EPIC - erosion productivity impact calculator
EU - European Union
ForestBGC - forest bio geochemical cycles
GIS - geographic information system
GLOWA-Elbe - Globaler Wandel des Wasserkreislaufes; Global Change in the hydrological cycle
IPCC - Intergovernmental Panel on Climate Change
LAI - leaf area index
LDSP - Landesbetrieb für Datenverarbeitung und Statistik Brandenburg; State Statistical Institute Brandenburg
LFE - Landesforstanstalt Eberswalde; federal forest agency
LHS - latin hypercube sampling
MESSAGE – meso-scale simulation study assessing the consequences of Global Change
Mha - mega tons
MLUR - Ministerium für Landwirtschaft, Umweltschutz und Raumordnung; Ministry of agriculture, environment and rural areas
MTR - Mid Term Review
PAGE - the pattern generator
PDF - probability density functions
RAUMIS - Regionalisiertes Agrar- und Umweltinformationssystem; agricultural policy information system for German administrative units
RUE - radiation-use efficiency
SCS - Soil Conservation Service (US)
SWIM - Soil and Water Integrated Model
TDR - time domain reflectometry

German terms:

Bundesanstalt für Geowissenschaften und Rohstoffe - Federal Institute for Geosciences and Natural Resources
Landesumweltamt Brandenburg - Federal Environmental Agency
Landesvermessungsamt - Federal Land Surveying Office

Zusammenfassung

Das übergreifende Ziel der vorliegenden Arbeit ist es, die Interaktion zwischen Landnutzungsänderung und dem Landschaftswasserhaushalt zu quantifizieren. Die treibenden Kräfte für Landnutzungsänderung, die in dieser Arbeit untersucht werden, sind administrative Entscheidungen auf europäischer und landespolitischer Ebene. Das Untersuchungsgebiet für die Analyse ist das Land Brandenburg. Als ein typischer Vertreter der semihumiden Landschaften Europas repräsentiert es eine Region, die besonders empfindlich gegenüber Landnutzungsänderung ist. Bedingt wird dieses durch eine Kombination geringer Sommerniederschläge mit der Dominanz sandiger Böden und hoher Verdunstungsraten, insbesondere von den großflächigen Wäldern und Forsten. Waldflächen sind Schlüsselelemente im Landschaftswasserhaushalt, da sie den Bodenwasserspeicher effizienter mit der Atmosphäre koppeln als die meisten anderen Vegetationsformen. Unter diesen Randbedingungen haben Änderungen in den landespolitischen und europäischen Richtlinien, die sich auf den Forstsektor im Land auswirken, auch entscheidenden Einfluss auf den Landschaftswasserhaushalt. Es ist deshalb erforderlich, Eingriffe in diesen kritischen Bereich hinsichtlich ihrer Wirkung auf den Wasserkreislauf quantitativ zu erfassen und zu bewerten. Im ersten Teil der Arbeit war es daher notwendig, ein geeignetes Modellkonzept zu finden. Der Ansatz sollte in der Lage sein, die hydrologischen Effekte auf Landschaftsebene zu modellieren, ohne dabei die Datenverfügbarkeit in diesem Anwendungsbereich zu überschreiten.

Das Ergebnis ist ein Modellkonzept, welches die hydrologischen Eigenschaften von Wäldern über die zeitlich/räumliche Variabilität des LAIs (Leaf area index – Blattflächenindex) abbildet. Der Ansatz ermöglicht die Simulation aller für die Betrachtungsebene relevanten Prozesse: die Interzeption des Niederschlages und dessen Verdunstung sowie die Transpiration von Waldbeständen mit und ohne Grundwasser in der Wurzelzone. Für die Abbildung der Blattflächendynamik berücksichtigt das Modell die Phänologie der unterschiedlichen Arten, die Allokation der Biomasse, wie auch die Einflüsse von Mortalität und sehr vereinfacht auch von Durchforstungsmassnahmen. Das Modell wurde in das ökohydrologische Einzugsgebietsmodell SWIM (Soil Water Integrated Model) integriert. Das SWIM Modell wurde in zwei Vorstudien als geeignet identifiziert, da es in der Lage ist, sowohl hydrologische als auch ökologische Prozesse auf der Einzugsgebietsebene im Nordostdeutschen Tiefland abzubilden. Nach der

Implementierung wurde das um das Waldmodul erweiterte Modell für die häufigsten Baumarten des Bundeslandes, Kiefer (Pinus sylvestris) und in Teilen Eiche (Quercus robur, Quercus petraea), getestet. Die Ergebnisse zeigten eine gute Wiedergabe des jährlichen Biomassezuwachses, eine zufriedenstellende Abbildung des Blattflächenindexes und der jährlichen Laubstreu. Die Ergebnisse für die Simualtion der jahreszeitlichen Dynamik (Phänologie) für beide Baumarten waren ebenfalls zufriedenstellend. Für den Vergleich mit Interzeptionsmessungen standen nur wöchentliche Summen zur Verfügung, die das Modell innerhalb der Vegetationperiode zufriedenstellend wiedergab. Der Vergleich der jährlichen Bilanz zeigte eine gute Übereinstimmung. Nach der Test- und Entwicklungsphase konnte das Modell für die integrierte Analyse der Wirkung von zwei Szenarien auf den Landeswasserhaushalt verwendet werden. Das erste Szenario beschäftigt sich mit der möglichen Zunahme der Waldfläche auf offengelassenen landwirtschaftlichen Flächen als Folge der Neuausrichtung der Agrarsubventionspolitik der Europäischen Union. Das zweite Szenario behandelt die Auswirkung des Brandenburger Waldumbauprogramms. Beide Szenarien wurden in explizite Landschaftsmuster übersetzt und in einer Auflösung von 50 m für die Gesamtfläche des Landes modelliert. Das erste Szenario führte zu einer Waldflächenzunahme auf 9,4% der Gesamtfläche des Landes mit negativen Folgen für den Landschaftswasserhaushalt. Bei vollständiger Aufforstung der zur Verfügung stehenden Flächen nimmt die Evapotranspiration im langjährigen Mittel um 3,7% zu. Diese relativ geringe Zunahme in der jährlichen Durchschnittsverdunstung überdeckt eine wesentlich stärkere Zunahme des langjährigen Mittels der Verdunstung im Frühling von 25,1 %. Diese starke Verdunstungszunahme wirkt sich bis in den Sommer auf die Grundwasserneubildung aus und verschlechtert so das ohnehin geringe Wasserdargebot. Im Vergleich dazu hat die Veränderung der Baumartenzusammensetzung von Kiefer zu Eiche auf 29,2 % der Landesfläche eine vergleichsweise geringe Abnahme der langjährigen mittleren Verdunstung von 3,4% zur Folge. Obwohl hier auch ein jahreszeitliches Muster vorliegt, ist der relative Effekt doch wesentlich geringer. Beide Szenarien zeigen über die Landesfläche gemittelt einen linearen Zusammenhang zwischen Veränderung in der Landnutzung und Änderung in den Komponenten des Wasserkreislaufes. Der lineare mittlere Verlauf überdeckt aber ein sehr heterogenes räumliches Muster der Veränderung, bedingt durch die spezifischen Umweltbedingungen in den unterschiedlichen Regionen des Landes. Insbesondere Landesteile mit oberflächennahem Grundwasser reagieren stark auf eine Ausweitung der Waldfläche wohingegen Regionen mit großen Waldflächen besonders empfindlich auf den

Waldumbau reagieren. Die Zonen starker Effekte überlappen sich nur in einigen Fällen, so ist es möglich, dass die positiven Wirkungen des Waldumbauprogramms in einigen Regionen durch eine mögliche Ausweitung der Waldfläche aufgehoben werden.

Zwei wichtige Quellen von Unsicherheiten in den Modellergebnissen wurden untersucht. Die erste Quelle liegt in den Unsicherheiten der stark sensitiven Kalibrierungsparameter für die Strahlungsbilanz, gesättigte Leitfähigkeit des Bodens und Abflussdynamic, die in einer Vorstudienanalyse in ihrem physikalisch sinnvollen Wertebereichen verändert wurden. Die kombinierten Unsicherheiten aller untersuchten Parameter zeigt eine mittlere Überschätzung der Wasserbilanz von 1,6% in Tieflandeinzugsgebieten in Brandenburg und angrenzenden Gebieten. Allerdings ist die Verteilung relativ weit mit 14,7% und -9,9% als Werte des 90ten und 10ten Perzentils. Die zweite Quelle für die Unsicherheit in der Szenarioanalyse entspringt der Parameterisierung des Forstmoduls. Hier wurden Unsicherheiten in der Verteilung der Altersklassen als auch der phänologischen und biometrischen Parameter untersucht. Die resultierende Streuung der Verdunstungswerte für das Gebiet Brandenburgs ist mit einer Standardabweichung von 0,6% für das zehnjährige Mittel allerdings relativ gering. Die beiden Analysen suggerieren einen dominanten Einfluss der Kalibrierungsparameter auf die Unsicherheit in den Ergebnissen der Szenarienanalyse. In diesem Fall ist die Wahrscheinlichkeit hoch, dass das Modell die Verdunstung eher unterschätzt und somit die Wasserbilanz sich in Richtung Grundwasserneubildung und Abfluss verschiebt. Das würde bedeuten, dass die Auswirkungen der Aufforstungen eher unterschätzt und die des Waldumbaus überschätzt werden.

Die vorgestellten Ergebnisse zeigen deutlich, dass Landnutzungsänderungen, die durch politische oder administrative Entscheidungen ausgelöst werden, Auswirkungen auf elementare Landschaftsfunktionen wie den Wasserhaushalt haben. Es wird deutlich, dass ein integrativer Modellierungsansatz, der die wahrscheinlichen Wirkungen administrativer Entscheidungen in Betracht zieht, Grundlagen für eine nachhaltige Entwicklung liefern kann. Auf Grund der genannten Umweltbedingungen kann Brandenburg hier als ein Beispiel für vergleichbare Regionen in Europa dienen. Diese Ergebnisse werden umso relevanter, je stärker die betroffene Ressource bereits eingeschränkt ist. In Bezug auf die Wasserressourcen im Land Brandenburg ist das der Fall und aktuelle Studien zum Globalen Wandel in der Region prognostizieren eine Verschärfung dieser Situation.

Summary

This thesis aims to quantify the human impact on the natural resource water at the landscape scale. The drivers in the federal state of Brandenburg (Germany), the area under investigation, are land-use changes induced by policy decisions at European and federal state level. The water resources of the federal state are particularly sensitive to changes in land-use due to low precipitation rates in the summer combined with sandy soils and high evapotranspiration rates. Key elements in landscape hydrology are forests because of their unique capacity to transport water from the soil to the atmosphere. Given these circumstances, decisions made at any level of administration that may have effects on the forest sector in the state are critical in relation to the water cycle. It is therefore essential to evaluate any decision that may change forest area and structure in such a sensitive region. Thus, as a first step, it was necessary to develop and implement a model able to simulate possible interactions and feedbacks between forested surfaces and the hydrological cycle at the landscape scale.

The result is a model for simulating the hydrological properties of forest stands based on a robust computation of the temporal and spatial LAI (leaf area index) dynamics. The approach allows the simulation of all relevant hydrological processes with a low parameter demand. It includes the interception of precipitation and transpiration of forest stands with and without groundwater in the rooting zone. The model also considers phenology, biomass allocation, as well as mortality and simple management practices. It has been implemented as a module in the eco-hydrological model SWIM (Soil and Water Integrated Model). This model has been tested in two pre-studies to verify the applicability of its hydrological process description for the hydrological conditions typical for the state.

The newly implemented forest module has been tested for Scots Pine (*Pinus sylvestris*) and in parts for Common Oak (*Quercus robur and Q. petraea*) in Brandenburg. For Scots Pine the results demonstrate a good simulation of annual biomass increase and LAI in addition to the satisfactory simulation of litter production. A comparison of the simulated and measured data of the May sprout for Scots pine and leaf unfolding for Oak, as well as the evaluation against daily transpiration measurements for Scots Pine, does support the applicability of the approach. The interception of precipitation has also been simulated and

compared with weekly observed data for a Scots Pine stand which displays satisfactory results in both the vegetation periods and annual sums.

After the development and testing phase, the model is used to analyse the effects of two scenarios. The first scenario is an increase in forest area on abandoned agricultural land that is triggered by a decrease in European agricultural production support. The second one is a shift in species composition from predominant Scots Pine to Common Oak that is based on decisions of the regional forestry authority to support a more natural species composition. The scenario effects are modelled for the federal state of Brandenburg on a 50m grid utilising spatially explicit land-use patterns.

The results, for the first scenario, suggest a negative impact of an increase in forest area (9.4% total state area) on the regional water balance, causing an increase in mean long-term annual evapotranspiration of 3.7% at 100% afforestation when compared to no afforestation. The relatively small annual change conceals a much more pronounced seasonal effect of a mean long-term evapotranspiration increase by 25.1% in the spring causing a pronounced reduction in groundwater recharge and runoff. The reduction causes a lag effect that aggravates the scarcity of water resources in the summer. In contrast, in the second scenario, a change in species composition in existing forests (29.2% total state area) from predominantly Scots Pine to Common Oak decreases the long-term annual mean evapotranspiration by 3.4%, accompanied by a much weaker, but apparent, seasonal pattern. Both scenarios exhibit a high spatial heterogeneity because of the distinct natural conditions in the different regions of the state. Areas with groundwater levels near the surface are particularly sensitive to changes in forest area and regions with relatively high proportion of forest respond strongly to the change in species composition. In both cases this regional response is masked by a smaller linear mean effect for the total state area.

Two critical sources of uncertainty in the model results have been investigated. The first one originates from the model calibration parameters estimated in the pre-study for lowland regions, such as the federal state. The combined effect of the parameters, when changed within their physical meaningful limits, unveils an overestimation of the mean water balance by 1.6%. However, the distribution has a wide spread with 14.7% for the 90^{th} percentile and -9.9% for the 10^{th} percentile. The second source of uncertainty emerges from the parameterisation of the forest module. The analysis exhibits a standard deviation of 0.6 % over a ten year period in the mean of the simulated evapotranspiration as a result of variance in the key forest parameters. The analysis suggests that the combined uncertainty in the model results is dominated by the uncertainties of calibration parameters. Therefore, the effect of the first scenario might be underestimated because the calculated increase in evapotranspiration is too small. This may lead to an overestimation of the water balance towards runoff and groundwater recharge. The opposite can be assumed for the second scenario in which the decrease in evapotranspiration might be overestimated.

The relative small area of the transition from agriculture to forest in the first scenario analysis leads to a profound change in groundwater recharge indicating a high sensitivity of the state towards such changes. On the other hand, in the second scenario, the transition from evergreen pine forest to deciduous oak forest, concerns a much larger area with a much less pronounced impact on groundwater recharge. In addition, the areas of the strongest response to the two scenarios do not necessarily overlap. Consequently, the chances for a neutralisation of the negative effects for the water balance from the increase in forest area by the change in species composition for some regions might be low. As a result, changes in species composition initialised by local forest authorities to adapt to decreasing groundwater levels and climate change can only be effective if it takes possible interaction with forest area changes at the landscape scale into account.

In general, it can be concluded that the situation in Brandenburg is comparable to other regions with a low climatic water balance. In these regions, most of the water is lost to the atmosphere by evapotranspiration and only a small amount contributes to runoff and groundwater recharge. Based on this environmental precondition, any land-use change that increases the forested area will increase evapotranspiration and over proportionally decrease in groundwater recharge and runoff. On the other hand, changes from evergreen species towards deciduous species can improve groundwater recharge. This analysis demonstrates the general interaction of policy-induced land-use change with other environmental issues such as the landscape water balance. This clearly indicates the need for environmental assessment procedures to evaluate the impact of decisions that influence land management and that such an evaluation should take account of the interactions of different levels of decision making.

1. Introduction

1.1 Integrated assessment procedures at the landscape scale

Landscape is a part of the earth's surface, distinct in its appearance and genesis from its surroundings. The landscape around us is in a process of constant change. Parallel in time and space, geogenic and biogenic processes are forming the landscape as they transform, redirect and interact with the anthropogenic influences leading to a highly complex network of interaction and feedback (Bork et al. 1998). The anthropogenic component in this network of interaction has intensified considerably since industrialisation. One clear indicator of this growing impact is the rising concentration of greenhouse gases in the atmosphere and the resulting increase in global surface temperature. This increased greenhouse gas concentration is either partly caused by or runs parallel in time with a massive change in land-use. Both processes, temperature increase and land-use change, are phenomena of Global Change that strongly influence the availability of water, the fundamental basis of life. They do so by the intensification and redirection of elements in the hydrological cycle. As the demand for drinking water increases, due to a growing world population, it competes with the rising water demand for intensive agricultural production, further industrialisation and urbanisation. Therefore, water supply becomes an increasingly important ecosystem service in many regions of the world (IPCC, 2001a; Krysanova et al., 2006; Schröter et al., 2005).

The qualitative understanding of the system landscape and its processes is well-established scientific knowledge (e.g. Bork et al., 1998; Zebisch et al., 2004). However, the integrated quantification is lagging behind (Busch, 2006) though a number of studies investigating specific aspects has already been published (e.g. Bork et al., 1995; Fohrer et al., 2001; Hattermann et al., 2004; Hattermann et al., 2005; Hörmann et al., 2003; Jakeman and Letcher, 2003; Molnar et al., 2002; Niehoff et al., 2002; Parker et al., 2002). This lack of quantification is mostly a result of the lack of methods and tools to investigate such highly complex systems (Busch, 2006; Fohrer et al., 2002; Hattermann, 2005; Hörmann et al., 2005; Zebisch, 2003). The development of spatial ecological, and especially ecohydrological computer simulation models, is filling this gap towards creating an integrated system approach (Habeck et al., 2006; Hattermann, 2005; Hattermann et al., 2006; Hörmann et al., 2005; Krysanova et al., 2006; Wattenbach et al., 2007). The research sector evolving from this development is that of integrated environmental modelling or, in the case of river catchments, integrated catchment modelling (ICM). Integrated, in the latter case, means that the complete cascade from policy decisions on social aspects to landscape processes and their interaction with eco-hydrological processes are incorporated (Aspinall and Pearson, 2000; Jakeman and Letcher, 2003; Molnar et al., 2002).

One of the most comprehensive integrated studies on the European scale was the ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) project assessing the continental scale ecosystem vulnerability to Global Change (Schröter et al., 2005). The project defines the essential multidisciplinary policy relevant questions that need to be answered in an integrated impact assessment (Metzger et al., 2006). The issues are:

- Which are the main regions or sectors that are vulnerable to Global Change?
- How do the vulnerabilities of two regions compare?
- Which scenario is the least, or most, harmful for a given region or sector?

The project extended the IPCC (2001b) definition of vulnerability to include other aspects of Global Change besides climate change, such as land-use change in the following manner:

- <u>Vulnerability:</u> The degree to which an ecosystem service is sensitive to Global Change plus the degree to which the sector that relies on this service is unable to adapt to the changes,

where sensitivity and adaptation are defined as:

- <u>Sensitivity:</u> The degree to which a human–environment system is affected, either adversely or beneficially, by environmental change.
- <u>Adaptation:</u> Adjustment in natural or human systems to a new or changing environment (Metzger et al., 2006)

The MESSAGE (Mesoscale Simulation Study Assessing the Consequences of Global Change) project, to which this thesis contributed, is an example of such an integrated environmental modelling approach that assesses, in this case, the vulnerability of the federal state of Brandenburg to the effects of Global Change. Its methods and results contributed to the first and second stage of the GLOWA-Elbe ("Globaler Wandel des Wasserkreislaufes" - "Global Change in the Hydrological Cycle") project framework. Figure 1 exemplifies the integrated approach as it is implemented within the GLOWA Elbe project. The GLOWA approach can be seen as a contribution to the concept of the Strategic Environmental Assessment Directive (2001/42/EC) which focuses on the environmental effects of future plans and programmes, such as change in subsidies (EU, 2006). The basic principle of strategic environmental assessment was defined by Sadler and Verheem (1996) as:

"A systematic process for evaluating the environmental consequences of proposed policy, plan or programme initiatives in order to ensure they are fully included and appropriately addressed at the earliest appropriate stage of decision-making on par with economic and social considerations."

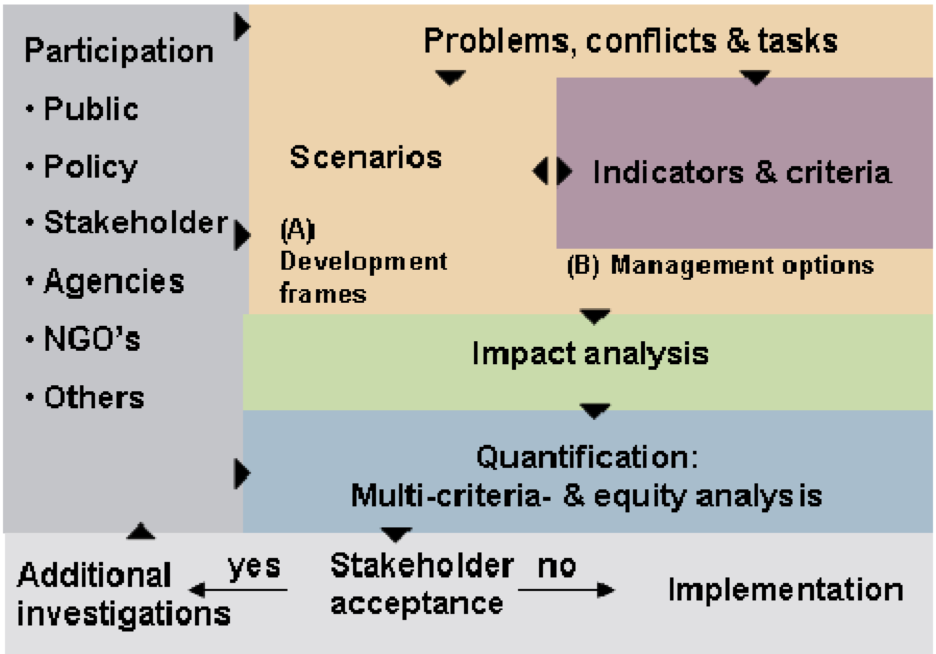

Fig. 1 The integrated approach of the GLOWA Elbe project (GLOWA, 2005)

However, the GLOWA approach extends the analysis by taking into consideration effects of climate change that might interact with future decisions. It follows the DPSIR approach of the European Environmental Agency (EAA). DPSIR stands for:

- **D**riving forces of environmental change
- **P**ressures on the environment
- **S**tate of the environment
- **I**mpacts on population, economy, ecosystems
- **R**esponse of the society

The DIPSR approach is again consistent with the implementation of the European Water Framework Directive (WFD) (Borja et al., 2006; Mysiak et al., 2005). The WFD is one of the most comprehensive pieces of European water legislation and it specifically asks for

the integrated implementation of a "good status" of all surface, ground- and coastal water bodies within the EU (Borja et al., 2006).
The subject of this thesis integrates into the “Quantification: Multi-criteria-analysis” of the GLOWA approach (Fig. 1) using policy boundary conditions and economic scenarios as drivers for a change of land-use, which forms a trigger for changes in landscape hydrology. The impact analysis of a change in forest species composition and afforestation on the groundwater recharge and runoff at the landscape scale as done here, however, represents an approach not yet realised in the GLOWA project.

1.1.1 The role of forests in landscape hydrology

The percentage of land covered by forests, and their structure and species composition, have a fundamental influence on the hydrological behaviour of a landscape (Brown et al., 2005). The main reason for this is that trees establish a very efficient connection between the soil water storage and the atmosphere. Trees are able to adapt their root systems to the local soil water conditions, hence, optimising their water uptake to effectively use the soil water available to the plant in their rooting zone. The deep root system enables them to continue transpiration in dry periods by taking water from deeper soil layers with adequate water supply (Feddes et al., 2001; Le Maitre et al., 1999; Mitscherlich, 1971). The process of interaction between soil, vegetation and the atmosphere forms the key element for any evapotranspiration calculation either with either explicit (e.g. Penman-Monteith (Monteith, 1965)) or implicit process description (e.g. Thornthwaite (Thornthwaite and Hare, 1965) and Priestley-Taylor (Priestley and Taylor, 1972)). The Penman-Monteith-Method illustrates the relationship between atmospheric and surface components using the concept of resistance. The transfer of water from the vegetation surface is restricted by the aerodynamic resistances, where aerodynamic resistance represents a function of surface roughness and wind speed. The larger the surface roughness of the vegetation (a function of height and surface structure) the smaller the aerodynamic resistance gets. This allows more water to be evaporated, which is one of the factors that lead to higher evapotranspiration in forests, as they have a relatively rough surface area. On the other hand, the bulk or surface resistance incorporates the resistance of water passing through the stomata of plants and the vapour that evaporates from the soil. In the case of forests, which cover the surface almost completely, the soil part is relatively small, making stomatal resistance the main factor of bulk resistance. The stomatal resistance is controlled by the water status of the vegetation and the CO_2 concentration in the leaf as well as solar radiation. If the plant opens its stomata, it needs to balance between the loss of water and the concentration of CO_2 in the leaf, as it needs both for effective photosynthesis. Wide open stomata maintain a high CO_2 concentration for efficient photosynthesis, but also lose a great amount of water that needs to be re-supplied by the rooting system. Therefore, only plants with a good water supply are able to maintain high photosynthetic rate which also leads to a low bulk resistance for water vapour (Baumgartner, 1971; Bosch and Hewlett, 1982; Jackson, 1999; Jarvis and Davies, 1998; Jarvis et al., 1985; Le Maitre et al., 1999; Müller, 1996).

Only a small flux of sensible heat is emitted from forested surface as most of the energy leaves as latent heat, the flux of water vapour. A measure of this effect is the Bowen ratio. A low Bowen ratio is one of the main characteristics for the forest-atmosphere interaction (Flemming, 1994). As a contribution to the low Bowen ratio, especially after rain events, tree-stands intercept considerable amounts of rainfall (e.g. 80 % for Douglas fir (Otto, 1994)), which is then subject to evaporation, restricted only by the aerodynamic resistance. The way rain is intercepted by trees is very different between species. The most obvious difference appears between evergreen and deciduous tree species as the interception storage of deciduous trees becomes very small in winter as they have no leaves. Many deciduous species like the common beech (*Fagus sylvatica*) are also very different in their crown architecture. The angle of their branches and twigs are acute. The rain that falls onto the leaves can flow down on twigs to branches and then towards the ground producing stem flow. The water produces a very wet zone around the base of the stem. This leads to relatively high percolation rates which increase the soil water storage and reduces interception losses. Consequently, most evergreen tree species have a higher rate of interception than deciduous ones, because they keep the leaves all year and have less stem flow as a result of a different crown architecture (Hörmann et al., 1995; Jochheim et al., 2001; Zimmermann et al., 1999).

The combination of rooting strategy, interception losses, high surface roughness, low albedo and large leaf areas in forests lead to higher evapotranspiration rates for trees than any other vegetation type under the same environmental conditions (Bosch and Hewlett, 1982; Brown et al., 2005; Le Maitre et al., 1999; Lützke, 1991b; Mitscherlich, 1971). In addition to the great flux of latent heat from forested surfaces, trees also change the physical properties of rain. During the process of temporal interception, the rain loses part of its kinetic energy and then falls onto a soft, energy absorbing macro-porous litter layer that prevents any kind of mesoscale relevant surface runoff. This process is the reason why forests are of high relevance as water storage components, especially during convective rain events where they reduce peak flows (Bosch and Hewlett, 1982; Brown et al., 2005; Niehoff et al., 2002; Zhang et al., 2001).

1.1.2 Forest species and age class distribution at landscape scale

The most important attribute of forests in determining their hydrological properties is their spatial and temporal structural development. The structure of a forest is determined by the tree species composition and their age. In natural forests the scale and timing of a disturbance (e.g. wind throw (Ulanova, 2000) or fire (Thonicke, 2003)) forms a precondition for tree species composition and age class distribution, whereas the species of trees and their age determines the sensitivity to disturbances. In a natural landscape, it has been found that species are therefore distributed according to their ecological behaviour (Bugmann, 2001; Ellenberg, 1996). The potential natural vegetation in the federal state of Brandenburg would be dominated by common oak and other deciduous species (Berlin 2005; Ellenberg, 1996), but today's forest species composition is predominantly formed by forest management. The distribution of species we see today is a result of the need for wood supply in the time of afforestation. As a result, the forest in Brandenburg is dominated by Scots Pine by more than 70% (LFE, 2000). The species composition also influences the seasonal dynamics, also called phenological behaviour, of a forest because tree species are different in their timing of bud burst, leaf unfolding and leaf senescence.

The sequences of disturbances lead to different stages of forest development to appearing within a landscape on small areas that form a patchwork of different structures (Bugmann, 2001; Ellenberg, 1996, Kohlmaier et al. 1995). This leads to a scale dependent distribution of age classes. On a small scale, e.g. one hectare, the time since the last disturbance determines the stage of development and therefore the distribution of age classes. With specific relevance to the focus of this study, the landscape, the age classes are evenly distributed as different development stages form an equilibrium (Bugmann, 2001; Ellenberg, 1996). In managed forests, age class distribution is a result of the temporal distribution of harvest/afforestation actions which is tree species-specific.

1.1.3 Modelling forest dynamics and hydrology

"The complexity of a forest ecosystem makes difficult any attempt to synthesize knowledge about forest dynamics or to perceive the implications of information and assumptions regarding forest growth" (Botkin, 1972)

The understanding of these complex systems has fascinated ecologists for a long time. Consequently, there is wide range of models of different complexity describing forest dynamics and temporal development. They can be categorised into classes according to Chertov et al. (1999) as illustrated in Fig. 2.

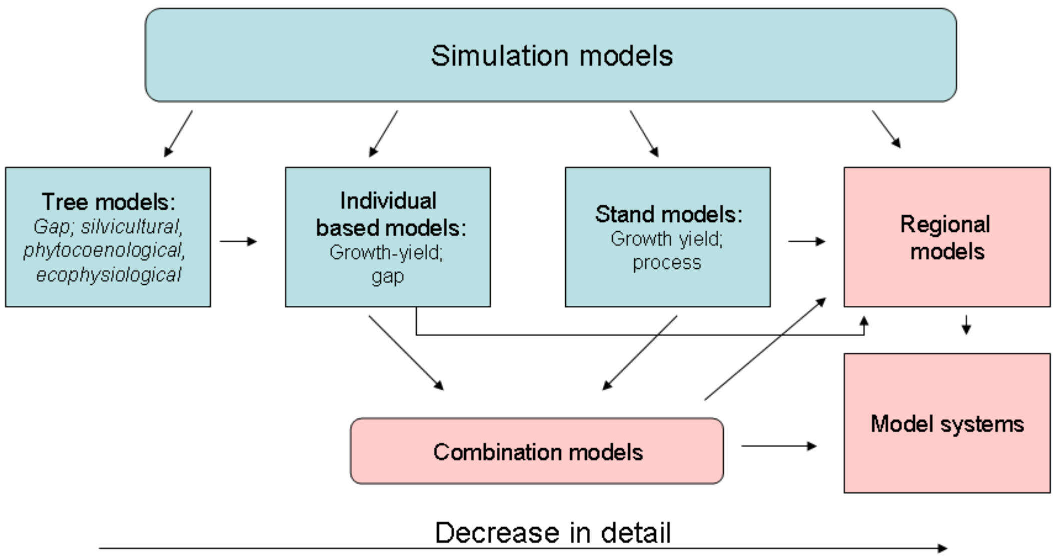

Fig. 2 A classification of simulation models for forest dynamics and tree growth respectively. The items in light red are considered as promising approaches for future development (Chertov et al., 1999)

Fig. 2 represents the models with the degree of detail decreasing from the left to the right. Following this scheme, tree models simulate an individual tree or group of trees and stand models group trees into stands and simulate them to form an ecosystem. Combined models integrate both concepts and regional models are even more simplified to be applicable at the landscape, regional or any higher spatial level. In order to realise the regional forest model envisaged by this study, Chertov et al. (1999) proposed the following steps:

- a spatial parameterisation of the forest structure in a landscape in combination with soil and climatic properties in land units using GIS (Geographical Information System);

- a compilation of types of forest dynamic for each land-use type and parameterisation of each stage of succession;
- the application of simplified combination stand models that take into account stand dendrometry and mass balance of organic matter and/or other substances
- all information must be integrated into GIS and can be combined with other models e.g. hydrology; and that
- results should be part of strategies for future land-use and forest management.

As Chertov et al. indicate, the combination of regional forest models with hydrological models can be a useful way of development. For a thorough analysis, it is also necessary to apply the criteria of Lindström et al. (1997) in order to make the model applicable at the catchment and landscape scale, respectively:

- the model shall be based on a sound scientific foundation;
- data demand must be met in typical basins;
- the model complexity must be justified by model performance;
- the model must be properly validated; and
- the model must be understandable by users.

In order to follow both sets of criteria in this thesis, the basic concept of an approach to simulate forest environmental interaction at the landscape and catchment scale, respectively, needs to be simplified as much as possible without neglecting the relevant processes embodied therein.

One of the key variables used in almost all forest models is the leaf area index (LAI) (Bugmann, 2001; Chertov et al., 1999). The LAI is defined as the projected leaf area in m^2 per ground area in m^2 making it a stand structure, tree species and age dependent value (Engel et al., 2002; Finch, 1998). It is the fundamental value to reflect and mathematically describe the surface of a forest stand that interacts with the environment. If we assume that it is possible to simulate the interaction of forests with the hydrological cycle based on a realistic LAI, the key demand for a landscape scale forest model is the ability to reproduce LAI accurately in space and time. As an example, the LAI of a Scots Pine stand (the most common tree species in the federal state of Brandenburg) can decline by natural mortality and management actions from 6.5 in a 25 year old forest to under 2.0 in a 120 year old stand (Hörmann et al., 2003). This change can trigger a substantial shift in the hydrological properties as demonstrated by Bouten and Jansson (1995), Gärdenäs and Jansson (1995), Jenssen (1997) and Wegehenkel et al. (2001). The same pattern can also be observed for deciduous tree species (Hörmann et al., 2003).

There are a number of forest growth models, which are able to simulate growth and the development of single trees or forest stands under different environmental conditions and at different scales of complexity (Badeck et al., 2001; Bugmann, 2001; Chertov et al., 1999; Pretzsch, 2001). However, all of them have a forest science focus, aiming chiefly to simulate environmental impact on forest growth and ecology and to a lesser extent looking at the impact of changes in forest's structure and species composition on the water cycle at the landscape scale. Most forest models, even models with lower process resolution, are rather complex from the catchment modeller's point of view. As an example, ForestBGC (Running, 1994; Running and Gower, 1991), a model of moderate process resolution incorporates 48 parameters and needs 11 initial variables to run. The data demand of such a model cannot be fulfilled in regional applications in most cases, making them inapplicable for the purpose of this thesis. Thus, these models all fall short of the Lindström et al. (1997) requirement that data demand must be met in typical basins.

1.2 The landscape of the federal state of Brandenburg

The federal state of Brandenburg is situated in the eastern part of Germany. It is characterised by a glacially formed landscape. The area can by divided into three zones that are unique in landscape and formation. The southern part of Brandenburg (Fig. 3) was formed in the Warthe-stage of the Saale glaciation. It is characterised by a strong relief emerging in the south-west passing eastwards in a range of ice pushed ridges. Northwards the country is dominated by three great Weichsel glaciation runoff valleys. They form a flat boggy landscape (Fig. 4) that is only partly interrupted by plateaus of different genesis (pushed by ice, fluvial or wind borne sand). The area is rich in lakes and is drained by the Havel–Spree river system into the Elbe River. The Nuthe catchment forms a part of the Havel–Spree river system in the central part of the state. Most of it is a flat boggy landscape that is only partly interrupted by sandy plateaus. The catchment drains into the Havel River in the vicinity of Potsdam. The runoff is highly anthropogenically controlled.

Fig. 3 The Elbe-Elster region in the south west of Brandenburg on the edge of the Elbe basin.

Fig. 4 The Havelland in the central part of Brandenburg is dominated by boggy soils.

Only small parts of the state at the eastern border drain into the Oder river system like the Stöbber catchment. The landscape of this small catchment is characterised by rolling hills, bog lands and some lakes, most prominently the Schermützelsee. The runoff is highly regulated and also buffered by lake water bodies which represents a typical situation for many areas in the state of Brandenburg (e.g. the Nuthe river). Further North the landscape

(Fig. 5) was formed during the latest glaciations, the Weichsel ice age. The dominant surface forms are downy ground and end moraines incised by valleys and lakes.

Fig. 5 The Uckermark region in the northern part of Brandenburg dominated by fertile soils with a high percentage of agriculture.

Over the whole area of the state, the soils have a decreasing fertility from the north to the south, only interrupted by the organic and fluvial soils in the great valleys. The terrestrial soils are mostly sandy and sandy loam. These sandy soils are widely covered by monocultures of Scots Pine, which is the dominant species and covers 79% of the state's forested area, enriched only by Oak (*Quercus robur* and *Q. petraea*) in 4% of the area, and Common Beech (*Fagus sylvatica*) in 2%. Around 50% of the state area is used for agricultural production (1,339 Mha in the year 2002), with 77% under crop production and 22% covered by grassland. 50% of the crops are cereals, mainly rye and winter wheat, and 13% oilseeds. The climate of the federal state is characterized by the transition from sub-oceanic in the north-western part to sub-continental conditions in the south-east. This climatic gradient is reflected by a decrease of annual average precipitation from more than 600 to less than 500 mm and an increase in temperature average and range from the west to the east (LFE, 2000; MLUR-Brandenburg, 2003; MLUR-Brandenburg and Berlin, 2002; Müller-Stoll, 1955; Scholz, 1962)

The federal state of Brandenburg in Germany was chosen as a case study in this thesis as it has the preconditions to be sensitive to land-use change because:

- Brandenburg is dominated by poor sandy soils, low precipitation and negative climatic water balance during the summer, placing agricultural production at high risk of drought with a high demand for fertilizers and irrigation. The resulting high production costs can lead to an increase in areas that might not be used for agricultural production, and are thus available for afforestation under changing subsidies. Decreasing groundwater levels in many areas, in turn, restrict irrigation attempts (Landgraf and Krone 2002; Gerstengarbe et al. 2003). These environmental conditions make it an exemplar for a landscape with a low climatic water balance in Europe;
- Forests cover 37% of the state area. The predominant tree species (79%) is Scots Pine (Pinus sylvestris), which causes problems such as a low groundwater recharge rate compared to deciduous species (Mueller, 2002, Lasch et. al. 2005, Fuerstenau et al. 2007), high risk of forest fires (Thonicke, 2003, Zebisch et al., 2005) as well as pests and diseases such as forest defoliator calamities (Hodar et al. 2003, MLUR-Brandenburg and Senat Berlin, 2002) All these factors produce pressure for a change towards a more natural tree species composition; and
- Due to the critical ecological preconditions, the projected rises in temperatures, as well as the decreasing summer precipitation, increase the risk of summer droughts, making water availability a crucial topic in Brandenburg. Furthermore, climate change could accelerate the process of the abandonment of arable land and further increase the risk of forest fires (Gerstengarbe et al., 2003, Zebisch et al., 2005).

1.3 European agricultural policy

Until 1992 European agricultural production was only marginally controlled by world market prices due to a complex protective subsidy system. The system, called the Common Agricultural Policy (CAP) was introduced in the 1950s. After the experience of famines in Europe during the previous centuries, farm incomes and a high supply level of agricultural production were maintained by manipulating producer prices (intervention, import duties). However, as it resulted in overproduction and runaway costs for subsidies, the EU started a massive reformation of the system in 1992 which led to a general decrease in subsidies and moved the focus away from production support. These first steps became famous as the so called “MacSharry” reform. They included a reduction of support prices for a number of agricultural products and an introduction of direct payments to compensate farmers for income losses. In addition, an obligatory set-aside scheme was implemented to withdraw land from production in addition to the introduction of payments to limit stocking levels and measures to encourage land retirement and forestation (Freibauer et al., 2004; Potter and Goodwin, 1998; Wikipedia, 2006). These measures reduced the correlation of subsidies with production and led to a significant percentage of set-aside land (around 10%). There was also strong pressure from the WTO (World Trade Organization) Doha negotiations to lower subsidies and introduce world market prices within the EU. In addition, the expansion of the union to the east led to a low acceptance of even higher expenses for agriculture in the society of the existing member states. The response was the implementation of "Agenda 2000" in 1999 with a planning horizon to 2006. The measures entailed a further reduction of production-related subsidies and the introduction of direct payments in order to maintain rural communities without subsidising non-world market oriented agricultural production. The focus was also moved towards environmental protection and conservation of the rural landscape. The effects of the CAP reform since 1992 were subject to a review in 2003, the so called Mid Term Review (MTR) (EU, 2003b). The key elements of the CAP reform including the MTR results are (European Commission, 2003) can be summarised as:

- a single farm payment for EU farmers with a transition towards a unified area based payment, independent from actual production (decoupling);
- this payment will be linked to the respect of environmental, food safety, animal and plant health and animal welfare standards ("cross-compliance");
- a strengthened rural development policy by the redirection of subsidies;
- redirection of a proportion of CAP subsidy payments into agro-environment and rural development schemes ("modulation") for bigger farms to finance the new rural development policy;
- a mechanism for financial discipline to ensure that the farm budget fixed until 2013 is not overshot;
- revisions to the market policy of the CAP;
- asymmetric price cuts in the milk sector, subvention for milk will be merged with the area related payments in 2013;
- seasonal correction for intervention price ("monthly increments") for cereals reduced by 50%; and
- reforms in the rice, durum wheat, nuts, starch potatoes and dried fodder sectors.

The consequences for the landscape pattern in Europe were, in the first place, a manifestation of the 1991 land-use as a status quo. The reason was that the "MacSharry" reform made land eligible for support only if it was under agricultural production at the time of its enforcement on the 31st December 1991. Therefore, it was not possible to convert agricultural land into any other land-use without the loss of financial support (Freibauer et al., 2004). Due to the changes implemented since 1999, the future of agriculture in Europe is now much more flexible and changes in land-use, especially a decrease in agricultural land under food crop production, is highly probable (Busch, 2006; Metzger et al., 2006)

1.3.1 The European agricultural policy impacts on Brandenburg

The effects of the first steps of the CAP reform in 1992 were the subject of an integrated study by Bork et al. (1995). The focus of the study was very much on the interacting effects of subsidy changes and the effects of production changes due to the breakdown of the former communist system in East Germany post 1989. The area of their study was 9300 square kilometres in the north east of Brandenburg. They could show that economic success of the specific agricultural production system in East Germany, in the form of rural cooperatives, was a major factor in the impact of changes in the economic boundary conditions. In cases of economic failure their scenario analysis showed a quite high percentage of abandoned land. One of the most sensitive environmental issues was that of groundwater recharge, which decreased with decreasing agricultural area under production, especially if it had been converted to forest. Based on their findings and the updated information about the future development of CAP reform and its possible consequences for the state, the following scenarios were assumed to be critical for the future development of forest area and species composition.

In the first scenario, the external driving force causing change in the landscape structure is the reformation of the EU-Common Agricultural Policy (CAP) termed here the "partial liberalisation scenario". It was assumed to be a plausible cause for changes for three reasons beyond those outlined in section 1.2. These are:

- Firstly, rural cooperatives manage great areas (30% of the farms are greater than 100ha (LDSP, 2005b)). These cooperatives are able to temporarily set-aside or fully cease production in large areas to optimize their production. On the other hand, if the large cooperatives stop production (due, for example, to insolvency) large areas may be permanently set-aside. Both situations increase the probability of potential loss of agricultural area, which is then available for afforestation;

- Secondly, a high percentage of Rye (*Secale cereale)* in comparison to other areas in Germany is grown. Rye is excluded from the intervention system since 2003 which implies an even stronger reduction in subsidies than for other cereals (European Commission, 2003); and
- Thirdly, a declining and aging population in peripheral regions leads to a loss in the qualified workforce (MLUR-Brandenburg, 2003) which may cause a loss of agricultural production and increase of set-aside land.

1.4 The development of forest species composition in the state area

Scots Pine has become dominant since the forest management of the last century was focused on industrialised wood production and consequently other services like groundwater recharge and biodiversity were neglected (Berlin, 2005). Today, the central aim of the governmental forest management authority is to shift to mixed and deciduous forests that reflect the local environmental conditions. The target date for completion of this conversion is 2045, with an increase of deciduous tree species from 16% (1996) to 19%, and of mixed stands from 14% to 37% projected (LFE, 2000). The consequences of even more ambitious targets for forest conversion of all pine forest to deciduous species are assumed in the scenario and the landscape response is investigated in this study.

1.5 Objectives

The federal state of Brandenburg provides a test bed for recent and potential changes in landscape structure caused by policy decisions taken at the governmental level of the European Union and the federal state. The state is sensitive to a shortage of water supply, especially from shallow groundwater due to its environmental conditions. It is, therefore, imperative to evaluate the effects of land-use changes in an integrated way in order to identify sustainable development trajectories. Here, two scenarios are evaluated in regard to their impact on the water balance of the federal state. The first scenario assumption of less European agricultural subsidies leads to a permanent set-aside of arable land which is subsequently turned into forest.

- The first objective of this thesis is to quantify the scenario effect on the water cycle in the state at the landscape scale.
- In objective two, the consequences of the second scenario for the conversion of the Scots Pine dominated forest towards deciduous forests initiated by the local forest authorities is investigated.
- Objective three is to first analyse the ecohydrological model SWIM in order to investigate its potential to simulate the scenario effects.
- The implementation of the modifications identified in objective three to be necessary to simulate forest growth and its interaction with the hydrological cycle represents the forth objective of this thesis.

2. Methods

The method section presents the basic concepts of the eco-hydrological model SWIM. It provides the basis for the development of the forest module and scenario analysis. The first part describes those elements of the model that are relevant to the objectives of this thesis and a brief summary of the other hydrological components is provided. This first part also explains the concept of the forest module approach. The second part introduces the concept of sensitivity and uncertainty analysis which is used to analyse and test the model. The third part describes the data used to run the SWIM model for the state area of Brandenburg as well as for the pre-study catchments. The last part defines the scenarios used in the analyses

2.1 The eco-hydrological model SWIM

2.1.1 The basic concept of the model

The SWIM model has been developed to simulate hydrology and water quality at the mesoscale (100-10000 km²) and integrates hydrology, vegetation growth, erosion, and nutrient dynamics at the watershed and regional scale (see Fig. 6). It originates from three older models named the CREAMS–Model (Chemicals, Runoff and Erosion from Agricultural Management Systems (Knisel, 1980)), SWAT (Soil Water Assessment Tool (Arnold et al., 1994)) und MATSALU (Krysanova and Luik, 1989; Krysanova et al., 1989). The structure and fundamental concepts of the SWAT model form the backbone of the SWIM model, and additions from the others are implemented in order to adapt the SWAT concept to middle European conditions.

The potential evapotranspiration is calculated in SWIM and the method can be, as in SWAT, selected on basis of data available to be either Priestley-Taylor (Priestley and Taylor, 1972) or Penman-Monteith (Monteith, 1965). Actual evapotranspiration is then estimated based on Ritchie (1972). Snow melt follows the Knisel (1980) approach. The proportion of the rain contributing to the surface runoff is estimated using the US Soil Conservation Service (SCS) curve-number approach (Arnold et al., 1990). The next level in the runoff cascade, that of interflow, is determined by Sloan et al. (1983) in their approach to the cinematic storage model. In turn, the groundwater module uses the simple linear storage model of Smedema and Rycroft (1983). The dynamics of nutrients in the model is described by Seligman and van Keulen, (1991) and Krysanova and Wechsung (2000). The actual river routing routine is based on the simplified approach of Maidment (1993) whilst sediment transport is described in Krysanova and Wechsung (2000).

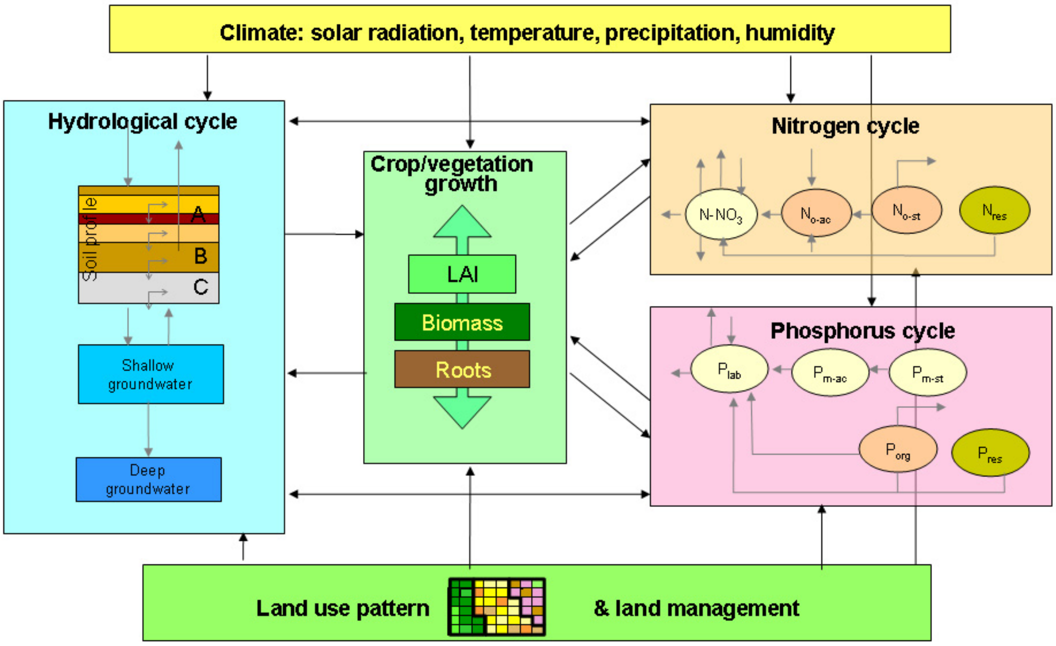

Fig. 6 The structure of the SWIM model and its input data requirements. The core of the model is the hydrological module which interacts with the vegetation part and the Nitrogen and Phosphorus cycle. Driving variables are land-use and climate.

The simulation routine follows a three level semi-distributed disaggregating scheme 'basin – sub-basin – hydrotope' and is coupled to the Geographic Information System GRASS (Neteler and Mitasova, 2007). A hydrotope or HRU (hydrological response unit) is defined by its unique combination of sub-basin, land-use and soil type (Krysanova and Müller-Wohlfeil, 1998; Krysanova and Wechsung, 2000). This model has been used extensively in studies to analyse the effects of land-use and climate change (Hattermann et al., 2004; Hattermann, 2005; Hattermann et al., 2005; Krysanova et al., 2005a; Krysanova et al., 2005b; Krysanova et al., 1999; Wechsung et al., 2000). These studies also reveal the hydrological concepts beyond the vegetation-hydrology interaction. The final reason to use the SWIM model in this study is its clear process orientation and the incorporation of all major aspects to analyse a landscape in an integrative way (Hattermann, 2005).

2.1.2 Vegetation growth in the unmodified version of the model

The vegetation growth is computed at hydrotope level with a daily time-step using a simplified EPIC approach (Erosion Productivity-Impact Calculator (Williams et al., 1983)). The EPIC model has been developed to assess the effect of soil erosion on agricultural productivity. It is able to simulate the effects of management decisions on soil, water, nutrient, pesticide movements and their combined impact on soil erosion, water quality, and crop yield. The key factors for the growth description within EPIC are temperature and radiation. The crop phenology is simulated using the concept of heat units (Boswell, 1929; Magoon and Culpepper, 1932).

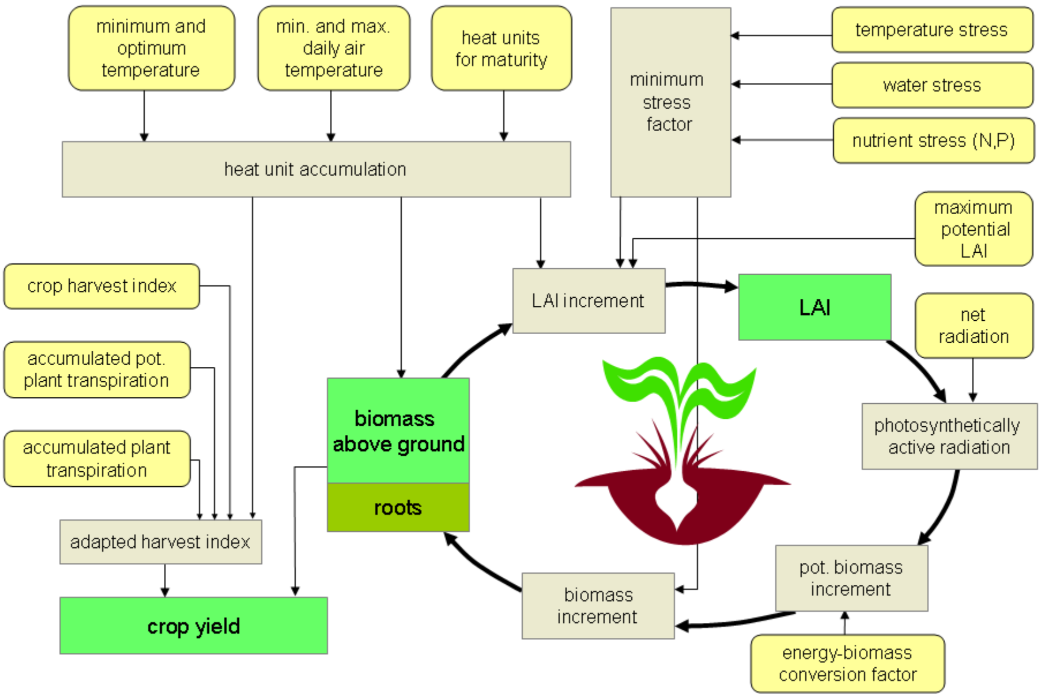

Fig. 7 The vegetation module in the original SWIM model and its input parameter and variables (yellow) internal parameters and variables (grey) and plant components (green) modified from Hattermann (2005).

The key idea is that plants require a species-specific defined sum of heat to reach maturity and that they will not grow below a certain minimum temperature (T_{base}). Based on this approach it is possible to calculate the heat units of a day (HU) from mean air temperature (T_{av}) above the minimum temperature threshold

$$HU = T_{av} - T_{base} \qquad if\ T_{av} > T_{base} \qquad \text{Eq. 1}$$

Within the SWIM and SWAT model the growth rate is assumed to be directly proportional to the increase in temperature. Over the growing season the sum of heat units (PHU) is calculated until it reaches the amount of units that is required for maturity starting at d = 1 on the day of planting

$$PHU = \sum_{d=1} HU \qquad if\ PHU \leq PHU_{\max} \qquad \text{Eq. 2}$$

The heat unit requirement (PHU_{max}) is a plant specific parameter. For forests and perennial vegetation the day of bud burst is defined as d = 1. The main focus of the model is on annual vegetation, though, to be applicable to non-agricultural catchments, assumptions about perennial vegetation including tree species were introduced into the vegetation growth routine in the SWIM/SWAT model complex (Neitsch et al., 2002). The concept of dormancy is used to account for the time of the year where perennial vegetation is present but does not grow. The time of dormancy is calculated based on a threshold day length. If the minimum day length of the year in a catchment is shorter than the threshold day length the plants that are not summer annual crops enter dormancy. In the case of trees, the leaf biomass is converted into residue and the LAI is set to a defined minimum value. Trees are also assumed to maintain their rooting system and to allocate 70% of their biomass increase into wood tissue, and only 30% into leaves during the growing season. With the onset of the growing season, defined either by the day of planting or the end of the dormancy period, the plant starts to grow driven by the interception of light that is directly converted into biomass assuming a plant species-specific radiation-use efficiency (RUE). The amount of light that can be intercepted is a function of LAI employing Lambert-Beer's law (Monsi and Saeki, 1953):

$$H_{photo} = 0.5 \cdot H_{day} \cdot \left(1 - \exp^{(k_l \cdot LAI)}\right) \qquad \text{Eq. 3}$$

where H_{photo} is the amount of intercepted photosynthetically active radiation on a given day (MJ m-2), H_{day} is the incident total solar radiation (MJ m-2), $0.5 \cdot$ is the proportion of this radiation that is photosynthetically active, k is the light extinction coefficient, and LAI is the leaf area index (Neitsch et al., 2002).

The biomass increase can then be estimated assuming a linear relationship between incoming intercepted photosynthetic active radiation and canopy photosynthesis (Monteith, 1977)

$$\Delta bio = RUE \cdot H_{photo} \qquad \text{Eq. 4}$$

where Δbio represents the increase in biomass; RUE is the radiation use efficiency and H_{photo} the intercepted photosynthetic active radiation.

These are the key features of the vegetation growth module. Once the potential vegetation growth is established it interacts with other components of the model to calculate the actual growth based on CO_2 concentration and water as well as nutrient availability. Fig. 7 modified from (Hattermann, 2005) gives a comprehensive insight of the vegetation growth model structure.

2.1.3 The implemented forest growth module

Some of the elements of vegetation growth, like the described calculation of biomass increase, have been retained in the forest module. However, LAI calculation and phenology, needed modification in order to work for middle European forests (Fig. 8). The key element of the forest growth approach is an allometric function for the ratio of leaf biomass to total biomass that is given by an age-dependent exponential function (Eq. 6). This ratio is then used to delineate LAI from daily total biomass. It follows the classical form of allometric functions widely used in forest research (Bugmann, 2001; Burger, 1947; Burger, 1948; King and Grant, 1996; Mitscherlich, 1971; Pretzsch, 2001; Whittaker and Marks, 1975) that is based on the “principle of allometrie” (Eq. 5) (Huxley, 1950). Huxley discovered that the size of an organ in relation to the total body or any other organ of a tree can be expressed as a power dependence:

$$y = bx^{\alpha} \qquad \text{Eq. 5}$$

where the size of part y is related to the size of part x by factor b and exponent α. In the case of the forest module y would represent the leaf biomass and x the total biomass.

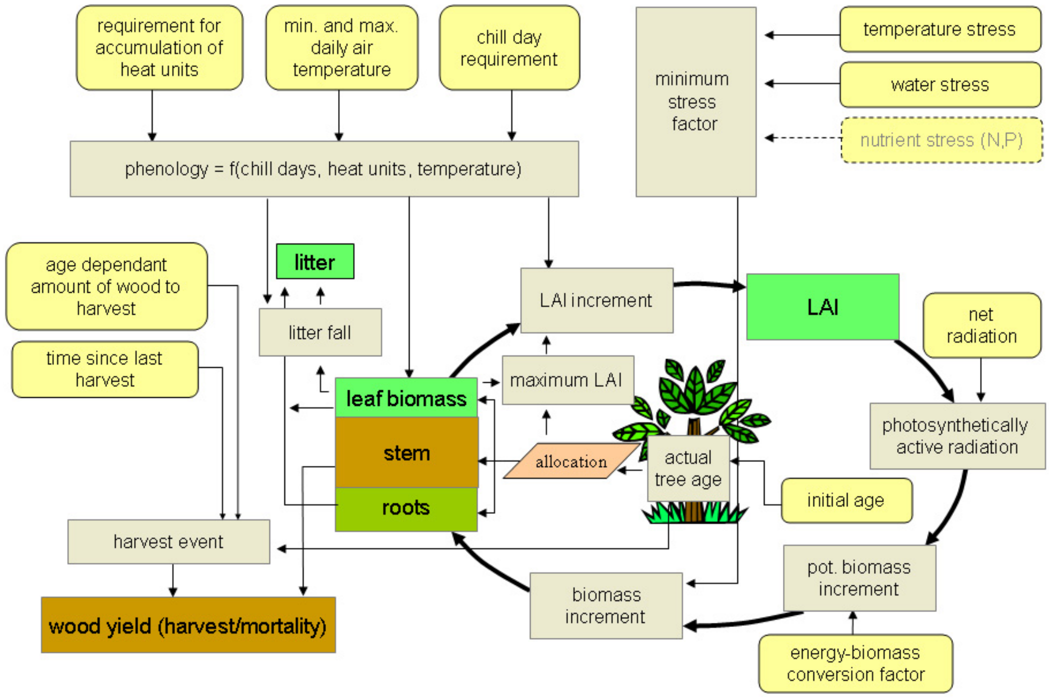

Fig. 8 The implemented forest growth module in SWIM. The main change in comparison to the original vegetation growth module (Fig. 7) arises from the growth calculation by the introduction of age to control the allocation into the different biomass pools. The age is therefore controlling the LAI increment using a dynamic maximum LAI, as well as the harvested biomass, and indirectly the amount of litter and biomass increase. The second essential change is the introduction of phenology as a controller for the LAI increment and litter fall. Input parameters and variables (yellow), internal parameters and variables (grey), woody biomass (brown), living plant components (green).

Huxley (1950) also discovered that α represents the ratio of the different growth rates as an age-dependent value. In order to calculate the age-dependent, tree species-specific leaf biomass to total biomass ratio (k_{foli}), Huxley's equation is combined with a classical exponential growth function (e.g. Chertov et al. (1999; Pretzsch (2001)). k_a, k_b and k_c are species-specific parameters and x_{age} is the age of the stand in years:

$$k_{foli} = k_a \cdot e^{(k_b \cdot x_{age})} + k_c \qquad \text{Eq. 6}$$

The parameters k_a, k_b and k_c can be estimated from long-term measurements (Burger, 1947; Burger, 1948). The daily potential maximum $LAI_{max,i}$ for each stand is calculated based on total above ground biomass bio_i (kg ha^{-1}) :

$$LAI_{\max,i} = \left(\frac{k_{fafw}}{k_{wdr}} \cdot (bio_i \cdot k_{foli}) \right) \cdot f_c \qquad \text{Eq. 7}$$

where $LAI_{max,i}$ denotes the maximum LAI at day i and k_{fafw} is the specific leaf area ($m^2\ kg^{-1}$), k_{wdr} indicates the ratio of wet to dry biomass (%), bio_i ($kg\ m^{-2}$) is the above ground biomass and f_c converts all-sided leaf area to projected one sided leaf area (LAI) and ha to m^2. The initial value for bio_i for i=1 is calculated from the forest stand initialisation. Any hydrotope is defined by a uniform forest stand with an initial total above ground biomass and age value. The above ground biomass is calculated based on inventory data using the total stand volume to compute the woody biomass and the DBH (diameter at breast height) to estimate the leaf biomass (Bugmann, 1994; Burger, 1947; Burger, 1948; Cannell and Dewar, 1994). After initialisation, biomass increase is calculated according to the original SWIM equations.

Critical for the correct representation of the LAI dynamic is the calculation of the phenology. The start of the growing season is simulated by using the empirical phenological model developed by Cannell and Smith (1983) in a version modified by Menzel (1997a). For Oak, the Germany-specific parameterisation of Schaber (2002) has been used instead of the Menzel (1997a) parameterisation as done for Scots Pine. The model is based on the assumption that an increasing number of chill days in winter will reduce the temperature sum that is required as stimulus in spring. The model postulates a logarithmic reduction of a critical temperature sum (TT_{criti}) by chill days (CD):

$$TT_{crit} = a + b \cdot \ln(CD) \qquad \text{Eq. 8}$$

where a and b denote species-specific parameters. The chill days are the number of days, starting from the first of November (i_1 = 305) when temperature falls below a threshold ($T_{B,cd}$) given as a plant specific parameter, to the day when the growing season starts:

$$CD = \sum_{i_1}^{i_{\max}} 1 \qquad if\ T_{aver,i} \leq T_{B,cd}\ in\ {}^oC \qquad \text{Eq. 9}$$

$T_{aver,i}$ indicates the daily average temperature (°C) and i_{max} denotes the day of the start of the growing season. The start of the growing season is calculated as follows: after the first of February (i_2 = 32), a thermal time is computed according to a temperature sum model

(Arnold et al., 1994). The temperature surplus (TT) (Eq. 10) is computed for days when the temperature exceeds the base temperature ($T_{B,st}$):

$$TT = \sum_{i_2}^{i_{max}} (T_{aver,i} - T_{B,st}) \qquad if\ T_{aver,i} \geq T_{B,st}\ in\ ^oC \qquad \text{Eq. 10}$$

The growing season starts when the temperature sum of TT exceeds the critical temperature sum (TT_{criti}) which is defined as plant specific parameter.

parameter	**symbol (unit)**	**value**	
		Scots Pine	Common Oak
allocation	k_a (no unit)	1.792	0.1026
	k_b (no unit)	-0.109	-0.0569
	k_c (no unit)	0.0249	0.0059
	f_c (no unit)	0.00004	0.00005
specific leaf area	k_{fafw} (m^2kg^{-1})	6.0	12.0
	k_{wdr} (%/100)	0.45	0.35
management/mortality	B_m (kg ha^{-1})	2500	1800
phenology	a (°C)	1394.5225	3175.68
	b (°C)	222.7066	579.73
	$T_{b,st}$ (°C)	5	5.69
	$T_{b,cd}$ (°C)	9	19.44
base temperature	T_b (°C)	0.0	3.0
optimum temperature	T_o (°C)	15.0	20.0
attenuation coefficient	k (no unit)	0.65	0.65
biomass energy ratio	BE (kg MJ^{-1})	16	16

Tab. 1 Parameters for the forest growth calculation

2.1.3.1 Modelling spatial distribution of species and age classes

In order to simulate the distribution of forest types and ages classes, aggregated frequency distributions for the total state area are used as the boundary condition for their spatial appearance in each grid cell or hydrotope. In a distribution generator approach, it is assumed that the different ecological preferences of trees for soil quality are a predictor for their appearance within a landscape (Fig. 9). As a first step, all grid cells or hydrotopes are classified and ranked according to a soil quality measure such as available field capacity. In the second step, the low quality units are filled until the probability for the appearance of this particular species with the lowest ecological preferences within the landscape is fulfilled (e.g. Scots Pine). The next units, which are consequently higher in their soil quality measures, are filled with the next species with higher ecological preferences (e.g. Norway Spruce – *Picea abies*) until its probability of its appearance is fulfilled. This continues within each of the SWIM land-use classes: evergreen, deciduous and mixed forest until the probability for each species under consideration is reached. In each step the tree species, which is assumed to occupy the grid cell, is supplied with an age attribute following the probability of age classes defined by the species-specific age class distribution for the area under study. Using the mean stand volume, the mean diameter at breast height and the number of trees per unit area, the total biomass is estimated and forms an additional attribute for the grid cell or hydrotope. The process depends on the number of grid cells or hydrotopes, as a very small number will prevent the algorithm from fulfilling the probability of appearance for the species and age classes. The approach is therefore only applicable for mesoscale to macroscale application, with many more spatial units than age classes over all tree species.

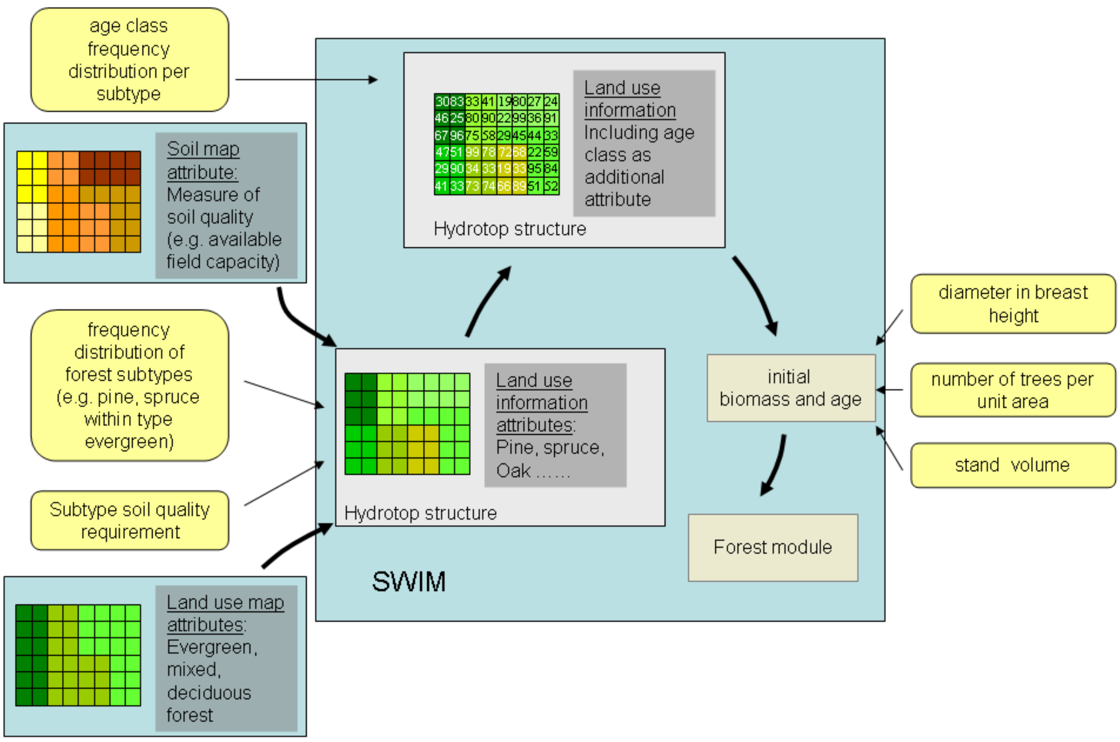

Fig. 9 The forest species and age class distribution generator approach.

2.1.4 Vegetation water cycle interactions of the unmodified model

There are three central points of interaction between the water cycle in the original SWIM model and the vegetation growth part (Fig. 10). The first and most important interaction is root water uptake, which is driven by the atmospheric water demand and influenced by the soil water content. Within a daily time-step (t) the water demand is distributed over the rooting profile using an exponential function:

$$w_{up,z} = \frac{E_t}{[1-\exp(-\beta_w)]} \cdot \left[1-\exp\left(-\beta_w \cdot \frac{z}{z_{root}}\right)\right] \qquad \text{Eq. 11}$$

$w_{up,z}$ is the potential water uptake from the surface to the depth z, E_t is the potential plant transpiration, β_w stands for the water uptake distribution coefficient. In SWIM and SWAT soils are divided into layers so that equation eleven is solved for each layer by calculating the water uptake for the top and the bottom depth (Neitsch et al., 2002). At this point, it is important to mention that the distribution of water uptake is highly dependent on the number of layers. Hence, it is important to have an equal layering for all soils in order to prevent computational artefacts. The actual water uptake is then calculated based on the equation:

$$w_{ua,z} = w_{up,z} \cdot \frac{W_{s,z}}{0.25 \cdot AWC_z} \qquad W_{s,z} \le 0.25 \cdot AWC_z \qquad \text{Eq. 12}$$

$$w_{ua,z} = w_{up,z} \qquad W_{s,z} \ge 0.25 \cdot AWC_z \qquad \text{Eq. 13}$$

$w_{up,z}$ is the potential water uptake from the surface to the depth z, AWC_z is the plant available water content and $W_{s,z}$ the actual soil water content.

The soil water status has implications for all runoff components. The first runoff component affected is the surface runoff or surface drainage. The ability of the soil to absorb water from incoming precipitation depends from its water saturation. The SWIM model uses the United States Soil Conservation Service SCS method to calculate the surface runoff whenever the rate of water reaching the soil surface is higher than the infiltration rate.

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \qquad \text{Eq. 14}$$

Q_{surf} is the excess of water, R_{day} is the rainfall of the day in mm, and I_a is the initial abstraction (interception, infiltration, surface storage). S is the retention coefficient which is influenced by the soil moisture conditions. It is defined as:

$$S = 25.4\left(\frac{25400}{CN} - 254\right) \qquad \text{Eq. 15}$$

CN is the curve number for certain conditions. The curve number is defined for a number of discrete soil moisture conditions (dry, moist, wet), soil type classes (A-high infiltration, B-moderate infiltration, C- slow infiltration, D- very slow infiltration) and land cover types (Neitsch et al., 2002). Land cover type is obviously a parameter defined by the vegetation; however, as this is a constant value for a simulation, it is not regarded as an interaction.

The second runoff element that is influenced by the soil water status is the subsurface drainage or interflow. Water, which has infiltrated into the soil, percolates through the soil layers using a storage routing technique (Arnold et al., 1990). The water storage of the soil is affected by the uptake of water by plants, $w_{ua,z}$,changing the water contents of the soil layer W_{Si}.

$$P_{erc_t} = W_{S_{t+1}} - W_{S_t} = W_{S_t}\left[1 - \exp\left(\frac{-\Delta t}{T_T}\right)\right] \qquad \text{Eq. 16}$$

T_T is the travel time through each layer in hours and is calculated with a linear storage equation. Lateral subsurface flow or interflow is calculated simultaneously with percolation using a kinematic storage model developed by Sloan et al. (1983). Interflow occurs in a given soil layer if the soil layer below is saturated, so that the amount of base flow increases with increasing values of saturated soil conductivity (Hattermann et al., 2005).

The water that finally percolates out of the lowermost simulated soil layer contributes to the groundwater recharge (R_c). Therefore, the vegetative uptake of water from the soil also influences this last element in the runoff cascade, that of the groundwater flow (q). The equations for groundwater flow and groundwater table depth are based on the model of Smedema and Rycroft (1983), assuming that the variation in return flow q (mm d^{-1}) at time-step t is linearly related to the rate of change in water table height h (m):

$$q_t = q_{t-1} \cdot \exp(-\alpha \cdot \Delta t) + Rc_{\Delta t} \cdot (1 - \exp(-\alpha \cdot \Delta t)), \qquad \text{Eq. 17}$$

$$h_t = h_{t-1} \cdot \exp(-\alpha \cdot \Delta t) + \frac{Rc_{\Delta t}}{0.8 \cdot S \cdot \alpha} \cdot (1 - \exp(-\alpha \cdot \Delta t)) \qquad \text{Eq. 18}$$

Here Rc is the groundwater recharge in mm per day and S is the specific yield (m^3 m^{-3}). The reaction factor α is a function of the hydraulic transmissivity T (m^2 d^{-1}) and the slope length L (m). The groundwater module is described in detail in Hattermann et al. (2004).

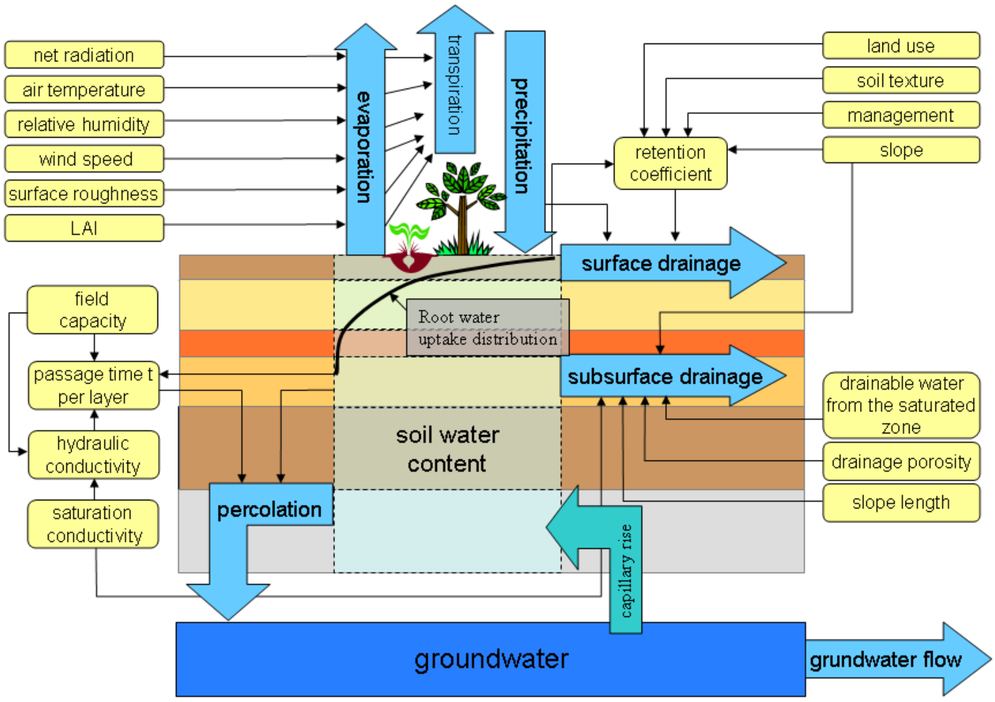

Fig. 10 The implementation of the vegetation water cycle interaction as it is implemented in the unmodified SWIM model, modified from Hattermann (2005).

2.1.5 Vegetation water cycle interactions in the forest version of the model

Two essential modifications were required for the inclusion of the forest module into the SWIM model in order to simulate the effects of forest area and species change. The first one was the interception of precipitation, and the second, the forest specific root water uptake from the soil profile (Fig. 11).

The simulation of interception is accomplished using a modified version of the Menzel (1997b) approach that has been tested for a broad range of vegetation types (Menzel et al., 1998). The basic advantage of this approach is its ability to simulate the different characteristics of deciduous and coniferous tree species with a distinct number of parameters on a daily time-step. For the description of the interception of precipitation, the maximum storage capacity $R_{int,pot,i}$ (mm) is calculated on a daily basis. For Oak, a logarithmic relation is assumed:

$$R_{\mathrm{int},pot,i} = f \cdot \left[\log(1 + LAI_i)\right] \qquad \text{Eq. 19}$$

where *f* denotes a species-specific parameter. The species-specific parameter *f* describes the relationship between increasing LAI and the extension of storage capacity. The value of *f* is set to 2.0 assuming that the storage capacity reaches 1.8 at a LAI of 7. If the LAI_i declines to zero in autumn, a residual value of 0.5 for $R_{int,pot}$, as storage capacity of the leafless trunk with twigs and branches, is assumed (Larcher, 1994).

A linear relation of LAI development to storage capacity is assumed for Scots Pine (Eq. 20) (Jenssen, 1997). The values used in the model are 2 mm for $R_{int,pine}$ at a LAI of 4. If the actual LAI_i exceeds 4, the storage capacity continues to increase linearly (Jenssen, 1997; Larcher, 1994; Otto, 1994; Rutter et al., 1971; Schröder, 1984; Schröder, 1985):

$$R_{\text{int},pot,i} = R_{\text{int},pine} \cdot \frac{LAI_i}{4} \qquad \text{Eq. 20}$$

where $R_{int,pine}$ is the maximum storage capacity (mm). The maximum storage capacity is filled only during a heavy rain event. The reason for this effect is that an increased saturation of the canopy leads to an increase in the part of the rain that is only temporally stored and later drops through or occurs as stem flow. Based on those approaches, the model postulates an exponential relationship between precipitation and actual storage (Hörmann et al., 2005; Menzel, 1997b):

$$R_{\text{int},i} = R_{\text{int}(f),i} + (R_{\text{int},pot,i} - R_{\text{int}(f),i}) \cdot \left[1 - e^{(-c \cdot p_i)}\right] \qquad \text{Eq. 21}$$

where $R_{int,i}$ represents the actual storage (mm), $R_{int(f),i}$ is the storage residue of the day before (mm) and p_i denotes the precipitation (mm) and c represents a species-specific parameter.

The species-specific parameter *c* describes the slope of the saturation curve. The slope represents the complex process of the partitioning of water into through-fall and stem flow in a simplified way. Based on Otto (1994), the value of *c* has been set to 0.4 for pine and 0.7 for oak, respectively. The evaporation of intercepted rain is computed in the same time-step as storage filling, assuming that evaporation of intercepted rain occurs during the day of rain. This is defined as:

$$E_{a,i} = E_{can,i} = E_{o,i} \qquad \text{if } R_{\text{int(f),i}} > E_{\text{o,i}} \qquad \text{Eq. 22}$$

$$R_{\text{int}(f),i} = R_{\text{int}\,i} - E_{can,i} \qquad \text{Eq. 23}$$

$$E_{can,i} = R_{\text{int},i} \qquad \text{if } R_{\text{int(f),i}} < E_{\text{o,i}} \qquad \text{Eq. 24}$$

$$R_{\text{int}(f),i} = 0 \qquad \text{Eq. 25}$$

where $E_{a,i}$ corresponds to the actual evapotranspiration (mm), $E_{can,i}$ denotes the evaporation of the intercepted rain (mm) and $E_{o,i}$ symbolizes the potential evapotranspiration (mm).
The potential evapotranspiration ($E_{o,i}$) is provided by the relevant SWIM modules (Krysanova and Luik, 1989).
If the potential evapotranspiration $E_{o,i}$ is less than the actual canopy storage $R_{int,i}$ (Eq.22), the residue is added to the storage of the next day (Eq. 23). Once the water in the canopy storage is removed (Eq. 24, 25), the remaining evaporative water demand is partitioned between transpiration and evaporation from the soil (Menzel, 1997b; Neitsch et al., 2002).

The root water uptake, as the second modification, is estimated based on the SWAT2000 approach (Neitsch et al., 2002). As a modification for forest, it is postulated that the root water uptake is not necessarily correlated with root distribution. Thus, potential water uptake from each soil layer can be equal to the potential transpiration (Eq. 27). This allows compensation of low water supply in the upper layers by uptake from deeper layers down to the maximum root depth of 2m (Adar et al., 1995; Plamboeck et al., 1999; Riek et al., 1994; Tölle, 1967).

The potential daily uptake $W_{up,z,i}$ (mm) for each soil layer z is computed based on the plant available soil water content $AWC_{z,i}$. (mm), starting from the uppermost layer $z = 1$ down to the layer of the maximum root depth. If the total soil water content $SW_{z,i}$ (mm) in one layer falls below 75% of the plant available water content, the uptake is reduced exponentially. If the actual water uptake ($W_{ua,z,i}$) (mm) from one layer is lower than the potential water uptake ($W_{up,z,i}$) (mm), the residue can be taken from the next deeper layer until the atmospheric water demand $E_{t,i}$ (mm) is satisfied or the total available water of the soil profile is used (Eq. 26-30):

$$E_{t,i} = E_{o,i} - E_{can,i} \qquad \text{Eq. 26}$$

$$W_{up,z,i} = E_{t,i} \qquad \mathrm{SW_{z,i}} > 0.75 \cdot \mathrm{AWC_{z,i}} \qquad \text{Eq. 27}$$

$$W_{up,z,i} = E_{t,i} \cdot e^{\left[5 \cdot \left(\frac{SW_{z,i}}{(0.75 \cdot AWC_{z,i})} - 1\right)\right]} \qquad \mathrm{SW_{z,i}} \leq 0.75 \cdot \mathrm{AWC_{z,i}} \qquad \text{Eq. 28}$$

$$W_{ua,z,i} = \min\left[\, W_{up,z,i} - W_{ua,z-1,i} ; SW_{z,i} - WP_z \,\right] \qquad \text{Eq. 29}$$

$$E_{ac,i} = \sum_{z=1}^{z_{\max}} W_{ua,z,i} \qquad E_{ac,i} \leq E_{t,i} \qquad \text{Eq. 30}$$

where $E_{t,i}$ symbolizes the potential transpiration (mm), $E_{ac,i}$ the actual transpiration (mm), and WP_z is the wilting point (mm).

If the sum of available soil water is lower than the plant water demand, the model allows the uptake from groundwater, if the actual groundwater level is within the rooting zone of 2 m (Riek et al., 1994).

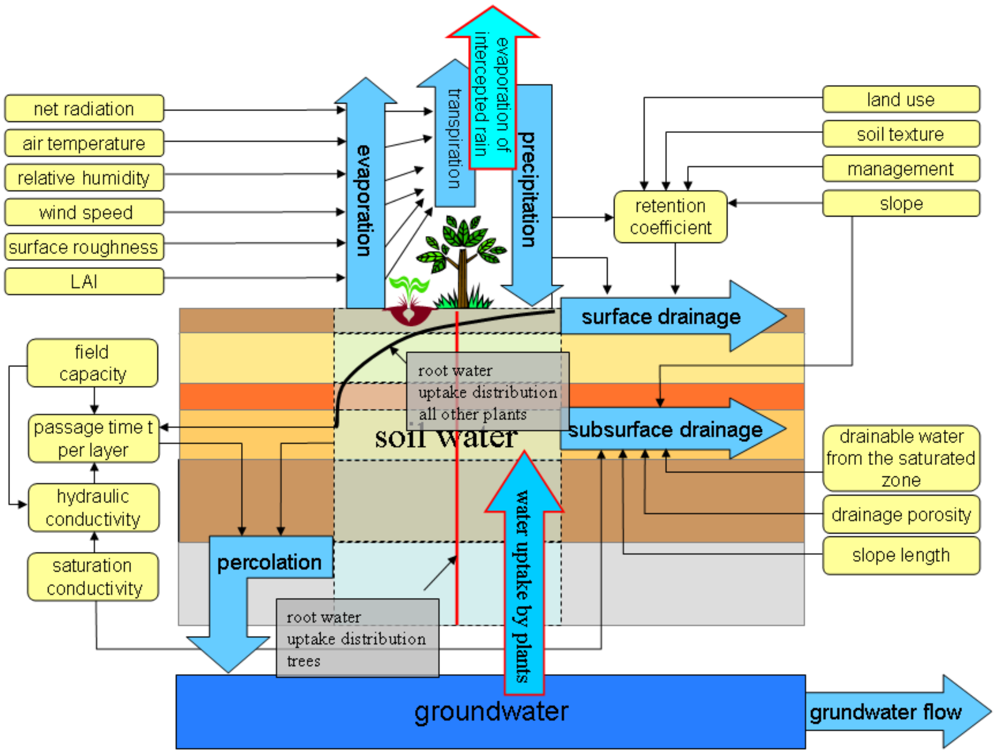

Fig. 11 The implementation of the new elements (framed in red) in the vegetation water interaction in the forest version of the SWIM model.

parameter	**symbol (unit)**	**value**	
		Scots Pine	*Common Oak*
interception	f (no unit)	-	2.0
	$R_{int,pine}$ (mm)	2	-
	LAI_b(m^2 m^{-2})	4	-
	c (no unit)	0.4	0.7

Tab. 2 Parameter settings for the calculations of interception of precipitation.

2.2 Uncertainty and Sensitivity

Uncertainty is an inherent attribute in all model applications (Beven and Binley, 1992; Beven and Freer, 2001). It describes the degree of how unsure we are about the validity of model results. Uncertainty assessment is therefore an important part of model application, especially if the results are part of a decision-making process (Refsgaard et al., 2007). In meteorological measurements the term 'uncertainty' is defined as: "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand". The term 'parameter' may be quantified, for example, as a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence (ISO, 1995). Uncertainty may be evaluated using a series of measurements and their associated variance (Type A, Fig. 12) or can be expressed as standard deviation based on expert knowledge or by using all available sources (Type B, Fig. 12).

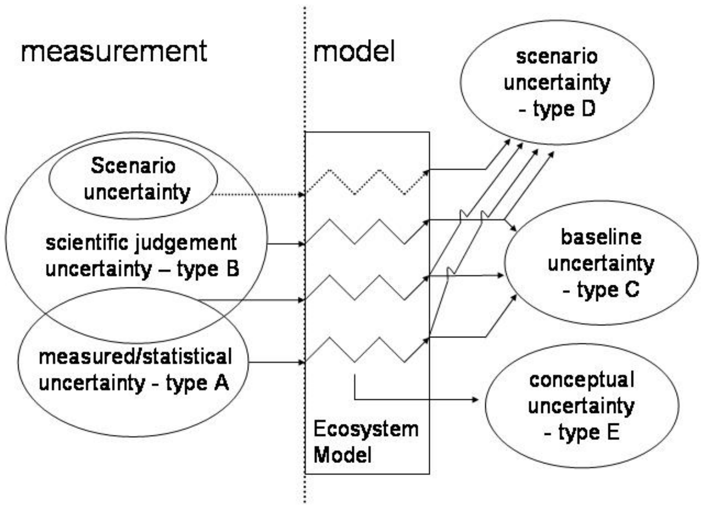

Fig. 12 Different types of uncertainty in measurement and modelling. The different uncertainties are expressed as sets and subsets (Wattenbach et al., 2006).

Fig. 12 gives an illustration of other types of uncertainty as we find them in modelling. The type C uncertainty, termed baseline uncertainties, originates from type A and B uncertainties associated with measurements used to determine the input factors of a model, and the propagation of these uncertainties through the model. Input factors are defined to be all values that feed into the model, such as initial values, driving variables etc. Type D, or uncertainties arising from scenario

assumptions, are related uncertainties inherent to predictive processes in modelling. They incorporate type C uncertainty, accompanied by the uncertainty in the prediction of future environmental conditions such as climate and their interaction with ecosystems. In contrast to type C and D uncertainty, which treat the model as a black box, type E, or conceptual uncertainty, refers to the uncertainty of internal parameters of the model equations such as rate constants and threshold values used in the model (Wattenbach et al., 2006).
The term ‘sensitivity’ is closely related to the term uncertainty as it describes the influence of the factor distribution (parameters and variables) on the distribution of the output. The first step of the sensitivity analysis was the screening of parameters (Saltelli et al., 2000) in applying the model in the Stöbber catchment area. In this first step, a simple measure of sensitivity is used:

$$s = \frac{Q_{ref} - Q_{sim}}{Q_{ref}} : \frac{p_{ref} - p_{sim}}{p_{ref}} \qquad \text{Eq. 31}$$

where s represents the sensitivity index, Q_{ref} is the mean runoff for the reference run with no parameter changed, Q_{sim} the runoff with one parameter changed and p_{ref} and p_{sim} are the corresponding parameter values. Each parameter is increased by 50% and the resulting runoff compared to the reference run with all parameters set to the default values.

Type C uncertainty of the original SWIM model in the Elbe river catchment emerging from calibration parameters, and type E uncertainty linked to internal parameters, were investigated in the second step of the model analyses. The sensitivity of parameters in regard to their influence on the runoff at the basin outlet was also investigated. The calibration parameters chosen for the analysis are the correction factors for saturated soil conductivity (sccor), for river routing (rcor), for radiation (rad), ¸for groundwater return flow and water table depth (alpha). The factors were sampled randomly, within their site-specific physically meaningful limits (Hattermann et al., 2005). In addition, factors for slope (slope), biomass energy ratio (be) and the SCS curve number (cnum) were sampled from a normal distribution with a mean of one by multiplying the sample factor with the default parameter value (Hattermann et al., 2005).

The analysis employs a more sophisticated method than the first step parameter screening in form of an Monte Carlo approach (e.g. Gottschalk et al., 2007; Hattermann et al. 2005; Verbeeck et al., 2006; Zähle et al., 2005). The necessary samples for the input are generated by probability density functions (PDFs) using Latin Hypercube Sampling (LHS). LHS is a stratified sampling technique where the distributions are divided into equal probability intervals. Samples are drawn from these intervals rather than randomly from the entire factor space. This ensures that all portions of the distribution are represented equally (McKay et al., 1979) with a smaller number of samples needed when compared to pure random sampling. This has the advantage of reducing the number of model runs, and it requires a small number of samples to establish a stable output distribution (Gottschalk et al., 2007; Verbeeck et al., 2006). The sensitivity is expressed using the partial correlation coefficients (PCC) of the rank-transformed data (Saltelli et al., 2000).

The uncertainty analysis of the forest module parameters uses a different measure for the influence of parameters on the model results, because in this case, parameter importance is the focus of the analysis. Important parameters are sensitive and, at the same time, uncertain. They can be identified using the contribution index. This is calculated by running a Monte Carlo simulation, consisting of multiple executions of the model, with all input factors sampled from their respective probability density functions. The Monte Carlo simulation is then repeated for the number of assessed input factors, each time holding one of the input factors constant at its default value, whilst allowing all others to vary within their defined range. The standard deviation of the distribution of the model output (actual evapotranspitation in this case) from the first Monte Carlo simulation represents the global uncertainty. The variation of the output distributions of the following simulations with each in turn compared to the global uncertainty gives a quantitative estimate of the contribution of each input factor to the global uncertainty. The contribution is expressed as the normalized percentage change in standard deviation with respect to the standard deviation of the global uncertainty (Vose, 2000). The contribution index is the measure of the importance of each factor in the overall uncertainty of the model output; a high percentage indicating that the factor is important in determining output uncertainty, a low percentage indicating a low importance. The contribution index is calculated using the following equation:

$$c_i = \frac{\sigma_g - \sigma_i}{\sum_{i=1}^{i_{\max}} (\sigma_g - \sigma_i)} \cdot 100 \qquad \text{Eq. 32}$$

where c_i is the contribution index in % of factor (i), i_{max} is the total number of model input factors considered and i the specific input factor of interest at a time, σ_g is the standard deviation of the global uncertainty, σ_i is the standard deviation of the simulations with setting factor (i) to its default value (Gottschalk et al., 2007). In the case of the forest module, five parameters were sampled. These were: initial age of a forest stand; the leaf biomass; the initial total above ground biomass; the temperature threshold to count chill days; and the temperature threshold to calculate the temperature sum; the latter two are in the phenology sub-module. The distribution of the probability density function and thresholds are given in Tab. 3. The distribution and factor ranges are based on expert knowledge because there are no measurements available to derive these attributes directly.

parameter	**distribution/ type of operation**	**minimum value (99.9% interval)**	**maximum value (99.9% interval)**
initial age	Uniform	-10 years	10 years
leaf biomass	Normal	-30%	30%
initial total biomass	Normal	-30%	30%
temperature threshold chill days	Uniform	-5 degree Celsius	+5 degree Celsius
temperature threshold degree days	Uniform	-1 degree Celsius	1 degree Celsius

Tab.3. Parameters chosen for the uncertainty analysis and their uncertainty ranges.

2.3 Data for the area of the federal state of Brandenburg

2.3.1 Spatial data

The forest data has been obtained from a biannual report published by the Federal Forest Agency (LFE, 2000). They include average age, DBH (diameter at breast height) and average stand volumes for the two dominant tree species, Scots Pine and Oak, for the state area. The management information has been taken from yield table data (Schober, 1987) assuming an average management regime for mean stand conditions for the area. Based on this information, age distribution has been classified using the biotope map provided by the Federal Environmental Agency (Landesumweltamt Brandenburg). The high resolution of this map has been aggregated to the SWIM land-use classes, namely evergreen forest, deciduous forest and wetland forest. Soil information has been obtained from a national agency for geo-sciences and resources (Bundesanstalt für Geowissenschaften und Rohstoffe) with a scale of 1:1000000 together with soil profile descriptions, providing the basic physical characteristics, such as saturated conductivity and bulk density for 72 different soil types. Soil quality has been based on a map in a 1:200,000 scale with seven classes (Brandenburger Ministerium für Umwelt, Naturschutz und Raumordnung)

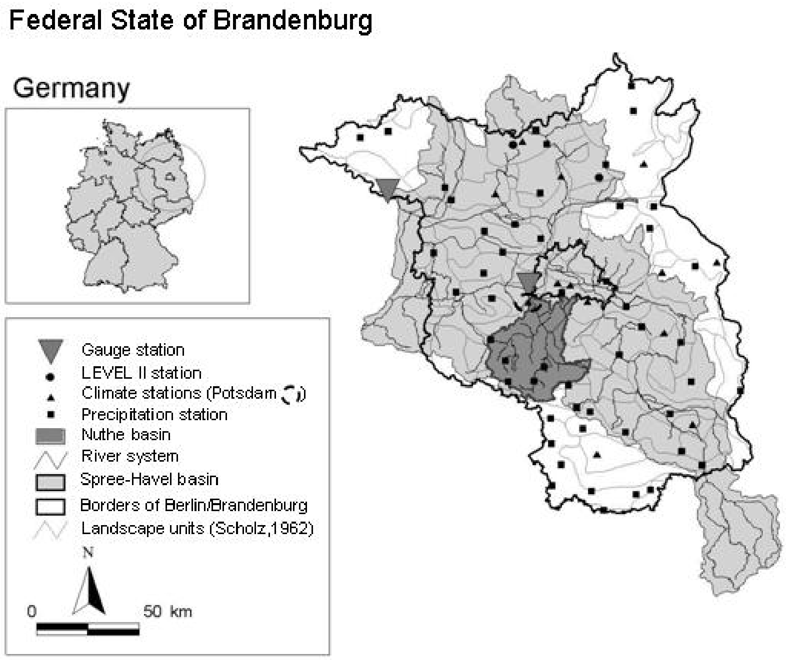

Fig. 13 The federal State of Brandenburg, the Nuthe-basin (dark grey), The Spree-Havel-basin (light grey) and the gauge stations (grey triangles) as well climate and precipitation stations (black triangles and black squares, respectively) and the Level II plots (dots). The natural landscape Units are after Scholz (1962). Potsdam is the closest climate station to the gauge Babelsberg at the outlet of the Nuthe basin.

An interpolated groundwater level map is used to initialise the groundwater model of SWIM, in order to take areas with groundwater levels above 2m into consideration.

The digital elevation model which was supplied by the federal land surveying office (Landesvermessungsamt) was aggregated to a 50 m grid resolution from a 25 m grid resolution.

The climate data observations were gathered from stations of the German Weather service (Fig. 13), and they were interpolated for the individual sub-basins using the inverse distance method based on the Euclidian distance between climate stations and centre point of the sub-basin (Hattermann et al., 2005; Wattenbach et al., 2005).
The same database for soil, climate and land-use was used in the Stöbber and Nuthe catchment studies.

2.3.2 Forest plot scale data

Forests in Europe have a fundamental role in environmental services most importantly as renewable resources, groundwater recharge zones and recreation. Therefore, they are the objects of intensive monitoring such as the Level II forest observation sites (Hörmann et al., 2003), which supplied the data used in the model evaluation. Out of 860 measurement plots that are scattered over the EU and associated countries, two plots in the federal state of Brandenburg are used in this study (Fig. 13). As a result of the already mentioned dominance of Scots Pine, all plots are situated in such stands. Therefore, only literature data were available to evaluate model behaviour for Common Oak. The data used were gathered on measurement plots in the federal state of Brandenburg under comparable environmental conditions of soil and climate (Lützke, 1970; Lützke, 1991a; Lützke, 1991b; Simon, 1984) or taken from literature (Lützke, 1991b; Otto, 1994). Data for the Level II plots were available from three publications, which provided measurements under comparable environmental stand conditions (Künstle et al., 1979; Lützke, 1991a; Lützke, 1991b) or standard textbooks (Larcher, 1994; Otto, 1994) were used. The comparison of forest growth and interception of precipitation has been done for the Level II plot at Kienhorst (Brandenburg, 13.59°E 53.01°N). The forest is a ninety-year-old Scots pine on sandy podzol soil. The climate information for temperature, precipitation and solar radiation were gathered from local measurements. The average annual temperature is 8.3 °C and the average annual precipitation sum 585 mm. Soil information has been taken from the profile description of the stand, the initial biomass and age from the stand description (Kallweit, 2001). The model is then run for the whole period without calibration of the model parameters.

For further evaluation of the hydrological properties the sap flow measurements of 10 Scots Pine trees (Lüttschwager, 2001) for the years 1998 and 1999 of the Level II stand Beerenbusch (Brandenburg, 12.58°E 53.08°N, mean annual precipitation 532 mm, mean annual temperature 9.6 °C, Scots Pine age: 62 years). The available stand descriptions also provided detailed climate, soil and stand data which were used to run the model over a four year period starting in 1996.

2.4 The Elbe catchment case study

2.4.1 The database

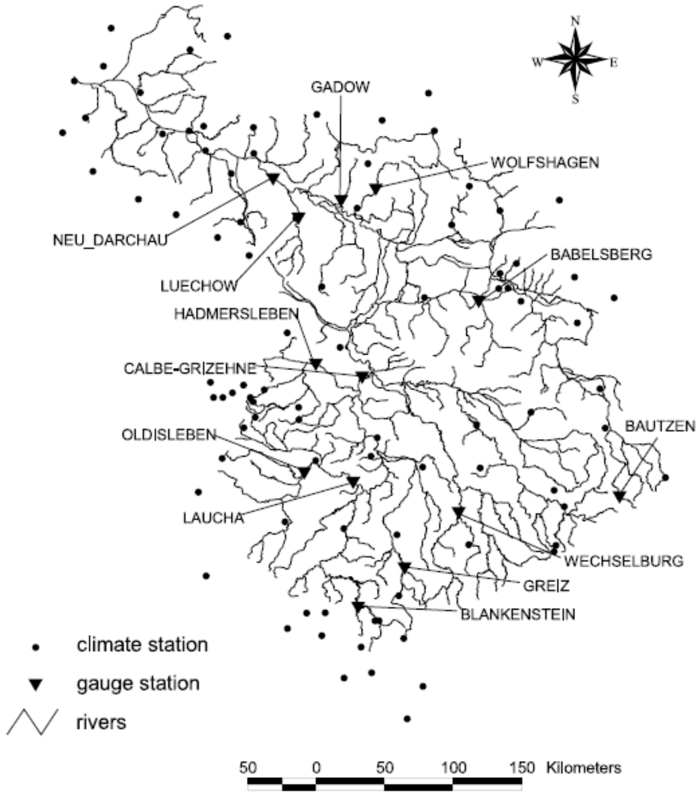

Fig. 14 The river network of the German part of the Elbe basin, the locations of the gauge stations, where comparisons with the observed river discharge were conducted, and the climate stations. From Hattermann et al. (2005)

The database of spatial information for the Elbe river basin (Fig. 14) has a lower resolution than the one for Brandenburg with a 250 m grid resolution. In this study, sub-basin boundaries provided by the German Federal Environmental Office (UBA) were employed. They were used to subdivide the catchment into 226 sub-basins as a prerequisite for the input of the “r.watershed” algorithm of the geo-information system GRASS where they were used in combination with the DEM (digital elevation model) to define the water flow parameters. The DEM is a composite of elevation maps with different scales resampled to a spatial resolution of 250 m to match the land-use information. Within the Elbe catchment, 12 sub-catchments were selected to understand the behaviour of the model in regions that differ in their landscape attributes. In simulations of the whole Elbe basin, the observed flow from the Czech Republic has been added to that calculated by SWIM and then routed through the sub-basins to the outlet of the river basin. The land-use map has been disaggregated from 44 classes into the 15 SWIM land-use units using the European CORINE land cover map (Hattermann, 2005). Soil information is based on the same data as used in the Brandenburg study.

2.4.2 Methods

The model was calibrated for the application in the Elbe catchment using rough non-generic automatic calibration, employing a Monte Carlo method and Latin hypercube sampling (Hattermann, 2005). The calibration criterion was the alignment of simulated and measured daily river discharge. As measures of alignment the efficiency (Nash and Sutcliffe, 1979) and the relative discharge difference were used to optimise the model behaviour over an 8 year calibration period (Hattermann, 2005)

2.5 Scenario definition and modelling procedure for the Brandenburg study

To generate the scenario input for the Brandenburg study the agricultural policy information system for German administrative units (RAUMIS) was employed in a first step within the MESSAGE project. This system has a resolution at the district level, based on a non-linear programming approach (Henrichsmeyer et al., 1996). In RAUMIS, total agricultural area is divided in arable land and permanent grassland. These categories are fixed within the optimization procedure which reflects the required regional constancy of permanent grassland area. Arable crops including set-aside and idling compete for scarce arable land. In regard to the adjustment behaviour of agriculture, a maximisation of profit is assumed and the optimal production structure is determined for farms within the region. RAUMIS takes into account the EU Common Agricultural Policy instruments such as: production quotas; direct payment schemes; decoupling; set-aside; livestock densities; minimum farming and agri-environmental requirements (Cypris, 2000).

The district level land-use trends were translated into a land-use pattern utilizing the PAGE - tool (pattern generator) as the second step in the MESSAGE project. PAGE disaggregates RAUMIS scenarios on district level to spatially explicit raster maps of future land-use, applying a combination of rule-based and statistical approaches. Firstly, a pixel per pixel suitability assessment for each respective land-use type is performed. Suitability is calculated as a function of natural conditions (soil quality, groundwater level, slope, and climate), spatial attributes (distances) and land-use restrictions (nature reserves). Secondly, the amount of land-use changes in comparison to current land-use is identified. And thirdly, land-use change is allocated based on the current land-use map and the suitability assessment (Zebisch et al., 2004).

The resulting land-use map with a 50m raster resolution was the basis of the simulations of the forest version of the SWIM model in the Brandenburg study. The SWIM model was used as the third element in the cascade of models to derive the spatial response of the eco-hydrological condition as affected by changes in the land-use pattern.

2.5.1 Applicability of the model for the state area

Table four shows a compilation of model results based on previously published studies (Hattermann et al., 2004; Habeck et al., 2005; Hattermann et al., 2006). The catchments represent typical lowland or mixed (lowland/loess) landscapes within or neighbouring the federal state. The results demonstrate the applicability of the SWIM model to simulate the long-term water balance and dynamic for the landscape under study, and enabled this study to use the parameterization for the appropriate model runs. Although the agreement is satisfying there remains a degree of uncertainty because of the discharge of brown coal mining water into the Spree-Havel river system in the corresponding time period (Wechsung et al., 2000) as well as the presence of unrecorded small scale water management activities (Hattermann et al., 2006). The additional runoff from brown coal mining would be of an average 14 mm for the long-term average at the Havelberg gauge (BMBF, 2002). However, Wattenbach et al. (2005) could demonstrate that the model acceptably reproduces the long-term water balance at the Havelberg gauge, which covers most of drainage from the state's area reasonably well. As the aim of the analysis presented here was the representation of the long-term water balance and its components we assume the model performance to be sufficient (Wattenbach et al. 2007)

river	**gauge station**	**topography**	**area [km^2]**	**efficiency monthly**	**difference in discharge %**
results of the calibrated model					
Spree	Bauzen	mountains / loess	280	0.71	1
Löcknitz	Gadow*	lowlands	447	0.82	-1
Stepenitz	Wolfshagen	lowlands	574	0.86	-1
Jeetze	Luechow	lowlands	1347	0.72	1
Nuthe	Babelsberg	lowlands	1993	0.66	0
Saale	Calbe - Grizehne	integrates all	23687	0.87	-1
Elbe	Neu-Darchau*	integrates all	80258	0.94	-1
results of the model in the validation period					
Loecknitz	Gadow	lowlands	447	0.81	6.6
Elbe	Neu-Darchau	integrates all	80258	0.94	4.0
Nuthe	Babelsberg#	lowland	1993	0.57	4.0

*Tab. 4 Efficiencies (Nash and Sutcliffe, 1979) of observed against simulated monthly river discharge and the discharge balance (mean relative difference of simulated and measured monthly discharge) for an 8 and 6 year period, respectively, for catchments within or covering parts of the federal state of Brandenburg (1981–1988,*1981–1986) The first part of the table shows results of the calibrated model whereas the second part presents examples of validation runs 1987–1992,respectively, #1989–2000 (Hattermann et al., 2005, 2006).*

2.5.2 The partial liberalisation scenario

As the name of the scenario indicates, with regard to EU subsidies, a more liberal policy is assumed. In this scenario, it is supposed that direct payments stay in place, but without any regulations like cross-compliance. Cross-compliance, in the case of European subsidies, is the principle that farmers need to comply with environmental protection requirements as a condition for benefiting from market support (EU, 2004). It is also assumed that no further support will be available for cereals, milk, and beef prices. The scenario is based on elements of the mid-term-review (MTR) of AGENDA2000 (EU, 2003a; EU, 2003b) with a target year of 2010.

The results of the scenario simulated by the RAUMIS model suggest a strong shift in agricultural production, resulting in an increase in abandoned land from 16.6% in the reference scenario to 47.3% for the total state agricultural area in the “partial liberalisation scenario”. The reference scenario is a projection of agricultural production until 2010 under unchanged Agenda 2000 policy. This complete shift of production to favourable areas allows profitable production. A price increase of 1.5 % for wheat (*Triticum aestivum*), but a decrease of the rye (*Secale cereale*) price by 19 %, in comparison with the reference scenario, were assumed by the model. Relative to other states, rye comprises a high proportion of Brandenburg’s cereal production. Thus, the decrease in rye areas reaches 67.1 %, which contributes to an increase of set-aside of 13.5 % compared to the reference scenario. The second largest influence, with 4.3 % of set-aside land is related to a decrease in oil seed production by more than 73.4 %. Thirdly, production in fodder maize (*Zea mays*) decreased by 37.2 %, leaving 2.2 % of arable land out of production. The remaining 10.7 % contributing to the scenario prediction of 47.3% of set-aside land, are evenly scattered over the other crop production types. As a result of the missing redirection of subsidies to maintain the rural landscape, it is assumed that it will not be possible to compensate costs for landscape conservation and, consequently, parts or all of the set-aside areas will fall into full cessation of farming and afforestation, or natural succession will take place.

2.5.3 The forest species change scenario

Decades of preference for Scots Pine as the main tree species has resulted in 33 % of monoculture pine forests growing on land that could potentially be used for deciduous and mixed stands. Using the government targets (LFE, 2000) to change this situation to a more natural forest distribution as a baseline, the scenario for the simulations leads to a stepwise shift from pine forest-dominated to 100% deciduous tree species. The spatial distribution for the intialisation year was obtained from the biotope mapping. Then forest areas under Pine were converted to Oak in discrete 10% steps using the PAGE algorithm (Zebisch et al., 2004). Each of the resulting land-use datasets were simulated separately using the SWIM model and the results were transferred into GIS for analysis.

2.5.4 Modelling procedure

In order to run the model on the area of the federal state, the definition of sub-units was necessary. Landscape units (Scholz, 1962) instead of sub-basins are used here, as they integrate not only hydrological aspects but also additional features like soils, geomorphology and biotope composition, all of which are relevant for the subject of study. In the next step within each landscape unit, the hydrotopes were defined based on their unique combination of soil and land-use. The resulting hydrotope map is then combined with the groundwater map to define the initial average ground water level. Each hydrotope is assumed as a homogenous tree-stand unique in tree species, stand age, and initial biomass. Based on the age class resolution of the forest inventory data, the new forest in the "partial liberalization" scenario had to be initialized as 15 years old with an initial mean biomass of 28880 kg ha^{-1} for pine and 13683 kg ha^{-1} for oak, respectively. The "forest species change" scenario followed the same concept except for the use of the current age class distribution for the transformed deciduous forest to mimic the behaviour after one rotation period. The model is run using daily weather data for every sub-basin between 1951 and 1998.

Results are plotted as graphs and maps. Graphs display mean values over the entire simulation period in all cases and, where meaningful for the identification of processes, additional temporal min and max values. These types of graphs are described in the results section by the term "response function". Response functions show the integrated sensitivity of a landscape to an external driving force (Zebisch et al., 2004). The maps represent the difference of the baseline simulation to the 100% implementation of the scenario. All values are averages over the total area of Brandenburg or the landscape unit area, hence integrating all land-use classes. The response in evapotranspiration within the maps has been related to classes using landscape attributes. Class I consists of all landscape units with a mean groundwater level greater than the overall mean, the mean of all units in the federal state. Class II are all units with lower soil quality, equal or lower groundwater levels and a higher percentage of forest compared to the overall mean. Class III are all units with groundwater levels, equal or below the overall mean and fertile soils.

3. Results and Discussion

The first part of the following section summarizes a study conducted in the Stöbber catchment which represents a test case for the model to analyse the sensitivity of calibration parameters for lowland catchments. The second part presents a summary of the relevant results of a much more comprehensive uncertainty and sensitivity analysis undertaken in the Elbe basin (Hattermann et al. 2005) that builds on the results of the preceding Stöbber study. In the third, part the implementation of the forest module is tested in the Nuthe basin and compared with long-term literature data as part of a multi-criteria evaluation. This is followed by an evaluation of simulated forest growth and hydrological fluxes on Level II plot data at daily or weekly temporal resolution (Wattenbach et al. 2005). The final section is a compilation of the Brandenburg case study results (Wattenbach et al. 2007) which includes an uncertainty analysis of the forest module parameters.

3.1 Evaluation and analysis of the unmodified SWIM model

3.1.1 The Stöbber catchment

The simulation experiment was run from 1993 to 1995, as runoff data were only available for this time period. Fig.15 shows the calibrated daily runoff graph based on the parameter set presented in Tab. 5. The model was first calibrated using the set of calibration parameters to align simulated and measured runoff. The results were assumed to be satisfying enough to start the analysis based on efficiency (Nash and Sutcliffe, 1979) of 0.21. An overview of the parameter sensitivity when each parameter was systematically altered, one after the other, in order to investigate single parameter effect on river discharge at the basin outlet, is provided in the following table 6.

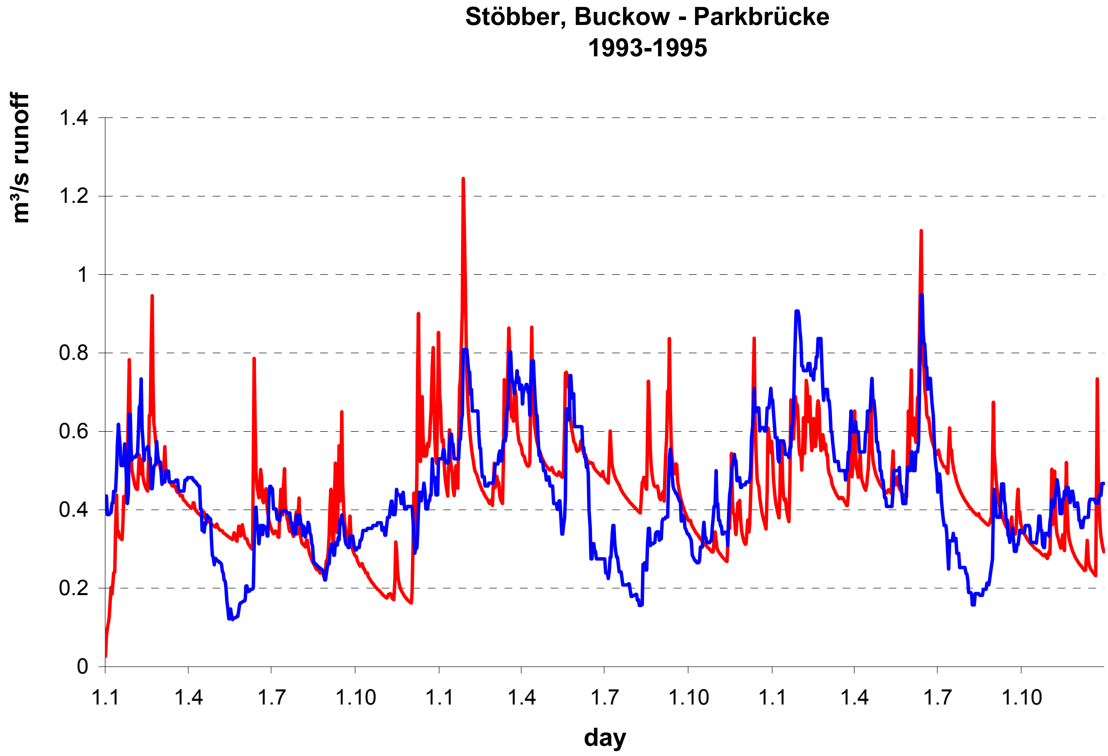

Fig. 15 Runoff at the Stöbber basin outlet, gauge Buckow – Parkbrücke. The efficiency (Nash and Sutcliffe, 1979) reached 0.21 and there are systematic discrepancies in the runoff during summer (red line simulated, blue line measured).

parameter acronym	purpose	calibrated parameter value
rad	correction factor for the proportion of long wave radiation in the calculation of the radiation balance	0.1
cnum	curve number for the SCS runoff calculation for wet soil conditions	20.
α	the calibration parameter to adjust the α factor in the groundwater module, see chapter 2.1.4 or Hattermann et al. (2004)	0.01
rcor	routing parameters for the channel runoff calculation	120.
snow	initial snow depth	1
sccor	correction for the saturated conductivity	0.25

Tab. 5 Nominal values and purpose of the initial SWIM calibration parameters. They are described in more detail in Hattermann et al.(2005).

The response has been classified into the relative classes of strong, medium and no response in regard to the change in runoff volume and dynamic in response to the change in the parameter value. The sensitivity analysis demonstrated the restricted capability of adjusting the model behaviour in order to represent the catchment runoff using the available calibration parameters. The problems in the calibration procedure could mainly be assigned to the calculation of evapotranspiration. That outcome was concluded because temperature, which is, apart from radiation, the only input when using the Priestley and Taylor (1972) method, showed a correlation (r=0.82) with the monthly difference between modelled and measured runoff (Fig. 16).

parameter	model output	minimum value	maximum value
snow		1	60
	runoff volume .	±	↑↑
	dynamic	±	±
rad		0.1	1.0
	runoff volume .	↓↓	↑↑
	dynamic	±	±
cnum		1	100
	runoff volume .	±	↑↑
	dynamic	±	↑↑
α		0.01	3
	runoff volume .	↓	±
	dynamic	↓	±
rcor		1	200
	runoff volume .	±	±
	dynamic	↑↑	↓↓
sccor		0.25	4
	runoff volume .	↓↓	↑↑
	dynamic	↓↓	↑↑

Tab. 6 ↓↓, ↑↑ strong response; ↓, ↑ medium response, ± no response.

The Priestley and Taylor method is known to underestimate potential evapotranspiration under semi-arid conditions (Berengena and Gavilán; 2005) because it assumes the air to reach equilibrium conditions over a well-watered vegetated surface whilst treating the atmospheric influence as a constant (see also chapter 1.1.1) (Priestley and Taylor, 1972). Additional indication for the possible misrepresentation of evapotranspiration is the high sensitivity of the calibration parameter *rad*. The value (0.1) set to calibrate the simulated runoff in the model still leads to a bias towards overestimating simulated runoff (Fig. 17). Another source for the lack of model performance is the missing information regarding the regulative measures taken at the gauge of the lake outlet. It can be assumed that the gauge was used to keep the lake's water table constant by reducing the runoff at the lake outlet thus potentially contributing to the difference between modelled and simulated runoff.

However, that effect could not be quantified and the hydrological analysis of the basin has been discontinued due to the lack of information to improve the behaviour of the hydrological part of the model (gauge regulation data, long-term runoff measurements etc).

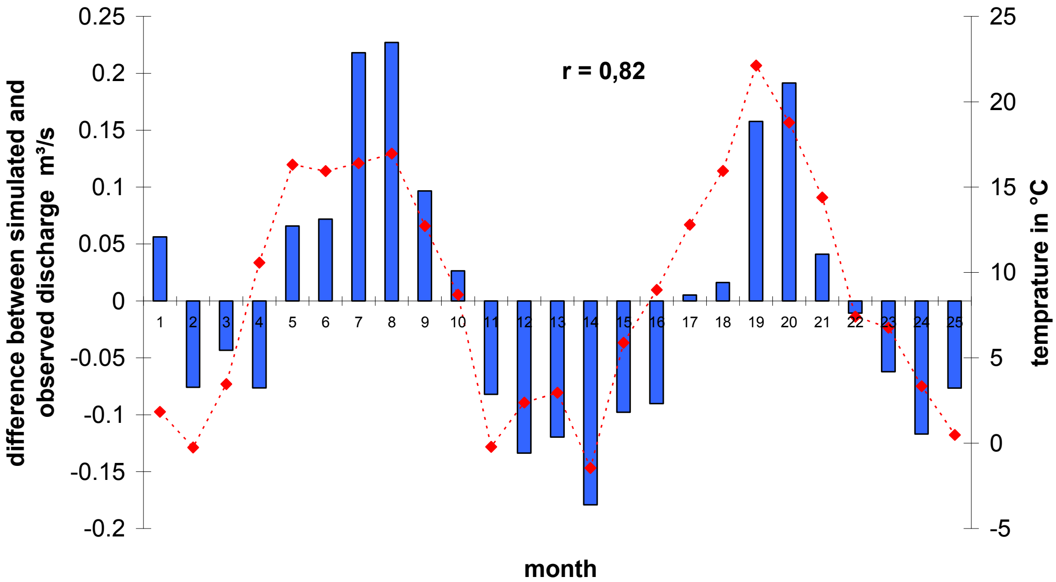

Fig. 16 Runoff difference (bars) and mean monthly temperature (read squares) are correlated (r=0.82).

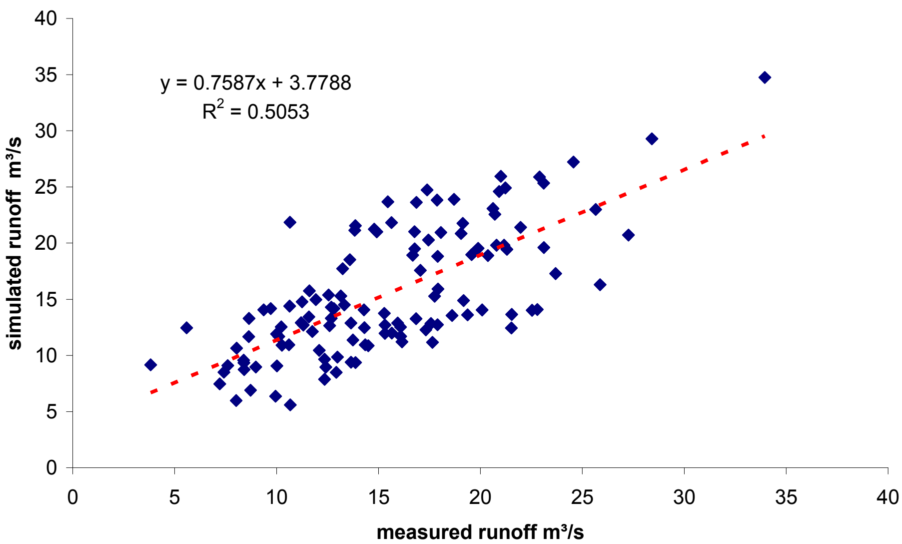

Fig. 17 Scatter plot of measured versus simulated runoff. There is a clear bias in the simulated runoff.

3.1.2 The Elbe catchment study –validation and uncertainty analysis

Based on experience gained from the pre-study in the Stöbber region, the exercise in the Elbe catchment presented a much more comprehensive analysis of the hydrological processes of the model SWIM.

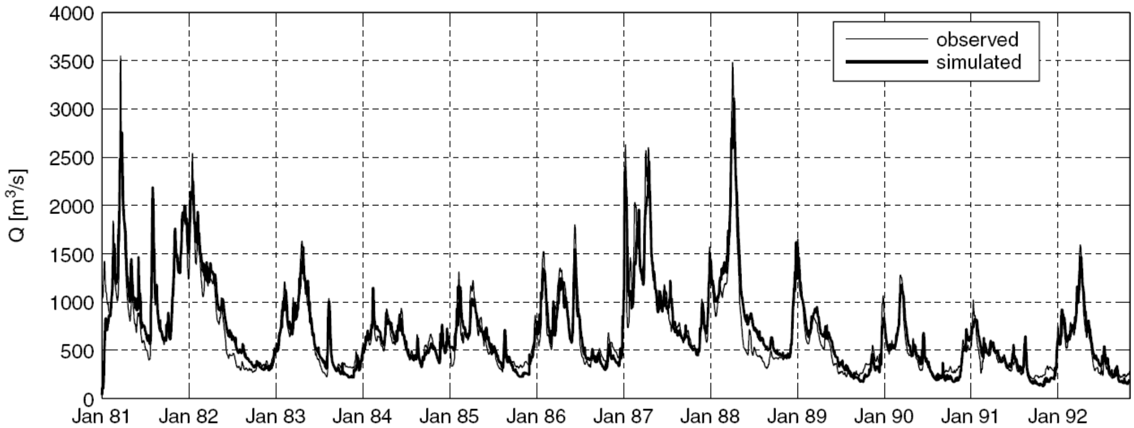

Fig. 18 Daily runoff simulation for the total area of the Elbe basin, 0.92 efficiency (Nash and Sutcliffe, 1979) and discharge balance 4.0% for the validation period 1987-1992 at gauge Neu Darchau from Hattermann et al. (2005).

The main objective was to investigate the model's sensitivity to additional parameters related to the calculation of evapotranspiration and plant growth in order to get a better understanding of the sources of the model behaviour identified in the pre-study. The Elbe catchment represented a more suitable case than the Stöbber because of the higher availability of data and a greater catchment size. The greater catchment area enabled us to compare regions different in soils, climate and runoff characteristics to gain a systematic understanding of model uncertainty and sensitivity. The validation followed a bottom-up approach in which the model has been first calibrated for 12 mesoscale sub-basins, covering the main sub-regions of the German part of the Elbe basin. The information gained from the mesoscale validation has then been used to validate the model for the entire basin as Fig. 18 demonstrates (Hattermann et al. 2005).

The study in the Elbe catchment confirmed the results of the sensitivity analysis in the Stöbber catchment regarding the effect of variations in the calibration parameters on the runoff at the catchment outlet (Fig. 19). The radiation correction with *rad* was the most sensitive factor followed by the correction factor *sccor* for the saturated conductivity of the soil. The biomass energy ratio *be,* on the other hand, had an unexpectedly small influence on the water balance, as the biomass energy ratio has an impact on the LAI as it determines the accumulation of biomass. This low sensitivity indicated an underestimation of the impact of vegetation on the water cycle in the model.

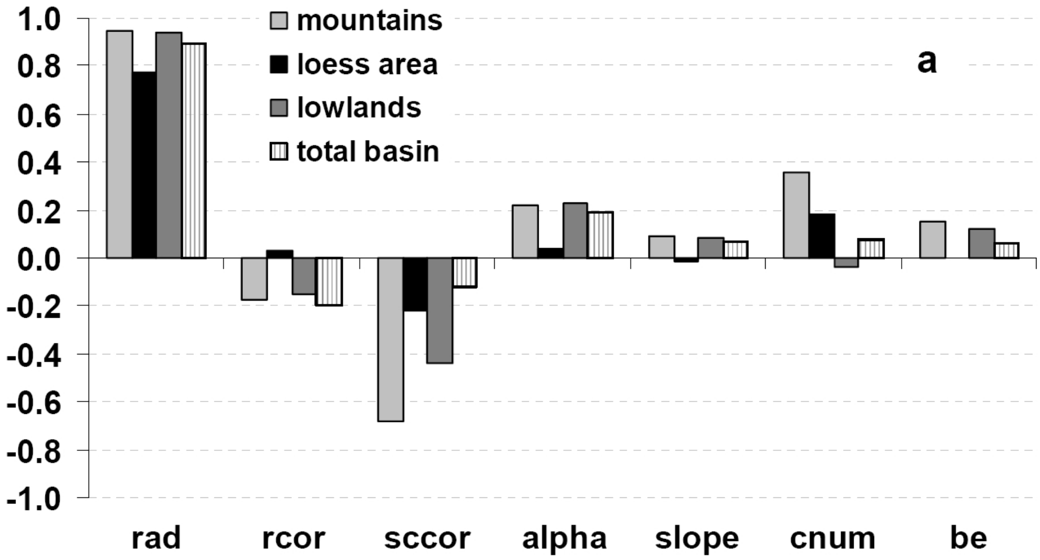

Fig. 19 The correlation of the water balance to the model parameters and input data, based on 300 Monte Carlo simulations. rad=radiation correction, rcor=routing correction, sccor=correction of the saturated conductivity of the soil, alpha= parameter to correct the groundwater table dynamic and transmissivity slope = internal parameter for the topography in the runoff calculation, cnum=curve number in the SCS method, be=biomass energy ratio (Hattermann et al., 2005).

The results also confirm the result of the Stöbber study in that a correct reproduction of evapotranspiration is essential for the quality of the simulated water balance. The model has the weakest performance in the relatively dry lowland and loess areas (Fig. 20) with a particular sensitive balance between runoff generation and evapotranspiration (Badeck et al., 2004; Zhang et al., 2001). In addition, the runoff in the lowland areas in the Elbe catchment is regulated by gauge targets set by regional water authorities and information about the measures taken there is not available at this scale. There are again other factors like lakes, ponds and wetlands that are not explicitly modelled in the SWIM model which therefore contribute further to the uncertainty in the results.

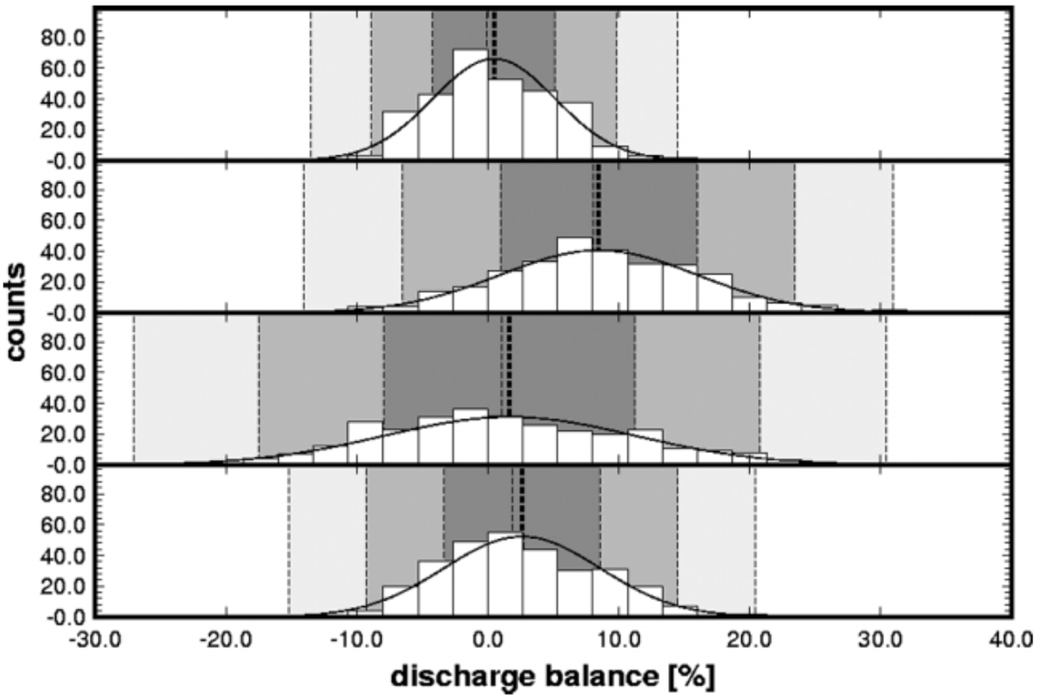

Fig. 20 Distributions of the model output 'discharge balance', based on 300 Monte Carlo simulations, from top to bottom for basins from the mountains, the lowlands, the loess area and the total basin. The probability density function of the deviation from the calibrated output for lowlands has a mean of 1.6%. with 14.7% for the 90th percentile and -9.9% for the 10th percentile. Gray areas represent the standard deviations (Hattermann et al., 2005).

3.2 Evaluation of the forest version of the SWIM model

3.2.1 Catchment scale application of the forest version

The Nuthe basin was selected to test the hydrological behaviour of the forest version of the SWIM model. To evaluate the behaviour of the hydrological components at the catchment scale, the classical approach of calibrating the model using the daily runoff at the basin outlet of the Nuthe river was applied. The results for the simulation of river discharge (Fig. 21) are within acceptable levels of agreement with the measured runoff at the Nuthe basin outlet (gauge Babelsberg 1981-1990, Efficiency = 0.54, discharge blance = -5). The results are also within the range of comparable studies for the Weiherbach, Efficiency = 0.57 (Fohrer et al., 2001) and for the Nuthe, 1981–1987 Efficiency = 0.57 (Habeck et al., 2005) 1989–2000 Efficiency = 0.57 (Hattermann, 2005).

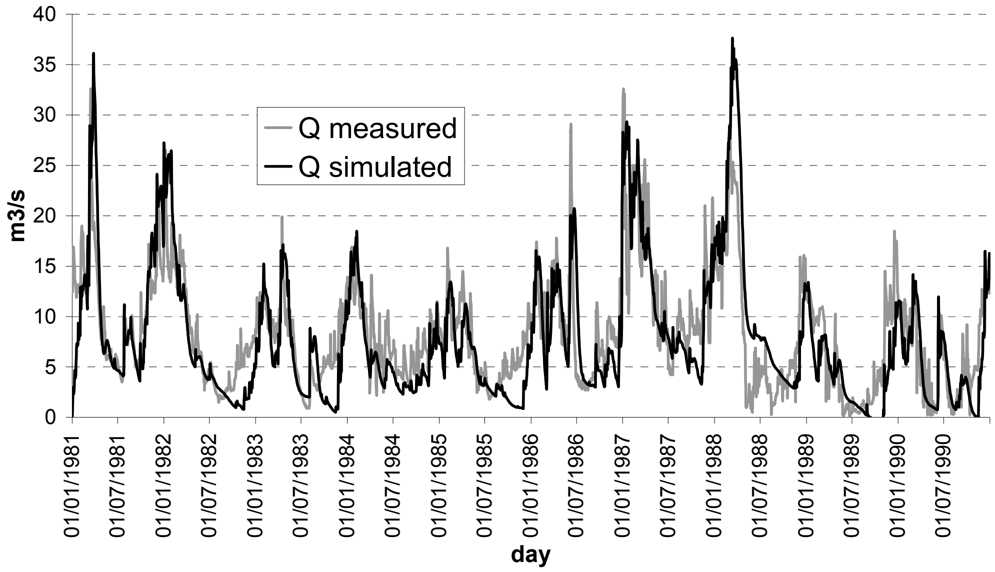

Fig. 21 Comparison of simulated and measured daily discharge from the Nuthe basin at the gauge Babelsberg, Q – runoff.

The high level of human interference (water management like implementation of drainage systems and weir plants) in this catchment makes it difficult to improve the runoff simulation without detailed information about these actions. However, the result could be achieved without the use of the calibration parameter for radiation, *rad*, thus eliminating one important source of uncertainty identified in the Stöbber and Elbe study. This was made possible by the implementation of tree species specific hydrological properties and their evaluation for the calculation of evapotranspiration. Furthermore, it was possible to evaluate simulated forest growth and forest hydrological fluxes as additional measures of the model's accuracy.

The data in Tab. 7 provide a compilation of literature values of annual biomass increase for different tree components. They are compared with a ten-year average over the appropriate age class simulated by the modified SWIM model and simulated values for the land-use class evergreen and deciduous forest of the original version SWIM model undertaken in the Nuthe basin.

The results of the modified model are of the same magnitude as the measured data. Differences between measurements and model results may be induced by the lack of detailed information regarding the stand conditions, because, in this case, only averages over the local conditions in the Nuthe basin were available for the simulations. Nevertheless, they show a clear improvement in comparison to the results of the original model version.

Variable	SWIM original	SWIM forest	data from literature	source
leaf biomass (t ha^{-1} year^{-1})				
Scots Pine	1.9 (±0.7)	4.8 (±0.8)	4.2	(Künstle et al.,1979)
			4.6	(Simon, 1984)
Oak	2.3 (±0.1)	2.5 (±0.02)	2.6	(Simon, 1984)
annual woody biomass increase (t ha^{-1} year^{-1})				
Scots Pine	2.2 (±0.7)*	3.6 (±1.6)*	4.8	(Künstle et al.,1979)
			4.9	(Simon, 1984)
Oak	2.9 (± 1.0)*	3.7 (±1.3)*	5.8	(Simon, 1984)
annual total biomass increase (t ha^{-1} year^{-1})				
Scots Pine	4.1 (±1.3)	10.1 (±1.6)	9.0	(Künstle et al.,1979)
			9.5	(Simon, 1984)
Oak	5.3 (± 1.0)	6.2 (± 1.3)	8.4	(Simon, 1984)

**not modelled – calculated difference of leaf and above ground biomass*

Tab. 7 Comparison of modelled and measured data of annual biomass for different tree compartments. The measurements where captured under comparable environmental conditions (values in brackets are one standard deviation from mean).

variable	SWIM original	SWIM forest	data from literature	source
Actual Evapotranspiration (%)				
Scots Pine [1]	39 (±5)	77 (±13)	83	Künstle et al., 1979
			86	Lützke, 1991a
Oak [2]	52 (±10)	67 (±7)	88	Lützke, 1970; Lyr et al., 1992
			86-99	Lützke, 1970
Transpiration (%)				
Scots Pine [1]		45 (±3)	47	Künstle et al., 1979
			39	Lyr et al., 1992
Pinus nigra			35	Rutter et al., 1975
Interception (%)				
Scots Pine[1]		25 (±3)	36	Künstle et al., 1979
				Lyr et al., 1992
			42	Gash, 1979
			28	Lützke, 1991b
			12-44	Otto, 1994
Oak		13 (±1.4)	10-30	Otto, 1994

1 no separation of ground vegetation and tree by the authors beside Lützke (1991b)

Tab. 8 Simulated hydrological components in comparison to data from literature, data given in percent of annual precipitation (values in brackets are deviation from mean.)

A compilation of data available in the literature for the different components of the forest water cycle is given in Tab. 8. Model results are ten-year averages for the Nuthe basin using appropriate age class averages for comparison. The modelled values of the forest version of SWIM agree well with the observations demonstrating the improvement in regard to the original model approach for the land-use classes evergreen and deciduous forest.

3.2.2 Evaluation of the forest growth at Level II plots

To validate the model at the plot scale, the data of the 1994 inventory of the Level II sites Kienhorst and Beerenbusch were used to initialise the model. Taking account of documented management and mortality data (Kallweit, 2001) provided for the stands, the annual biomass loss in the SWIM module was adjusted to 1400 kg ha^{-1} $year^{-1}$ from the default 2500 kg ha^{-1} $year^{-1}$ representing the loss of twigs, cones and other litter except leaves. In addition, extraction of wood in the plot Beerenbusch and Kienhorst caused a loss of 3355 kg ha^{-1} and 980 kg ha^{-1} in 1999, respectively.

The model-run was performed between 1994 and 1999 using the default parameters for forest growth given in Tab. 1 and compared with measurements from 1996 -1999 (Tab. 9).

		plot Beerenbusch		**plot Kienhorst**	
compartment	***year***	*measured*	*simulated*	*measured*	*simulated*
LAI (autumn)	1998	1.85	1.85	1.7	1.3
woody biomass increase (kg ha^{-1} $year^{-1}$)	1998	4805	4866	2610	4330
litter production (kg ha^{-1} $year^{-1}$)	1996	1771	2198	1571	1534
	1997	2071	2229	1697	1585
	1998	2194	2247	2119	1618
	1999	2231	2265	1882	1649

Tab. 9 Comparison of modelled and measured biomass compartments and LAI at the Level II plots Beerenbusch and Kienhorst.

3.2.2.1 Beerenbusch

Biomass and LAI

The simulated average annual woody biomass increase of 4866 kg ha^{-1} $year^{-1}$ between 1994 and 1999 is in close agreement with the measured rate of 4805 kg ha^{-1} $year^{-1}$ observed by Kallweit (2001).However, the model slightly overestimates the biomass increase by 61 kg ha^{-1} $year^{-1}$ (1.2%).
The simulated LAI for autumn 1998 (1.85) is the same as the measured value (1.85) Kallweit (1999, personal communication). The corresponding simulated leaf biomass (5112 kg ha^{-1} $year^{-1}$) for the same time is 67 kg ha^{-1} $year^{-1}$ (1.3%) lower than the calculated value (5179 kg ha^{-1} $year^{-1}$) using the formula of (Burger, 1948) and the DBH of 1999. Thus, the underestimation in leaf biomass may explain the overestimation in the increase of woody biomass because the difference is counted as wood in the SWIM model.

Furthermore, the simulated LAI is in acceptable agreement with average measured LAI values for the whole period (1996-1999) as published by Jochheim et al. (2001) for the Beerenbusch plot. The four year average LAI simulated by the model is 2.2 and 2.6 for the whole year average and for the vegetation season (May sprout - litter fall), respectively. The highest simulated LAI of 2.7 is in the range of the uncertainty of measured values of 2.6 – 2.9. Here, the lower measured value was determined by a single measurement in 1999 using a LI-COR LAI 2000, whereas the higher value was based on litter measurements representing an average for 1996 to 1999 (Jochheim et al., 2001). Because of the lack of continuous seasonal measurements of LAI on the Level II plots, the comparison of the temporal dynamic was completed in the catchment study (see section 3.2.1).

Jochheim et al. (2001) also simulated the LAI for the same plot using the forest model Forest-BGC (Running, 1994; Running and Gower, 1991). They found a four-year average LAI of 2.9. A comparison with the 4C model (Bugmann et al. 1997) at the same plot shows a higher value of 3.7 as an average over the total period.
The values given by Kallweit (2001) for leaf areas, which are based on estimation tables for dry matter and litter measurements, confirm the SWIM model results as well. The all-sided leaf area given by the author was converted into the one sided LAI

by a division by 3. This value was based on the one-sided LAI value of 1.8 supplied by Kallweit (1999, personal communication) for autumn 1998 and the double-sided value of 5.5 for the same year (Kallweit, 2001). The weighted average of the annual one-sided LAI for this period is 2.1 compared to 2.2 as calculated by the model. The observed average summer value of 2.5 is only slightly lower than the simulated LAI of 2.6. The simulated and measured winter average LAI values are the same (1.8). Moreover, the needle litter mass measurements are also in good agreement with the SWIM model results, which are slightly higher with an annual four-year average of 2235 kg ha^{-1} $year^{-1}$ versus a measured value of 2067 kg ha^{-1} $year^{-1}$ (Tab. 9).

3.2.2.2 Kienhorst

Biomass and LAI

The comparison of the woody biomass increment at Kienhorst, gives figures of 2610 kg ha^{-1} $year^{-1}$(Kallweit, 2001) measured and 4330 kg ha^{-1} $year^{-1}$ simulated by the model. It should be noted that the model considerably overestimates the wood biomass increase by 66 %. This large difference is a result of a low validity of the allocation parameterisation for the specific stand, as the default parameter values are used, which results in an underestimate of leaf biomass. The model underestimates the average summer leaf biomass given by Kallweit (2001) of 6908 kg ha^{-1} $year^{-1}$ by 2118 kg ha^{-1}, which compensates the error in biomass increase leading to a good agreement in total annual above-ground biomass increase of measured 9590 kg ha^{-1} $year^{-1}$ compared with 9120 kg ha^{-1} $year^{-1}$ simulated. However, a comparison of the leaf biomass calculated using the default formula of (Burger, 1948) based on the DBH of 1999 identified the reason. The formula yields 3874 kg ha^{-1} $year^{-1}$ in comparison to 4947 kg ha^{-1} $year^{-1}$ calculated by the SWIM model. Both are lower than the values given by Kallweit (2001) which indicates a low validity of the module assumtions for this stand.

The comparison of annual litter measurements and simulated values given in Tab. 9 shows a good agreement, except for 1998, but it also underlines the above-mentioned effect of a systematic underestimate of leaf biomass. Nevertheless, the model reproduces the relative annual variability of leaf biomass. The underestimate in needle

litter and biomass corresponds with an underestimation of LAI. The model underestimates the measured LAI (1.7) for autumn 1998 by 0.4 (23%).
An evaluation of the LAI simulation using the results of Jochheim et al. (2001) confirmed the underestimate of LAI by the SWIM model. The comparison for Kienhorst gives a SWIM simulated mean LAI of 1.6 over all years and yields 1.9 for the vegetation season with a maximum of 2.0 in relation to 2.3-2.6. These numbers are given by the authors as measured values (the lower value was measured by LI-COR LAI 2000 the higher one results from litter measurements (Jochheim et al., 2001)).
However, the comparison of the SWIM model performance with the forest model FOREST-BGC (Running and Gower, 1991; Running, 1994) used by Jochheim et al. (2001), at the same stand with regard to the simulation of the mean annual LAI, shows a lower divergence (0.3–0.6 (SWIM) versus 0.6–0.9 (FOREST-BGC)). The FOREST-BGC model overestimates the LAI (3.3). The 4C model (Bugmann et al. 1997) is in the range of the measurements by simulating a LAI of 2.3 as average over the total period.

As mentioned before, the explanation for the systematic error in wood biomass increase of the SWIM model is a result of the low validity of the allocation parameterisation for that specific stand. This is a reasonable outcome because the parameterisation was done for an average stand. Thus, the model deviation is more a measure of the variation of the Kienhorst plot from an average plot, rather than of the quality of the parameterisation. The stand in Kienhorst has 29% below average nitrogen deposition rates when compared to other Level II plots in Brandenburg. It also has strong limitation in the supply of phosphorous with only 13.6 % or 90 kg P_{org} in the top 30 cm compared to other sites (Meiwes et al. 2007). The relatively restricted supply of these two key nutrients in combination with general poor soil conditions of a Ferric-Podzol on silty sand lead to a wood growth rate below the average yield table values (Schulz and Härtling, 2003) used to parameterise the forest module.

3.2.4 An evaluation of the phenology sub-module

As an additional measure of model quality with regard to regional forest simulations as well as a further strategy used to evaluate the seasonal dynamic, phenology data from 63 stations around and within the Nuthe basin are used. The results calculated for the day of the year (DOY) of leaf unfolding of Common Oak (Fig. 22) are in acceptable agreement with the observations, demonstrating the ability of the model to represent the interannual variability.

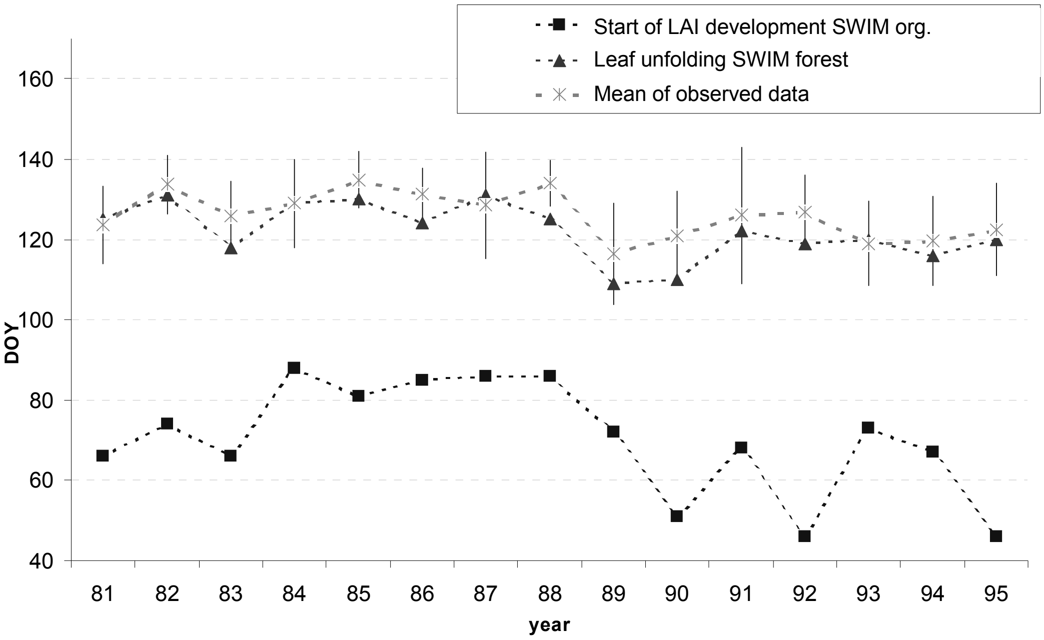

Fig. 22 Comparison of calculated values (triangles) for the day of the year (DOY) of leaf unfolding of Common Oak (Quercus robur) with means of measured data (stars) of the German weather service (horizontal lines are the standard deviation of the measurements) and modelled data (squares) of the simple temperature sum approach in the original SWIM version.

The comparison with the simple temperature sum approach used in the former model version shows a clear improvement.

For Scots Pine, (Fig. 23) the model systematically underestimated the date of May sprout but demonstrated an acceptable representation of the inter-annual variability. The results for the simulation of Scots pine phenology are based on a parameterisation by Menzel (1997a) where data observed in phenological gardens were used for parameterisation. Unfortunately, no parameterisation point was located close enough to the area of study to represent the local conditions. Thus, the possible source for the underestimate in the simulation of May sprout is that the model parameterisation does not fit the local conditions adequately. This is underlined by the good model performance for the calculation of leaf unfolding of Common Oak based on the parameterisation of Schaber (2002), who validated the parameters in area of study Brandenburg.

A sensitivity study was carried out by shifting the day of the year for leaf unfolding and May sprouting 10 and 44 days forward as well as 6 days back compared to the date calculated by the SWIM model. The first value (10 days) was based on the findings of Myneni et al. (1997), Menzel and Fabian (1999) and Schaber (2002) who observed a prolongation of the vegetation season in these ranges. The increase of the vegetation season by 44 days was selected as this was within the error range of the base version of SWIM. Finally, the reduction by 6 days was implemented to test the response of the model.

The results demonstrate the influence of the phenology on the 10 year modelled average water balance which is changed by values of: -1% (10 days earlier); -5% (44 days earlier) and 2% (6 days later), respectively. The change by 44 days, which corresponds to the values calculated by the simple temperature sum approach used by the original version of the SWIM model, leads to a systematic underestimate of the water balance thus demonstrating the necessity of using forest growth measurements as an additional evaluation criterion. This brief sensitivity study clearly shows the influence of phenology on the landscape water balance, a factor which was not recognised by the original approach. In connection with this observation, the findings of Myneni et al. (1997), Menzel and Fabian (1999) and Schaber (2002) illustrate the effect of an extension of the vegetation season in Europe in response to climate change. With regard to further work, the negative impact on the water balance could aggravate the effect of global warming even more and should be investigated.

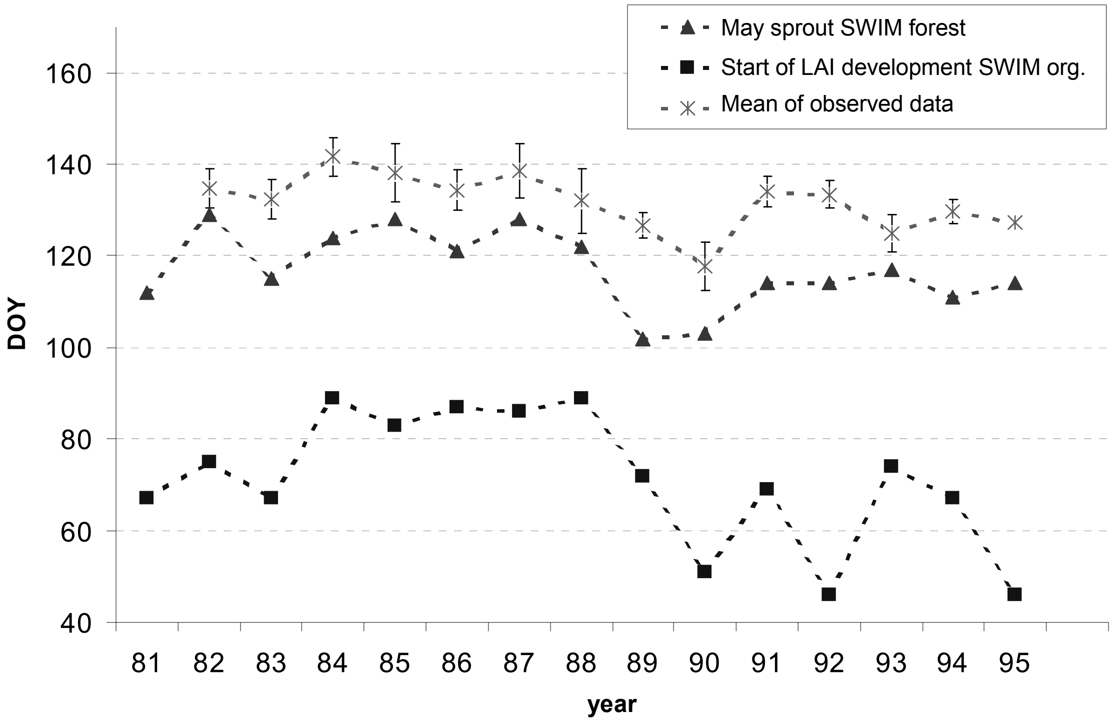

Fig. 23 Comparison of calculated values (triangles) for the day of the year (DOY) of may sprout of Scots Pine (Pinus sylvestris)) with means of measured data (stars) of the German weather service (lines are the standard deviation) and modelled data (squares) of the simple temperature sum approach in the original SWIM version.

3.2.5 An evaluation of the transpiration and interception sub-modules

The daily values for sap flow measurements during the vegetation period at the Beerenbusch plot (22/06/98 – 11/10/98) agree well with the tree transpiration simulations for the same period ($r = 0.81$) (see Fig. 24 a, b, c). However, Figure 24a demonstrates that the model, slightly but systematically, calculates higher transpiration rates. The analysis of the residuals (Fig. 24c) shows no trend but acknowledges the overestimate, especially of values close to the mean simulated values.

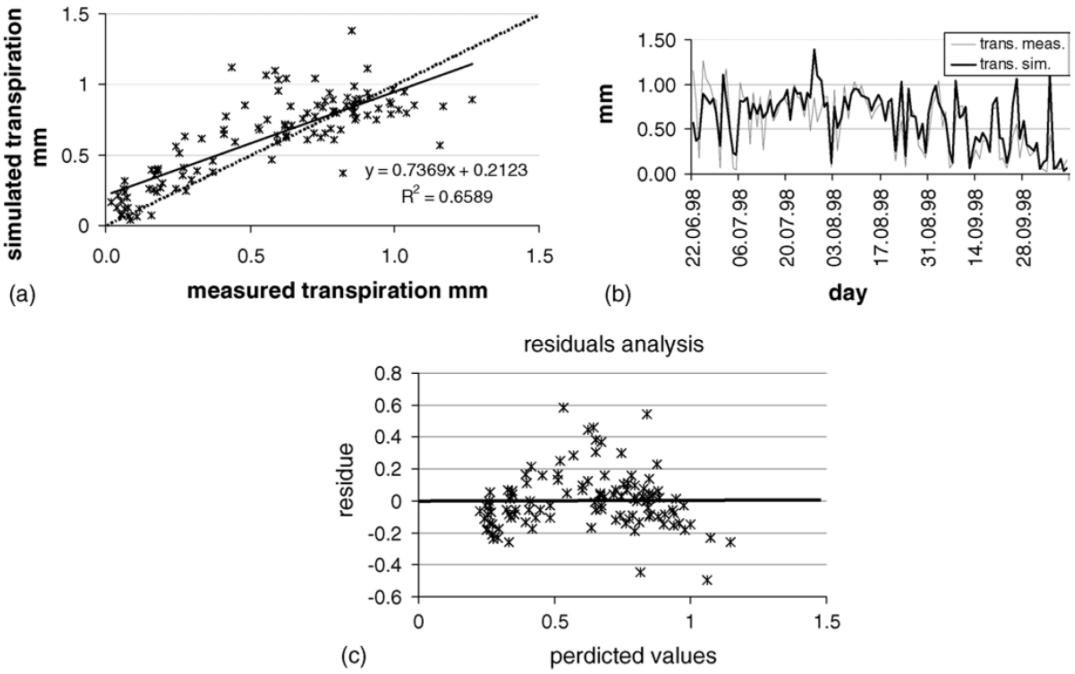

Fig. 24 (a): Correlation of simulated and measured transpiration (b): the daily simulated values for transpiration (black line) in comparison with measured data (grey line) (c) comparison of the residuals with predicted values for the year 1998 (Level II Beerenbusch).

To continue, the simulated transpiration in 1999 does not reflect the observations of the sap flow rate as well as in 1998 when comparing the same period 27/03/99 to 15/11/99 (Fig. 25 a, b, c). The correlation coefficient is only r = 0.65. The model overestimates the transpiration especially in the spring period from the start of measurements on the 27th of March until the 17th June. The analysis of the residuals (Fig. 25c) shows again no trend therefore indicating no systematic effect.

It is important, however, that the greatest difference between the two measured time series of 1998 and 1999, and a possible explanation for the lower model performance in 1999, is the different correlation of the transpiration measurements to solar radiation. The transpiration measurements of 1998 are highly correlated (r = 0.89) with the solar radiation compared to a correlation of r = 0.71 in 1999. This indicates a possible restriction in transpiration capability, which is not considered in the simulation. This is supported by the higher correlation of r = 0.81 between simulated transpiration and measured solar radiation for 1999 when compared to the correlation between measured values.

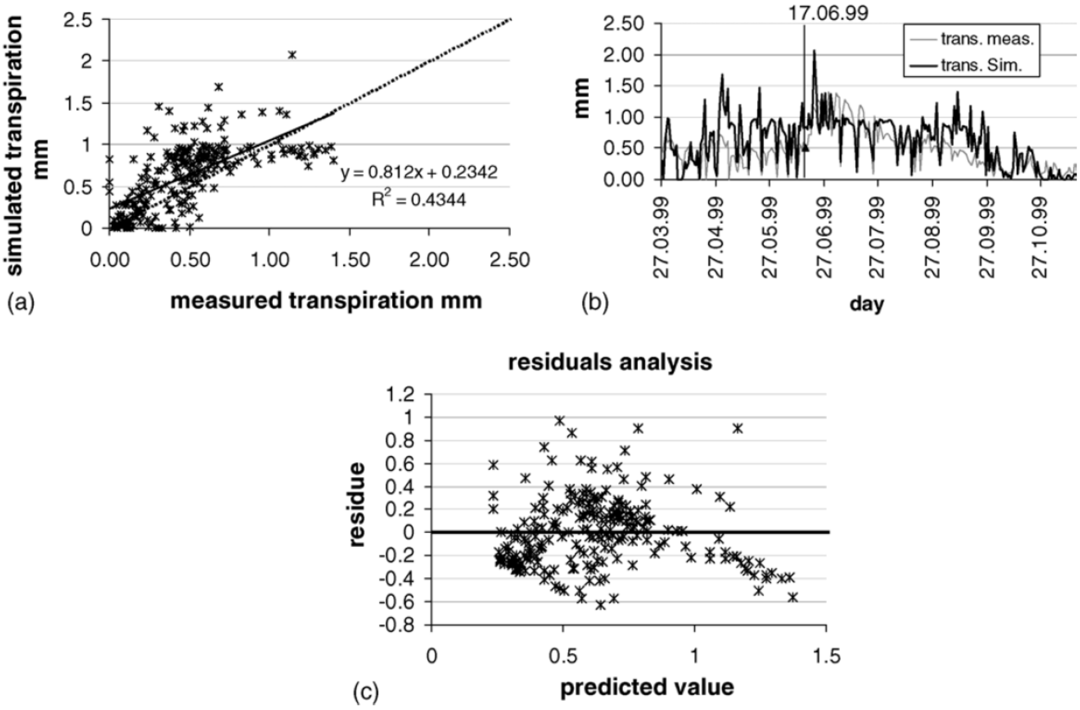

Fig. 25 (a): Correlation of simulated and measured transpiration (b): the daily simulated values for transpiration (black line) in comparison with measured data (grey line) (c) comparison of the residuals with predicted values for the year 1999 (Level II Beerenbusch).

The period of the highest divergence between simulated and measured transpiration, as well as between measured solar radiation and measured transpiration in 1999, is in spring, from the beginning of the measurements until the 17^{th} of June (Fig. 25b). Lüttschwager (2001) explains the discontinuity in the time series of measured transpiration as an effect of the increase in LAI during May sprout. Thus, we have to assume that the model is not able to represent this effect in an accurate way. After the 17^{th} of June, until the end of the measurement period, the correlation of simulated and measured transpiration is higher (r = 0.73) than for the total period (r = 0.65).

Another source for the model evaluation is provided by the LFE in form of cumulative annual values for the soil water content measured by TDR (Time Domain Reflectometers) probes. A comparison of the measurements with the values simulated by the forest version of the SWIM model shows a mean underestimate of 20 % at 30 cm depth and 15% at 70 cm depth for the period 1997 - 1999. This may indicate a problem in reproduction of the depth allocation of the water uptake. A high degree of uncertainty still remains present here because of the simple multilayer storage approach used in the SWIM model. A different possible explanation might be that the maximum simulated water content reaches only field capacity, whereas the TDR probe values can exceed this value (Jochheim et al., 2001). It is suggested that a more comprehensive evaluation has to be subject of further model studies.

The interception values for the Scots Pine stand at Kienhorst were simulated for 3 years (1996-1998) with a daily time-step and then summarized on a weekly and annual basis in order to compare them with the measured data. The weekly aggregated simulation results show an overall good agreement with the measurements during the vegetation period (Fig. 26 a, b, c). However, there are very strong underestimates apparent during early spring and late autumn.

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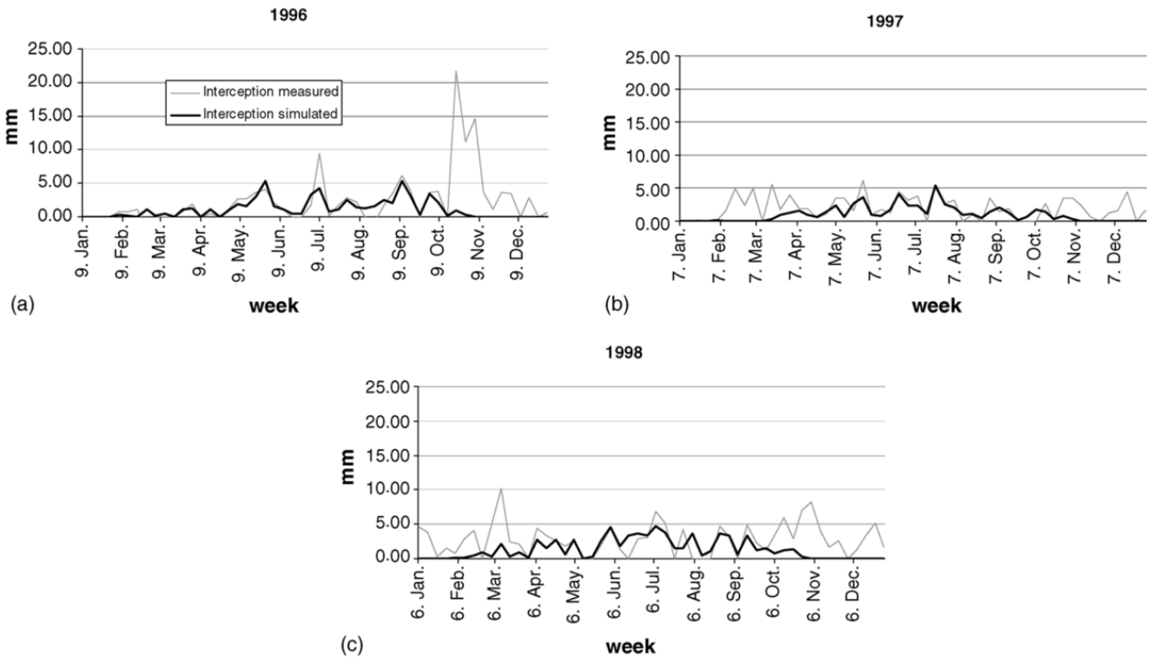

Fig. 26 Simulated values weekly intercepted rainfall aggregated from daily-simulated values (black line) in comparison with measured data (grey line) for 1996 (a) 1997 (b) 1998 (c) (Level II Kienhorst).

One possible explanation for this tendency might be the influence of wind. It must be borne in mind that it is not explicitly considered in the model. In this regard, Crockford and Richardson (1999) mentioned the uncertainties in the interception measurement methods when considering the position of the rain gauge in relation to the canopy and the influence of wind. They mention that an estimate of zero for interception and an overestimate of rainfall by as little as 2.4 mm would lead to an overestimate of interception by 100 % which might explain the discrepancies in the comparison when it is recognised that autumn and spring are both periods of higher wind activity.

3.3 The Brandenburg study: scenario impact assessment

3.3.1 Scenario I: partial liberalization

The increase in forest area intensifies evapotranspiration, hence, changing the mean annual water balance of the federal state area (Fig. 27) (see section 2.5 for the scenario details). Evapotranspiration, as the largest efflux component of the regional water balance, changes only slightly from 0.53 (10% afforestation) to 3.7 % (100% afforestation) compared to no afforestation in the annual average over the entire simulation period. This change has a strong influence on the other components of the water balance, changing mean annual groundwater recharge from -1.4 (10% afforestation) to -9.8 percent (100% afforestation), and average annual runoff from -1.2 (10% afforestation) to -4.8 percent (100% afforestation), respectively.

However, the comparison of the mean values alone does not reveal the full picture. If we also consider the change in average annual minimum groundwater recharge, a much more pronounced effect from -4.0% to -29.4% can be observed. The increase of forest area has only a moderate impact on the mean annual runoff. It does, however, alter the peak flow (maximum runoff) considerably providing figures up to -19.9%.

The picture changes also if the seasonal pattern is taken into consideration. The change in the annual mean is caused by a strong increase in evapotranspiration of (e.g. 25.1 % at 100% afforestation) in spring (March to June), which is partially offset by a decrease in evapotranspiration of -6% over summer and autumn.

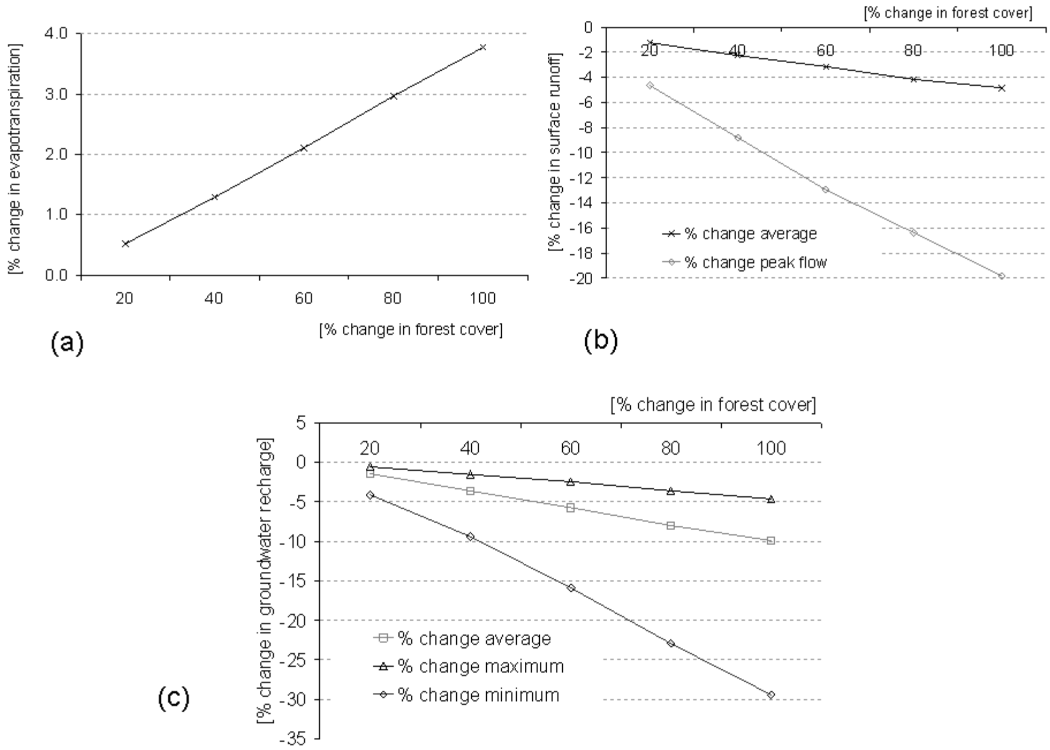

Fig. 27 Change in annual sum of evapotranspiration (a), groundwater recharge (b) and runoff (c) caused by an afforestation of ceased land as a result of the "partial liberalisation scenario" effects for the total state area.

The analysis of the average monthly values (Fig. 28a-c) underlines these findings, as a slight increase in evapotranspiration in spring (Fig. 28a) causes a more pronounced decrease in other hydrological components (Fig. 28b and c). This seasonal pattern is important, as spring has the highest total amount of rainfall and is therefore essential for groundwater recharge (Fig. 29). Although the reaction of the groundwater component shows a time lag, caused by the transfer time the water needs to reach the aquifer from the surface, the response is clearly visible and dominant over the entire year. Quite crucial is the fact that the time lag causes the strongest decrease in recharge in mid-summer, where the water demand of the vegetation becomes critical as the soil water storage capacity becomes close to exhaustion. Thus, the lack in recharge can increase the severity of summer droughts by decreasing groundwater levels to such an extent that plant water uptake is impaired.

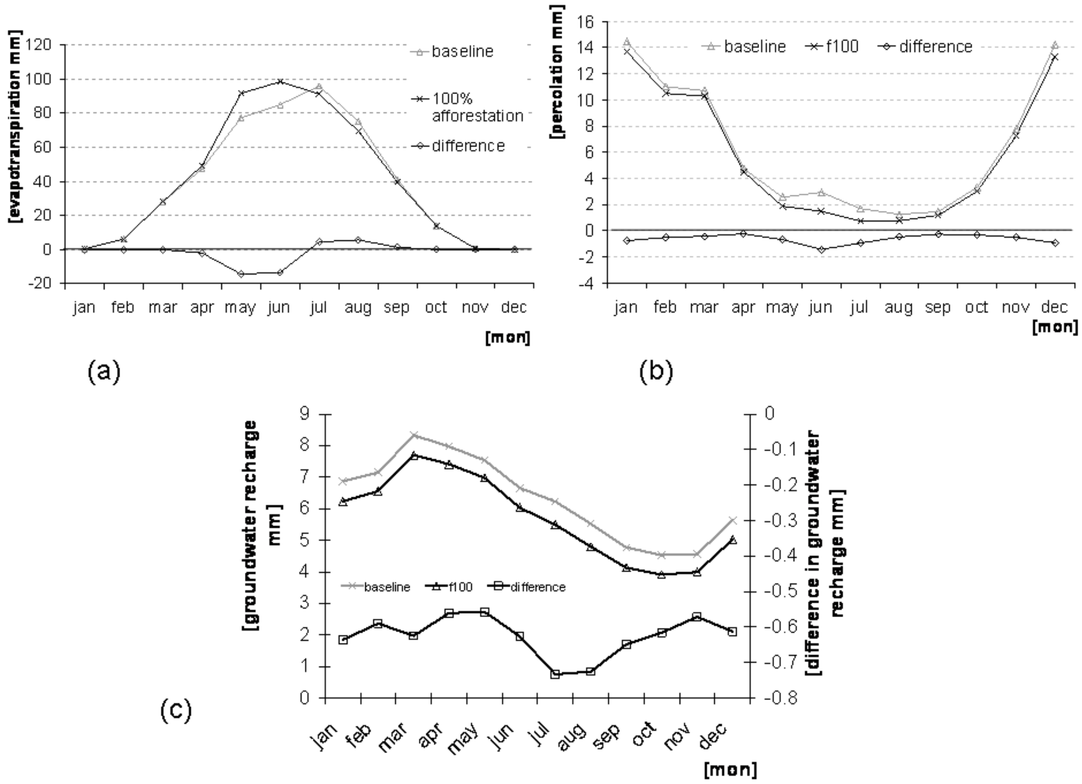

Fig. 28 Change in monthly average evapotranspiration (a), percolation (b) and groundwater recharge (c) (50 years) caused by an afforestation of ceased land as result of the "partial liberalisation Scenario" effects for the total state area.

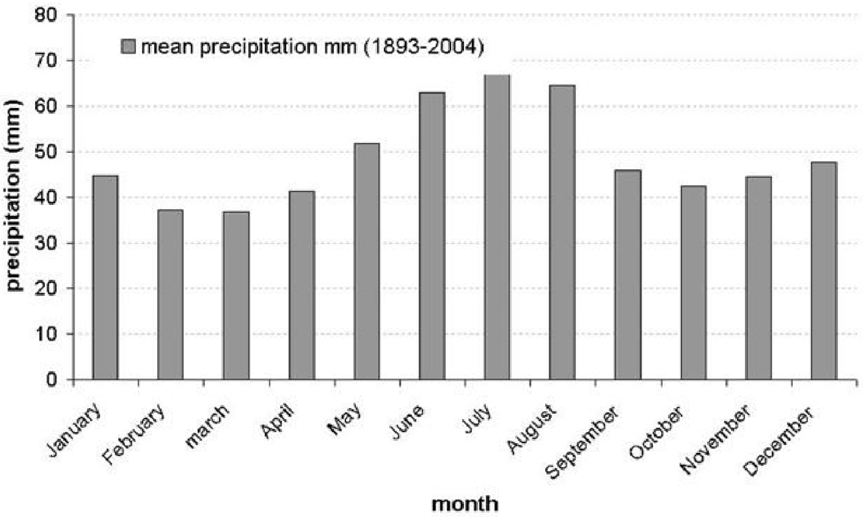

Fig. 29 Average monthly precipitation for Potsdam (PIK, 2006). The sum of precipitation is highest in spring although July is the wettest month.

Overall, the aggregated response functions for the total state area show a smooth and almost linear response. However, this is masking a strongly heterogeneous response on the landscape unit level (Fig. 30). The responses at this level can be divided into three categories. Class I incorporates most areas with the strongest response to the scenario as this class integrates lowland areas with a higher percentage of high groundwater levels (2.0 m below surface and above) than the average for other units of the federal state. In these areas, trees are able to access the capillary rising zone of the shallow aquifer. The shift from fallow to forest increases evapotranspiration by up to 33mm thus causing a considerable reduction in runoff and groundwater recharge. They are also areas where conversion takes place within the first steps of transforming agricultural land into forest, as the high groundwater levels make them unsuitable for agriculture. However, their response is also highly correlated to the percentage of convertible land (fallow) on groundwater influenced soils. As an example, the area labelled “1” in Fig. 30 A is groundwater influenced (class I), however, the area belongs to the boggy lowland regions where most of the peat soils are under grassland.

Class II aggregates areas with dry sandy soils and lower soil fertilities than the state average. These areas are critical for the change in groundwater recharge as the low soil quality leads to a fast conversion into forest. The process is accelerated as these areas are rich in forest in the base year and conversion starts from the edges of these forests. Additionally, the corresponding forest class is pine forest, inducing an increase in interception of precipitation resulting in more evapotranspiration and reduced groundwater recharge. However, as these areas already have a high percentage of forest cover, their aggregated response on the landscape unit level can be less pronounced due to the lack of convertible land (e.g. Fig. 30: label 2). Less crucial, and aggregated in the third class, are areas with good and moderate soil conditions (soil quality above the mean of all landscape units). These areas react only in the late phase of conversion when they are transformed into deciduous forest allowing water to drain into the aquifer during spring. Although these classes are not exclusive, it is possible to categorize the complexity of the landscape response and to identify sensitive areas for land-use change impacts.

To widen the debate, the review of Brown et al. (2005) allows us to relate the results presented here to the global picture. Their review of global paired catchments studies confirms the qualitative results that an increase in forest area reduces the water yield within a catchment. The findings in the review also agree with the result for the seasonal pattern of change. They summarize that for winter rainfall dominated catchments, the reduction in summer flow is proportionally much larger then in winter which corroborates what was observed in the simulation results. Furthermore, the order of magnitude for the results presented here is within the range of the reviewed experiments. Brown et al. (2005) cite the study of Bosch and Hewlett (1982) who compared the results of 94 experimental catchments situated in different regions of the world. Their estimated response of maximum water yield in the first five years, for a conversion from non-woodland to coniferous types, is a reduction of -40 mm per 10% conversion and -25 mm for deciduous species, respectively. The SWIM simulations yielded a reduction in water yield of -16.5mm for the five year mean of the monthly maximum. If we consider the five year mean, the change is -21.5 mm if compared to the simulation with full afforestation of all abandoned land, which corresponds to 9.4% of the total state area. However, Brown et al. (2005) also conclude that the time period of 5 years used by Bosch and Hewlett (1982) is too short to show the full impact of a vegetation change, as the new equilibrium state might be reached much later. They also argue that the use of the maximum leads to a high bias as a result of climate variability.

Farley et al. (2005) demonstrated a quite conservative ratio of 14-15% for the change in runoff, if it is expressed as a percentage of mean annual precipitation (MAP). The MAP for the federal state of Brandenburg over the simulation period is 612 mm. The mean annual runoff for the area is 160 mm for the base line and 143 mm for the full afforestation of fallow, respectively. This is a difference of 2.8 % when relating the two runoff values to MAP. The total area of the state which is affected by the change is 9.4 %. The numbers of Farley et al. (2005) are based on a change on 75% of the catchment area. This gives a ratio of 7.9 to scale the simulated scenario response to 75%, provided that we assume a linear trend as in Farley et al. (2005). If we now multiply 7.9 with the change of 2.8 % it yields 22.1% which is relatively close to the values reported by Farley et al. (2005). The difference might be explained by the fact that in this comparison we changed from cropland directly to forest and not from grass or scrubland into forest as in the catchments studied in Farley et al. (2005). It needs to be borne in mind that croplands have reported lower evapotranspiration rates than perennial vegetation (Larcher, 1994).

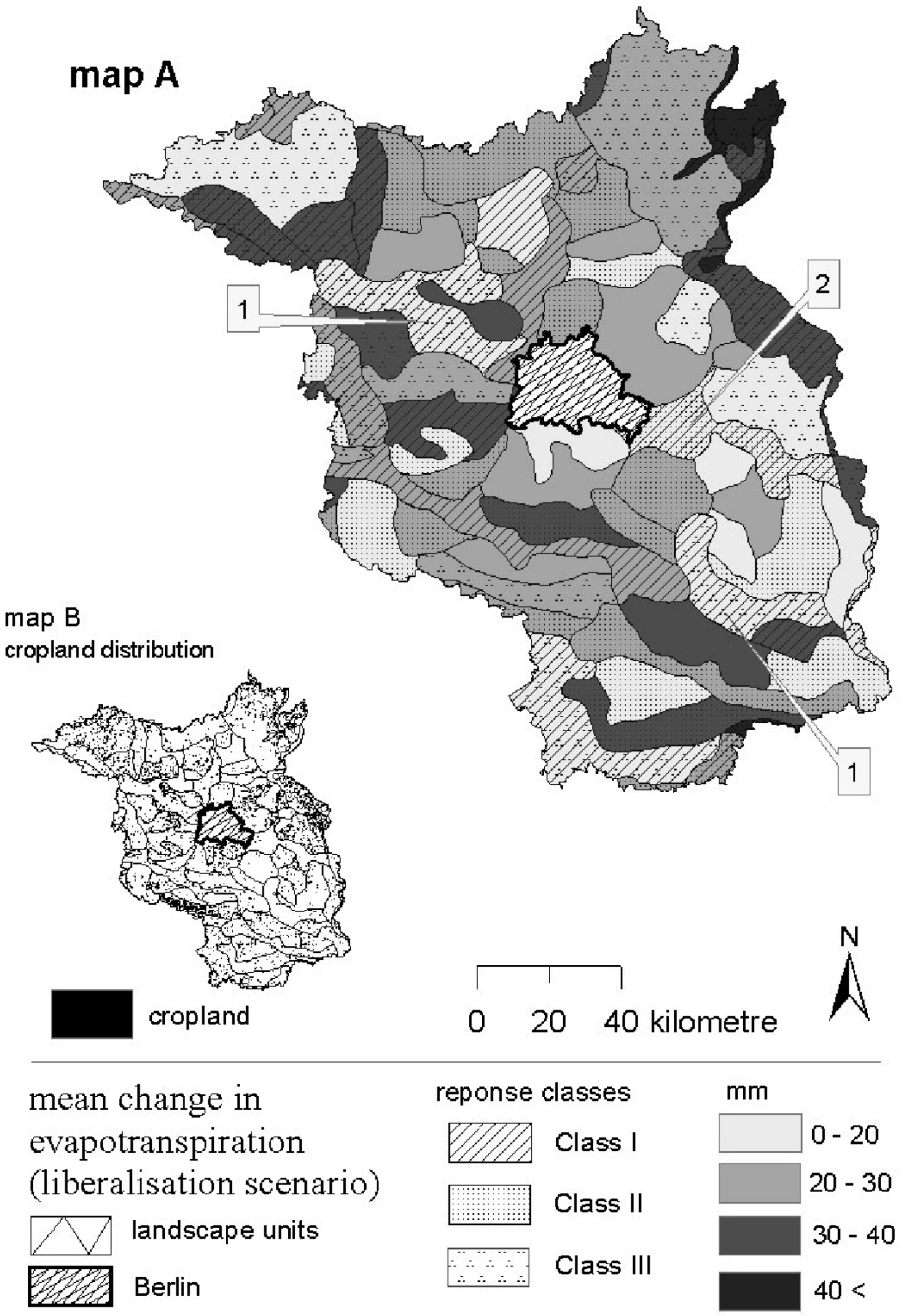

Fig. 30 Effect of the "Partial Liberalisation"-scenario on the change of evapotranspiration for the total area of landscape units (Map A). Class I: areas with high groundwater levels. Class II: areas with low soil fertility and high percentage of forest. Class III: are the remaining areas with good soil quality and low forest percentage. Insert (Map B): cropland areas.

One important source of uncertainty in this study originates from the predicted landscape pattern and its interaction with the SWIM model. Zebisch et al., (2004) clearly showed that environmental conditions are not solely responsible for the distribution of landscape elements and that historical and current social conditions are important factors too. There may also be a number of areas that are identifiable as sensitive, but which may stay in production because of local economic or social reasons. Zebisch et al. (2004) showed that the pattern generator (PAGE) could reproduce the current land-use with a spatial correlation of 0.7. Thus, we could assume the same accuracy/precision for future land-use pattern. However, investigating the effect of the propagation of this source of uncertainty was not the subject of this study. The second source of uncertainty is the process description in the SWIM model itself. As explained in section "Applicability" the model is robust in reproducing the hydrological properties, though it needs to be said that a landscape scale evaluation of other non-hydrological components was not part of this study.

3.3.2 Scenario II: forest species change

The effect of the conversion of pine forests into deciduous forests is in the same order of magnitude as the effects caused by the "partial liberalization" scenario although it covers a greater area of conversion. In the forest species change scenario, 29.2% of the total state area was converted from pine dominated forest to oak forest compared with only 9.4% of the total state area which was converted from agricultural land to forest in the liberalisation scenario. The relative aggregated average response of the state shows a clear decrease in evapotranspiration by up to -3.44% at 100% in the conversion of pine to deciduous forest (Fig. 31a-c). This clearly influences the runoff (+2.0%) (Fig. 31b), as well as the groundwater recharge (+4.8 %) (Fig. 31c). Conversely, the opposite occurs if the proportion of deciduous dominated forest is reduced to 20% where evapotranspiration increases slightly. It can be stated that the change in groundwater recharge (Fig. 31b) shows a clear pattern with the increase in minimum recharge is stronger than the increase for the mean or maximum. This is a clear result of the lower water interception storage of deciduous tree species. This effect, combined with a higher proportion of stem flow, renders even relatively small rain events more effective for recharge than evergreen cover. There is, however, no change in peak flow, although the transition towards deciduous species did increase the mean surface runoff.

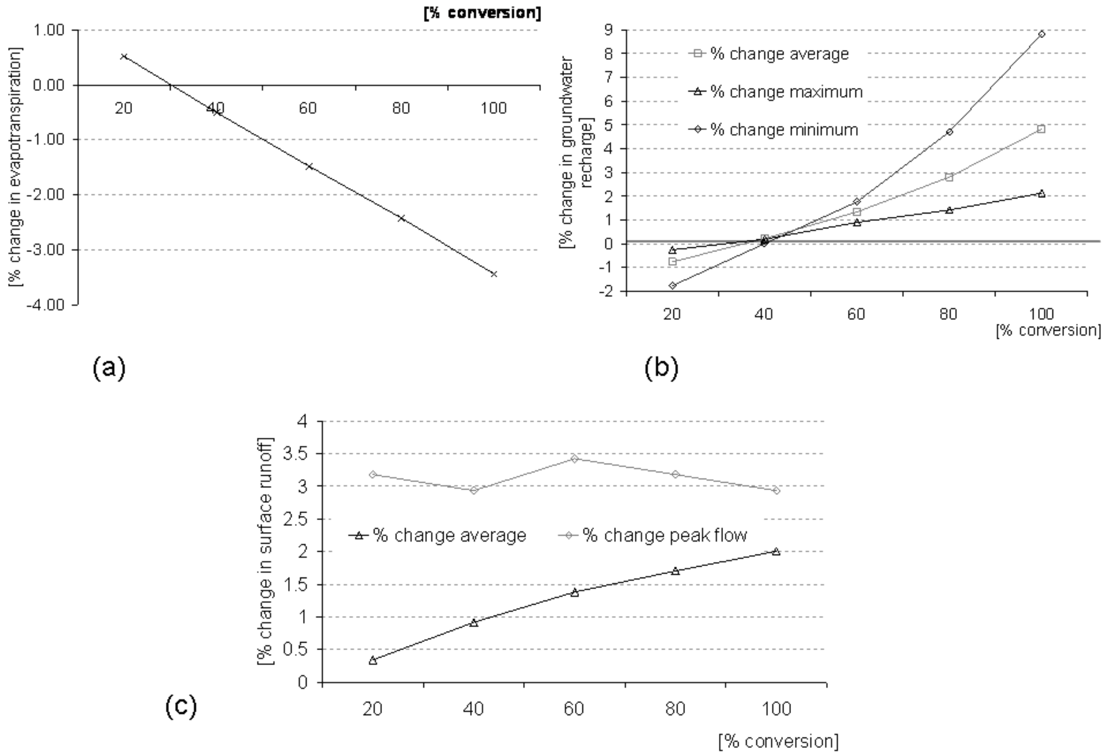

Fig. 31 Change in annual mean sum of evapotranspiration (a), annual mean sum of groundwater recharge (b) and annual sum of runoff (c) caused by an transformation of Scots Pine forest to Common Oak forest as assumed in the "forest species change" for the total state area.

The results of the monthly averages (Fig. 32a-c) showed a similar trend in regard to their seasonality if compared to the results of the "partial liberalization" scenario analysis. However, the seasonality was less pronounced, with the largest differences in the scenarios being between March and June when deciduous trees unfold their leaves. It was also noticeable that the scenario with a conversion to 100 % deciduous trees leads to a higher recharge than the base line run. The time lag in the reaction was again persistent leading to the difference in recharge from June to August.

The spatial analysis (Fig. 34) of the data shows a high spatial heterogeneity, similar to the "liberalisation-scenario" with a standard deviation of 11.2 and 12.1, respectively. In this case, the most sensitive areas are those with a high percentage of forest where pine is the dominant species, which implicitly results from the scenario assumption (see Fig. 33 and Fig. 34 insert D). However, only 52.8 % of the variance can be explained by the percentage of pine forest, which is clearly an effect of the aggregation to landscape units but which also represents the effect of the soil type and groundwater access of vegetation.

The results are in good agreement with extensive measurement campaigns by Müller (1996) which show the impact of pine monocultures on the water balance in forest stands and the increase in groundwater recharge by transforming them into deciduous forest types. When comparing the results with the compilation of Brown et al. (2005), they are in good agreement as well. They refer to the work of Sahin and Hall (1996), who analysed 145 catchments from different regions of the world, comparing them based upon their dominant vegetation. They used the 5 year mean of change to compare the different catchments. They concluded that a reduction of forest to non-forest vegetation leads to an increase of water yields of 20-25mm for evergreen and 17-19mm per 10% for deciduous species. In scenario analysis, land-use changed from evergreen to deciduous which should lead to a change between 3mm and 6mm according to the findings of Sahin and Hall (1996). For a change on 29% of the total area the predicted change would be between 8mm to 16mm. Therefore, the simulated change of 3.1 mm is clearly lower than these predicted changes, but remain in the same order of magnitude.

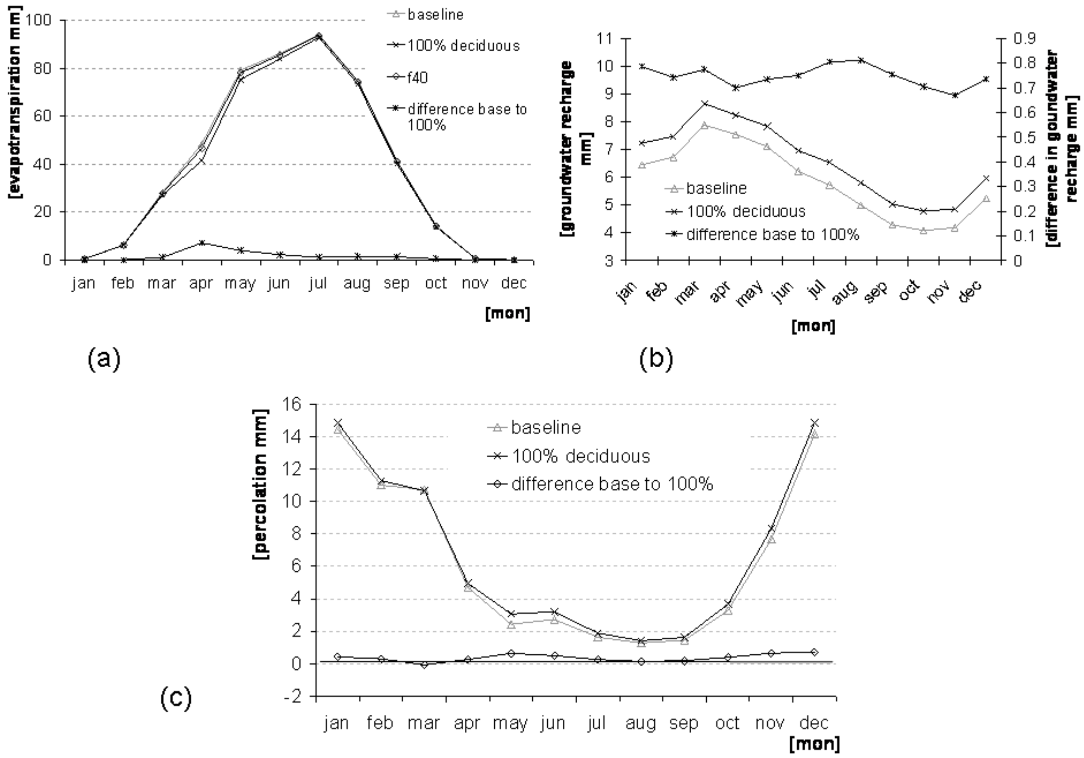

Fig. 32 Change in monthly average evapotranspiration (50 years) caused by a transformation of Scots Pine forest to Common Oak forest as assumed in the "Forest species change" for the total state area (a). f40 represents the nearest approximation of the target of regional forest authorities if we consider mixed forest as deciduous dominated. Change in groundwater recharge (b) Change in monthly average percolation (c).

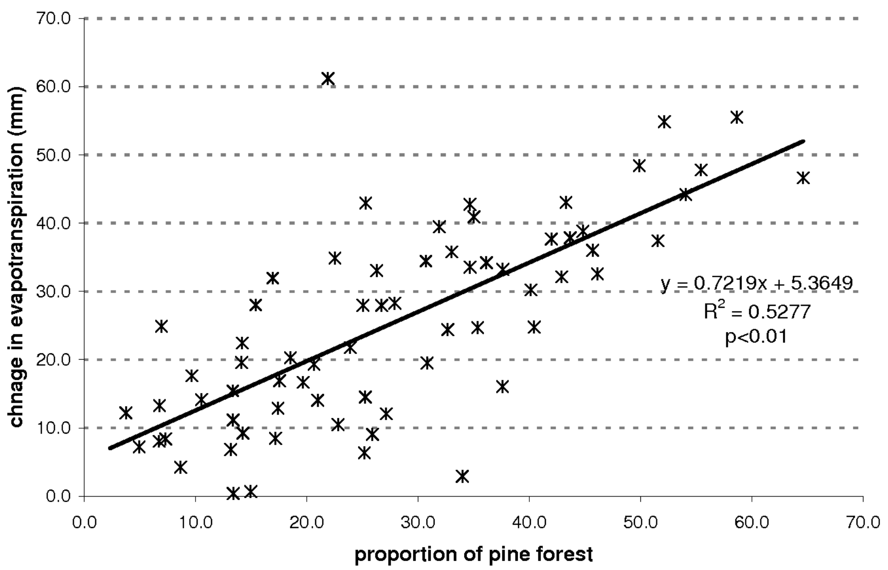

Fig. 33 Correlation of proportion of Scots Pine dominated forest in the baseline scenario and change of evapotranspiration during conversion to Common Oak forest averaged for landscape units in the "Forest species change" scenario analysis.

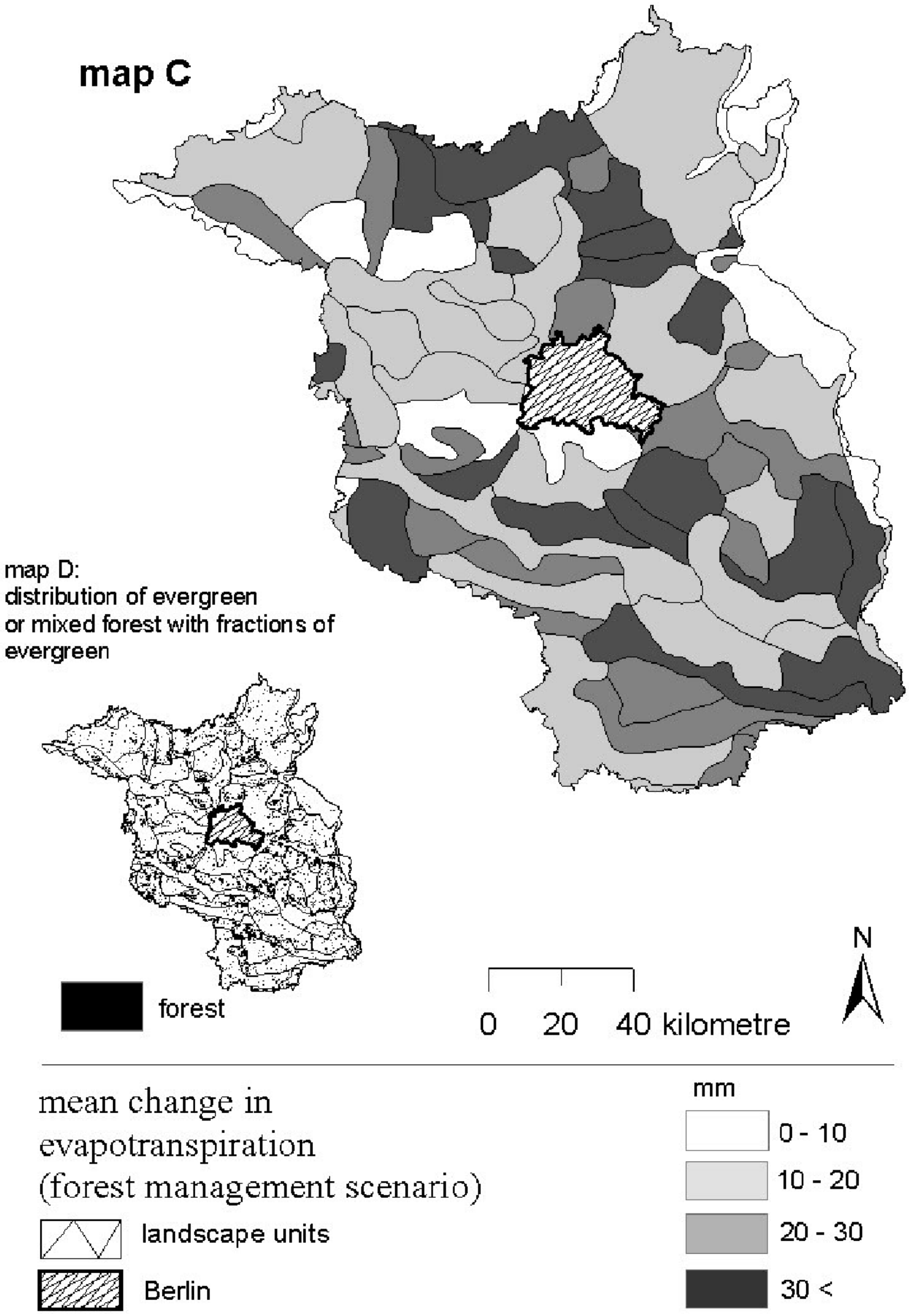

Fig. 34 Map (C): Effect of the "Forest species change"-scenario on the change in evapotranspiration for in landscape units. Insert map (D): evergreen or partly evergreen forest; the map shows areas of Scots Pine dominated forests underlining the causality of change in evapotranspiration and pine forest areas as assumed in the scenario.

3.3.3 Uncertainty analysis

In order to identify the number of runs needed to achieve stable uncertainty results, the standard deviation was calculated after each model execution for one Monte Carlo simulation (Gottschalk et al., 2007; Verbeeck et al., 2006). Figure 35 shows that after 200 model runs, the standard deviation in the ten year average AET converged towards 2.9. Therefore, 200 model runs in one Monte Carlo simulation was assumed to be a reliable number to base the model output uncertainty on. The results for the global uncertainty analysis are presented in Fig. 36 a-c. The output distributions of the sites were tested for normality using the Kolmogorov-Smirnov test. The results could be assumed to be normally distributed ($0.2294 < P < 0.5925$). The global uncertainty, as a result of the change in the initial and process parameter settings, changes from year one towards year 10.

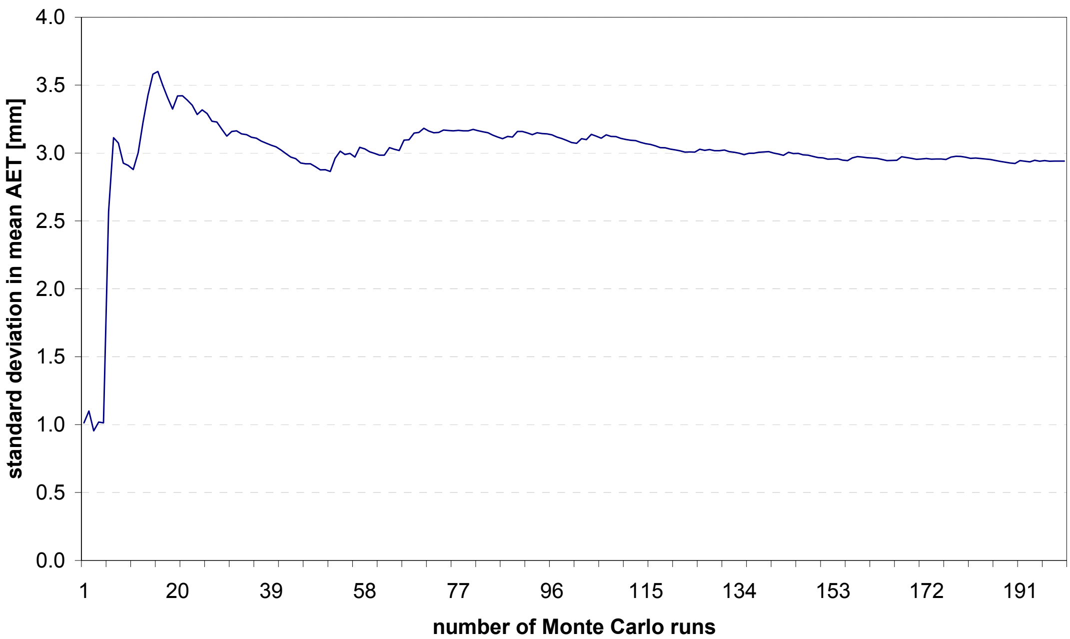

Fig. 35 The standard deviation [mm] of the ten year average AET presented as a function of the number of model executions of one Monte Carlo simulation. It converges towards 2.9 after 200 runs allowing us to assume stable results.

This change over time is due to the exponential age LAI relationship. As the age of the simulated stands progresses over time, the model becomes less sensitive to the change in initial age. Consequently, the global uncertainty, expressed as the standard deviation of the output PDF, decreases from 3.6 in year one to 2.8 in year ten.

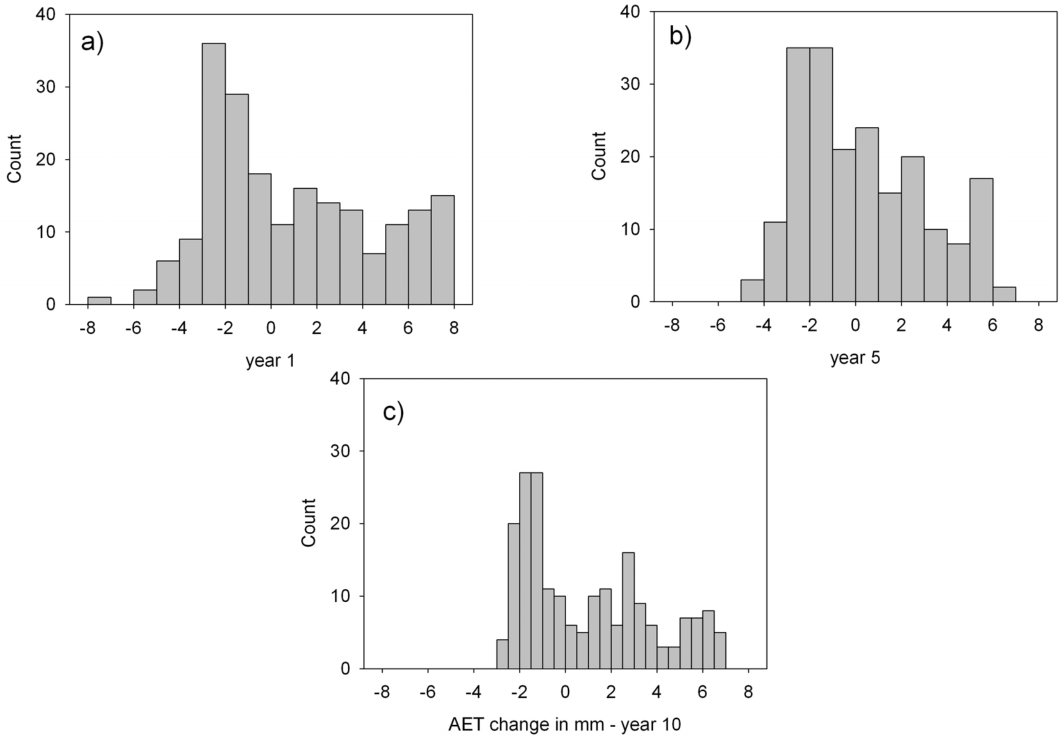

Fig. 36 a-c Probability density functions of AET over time. In plot a) the distribution for the first simulation year, plot b) for year 5 and plot c) for year 10.

The distribution is also shifted towards more positive values because forest stands of very young ages are below the maximum LAI; as they become older their LAI reaches the species-specific maximum resulting in higher evapotranspiration. Figure 37 shows the correlation between the change in age and the ten year average change in AET underlining these findings. The exponential function fitted to the points can explain 91% of the variance in the results making age the most important factor.

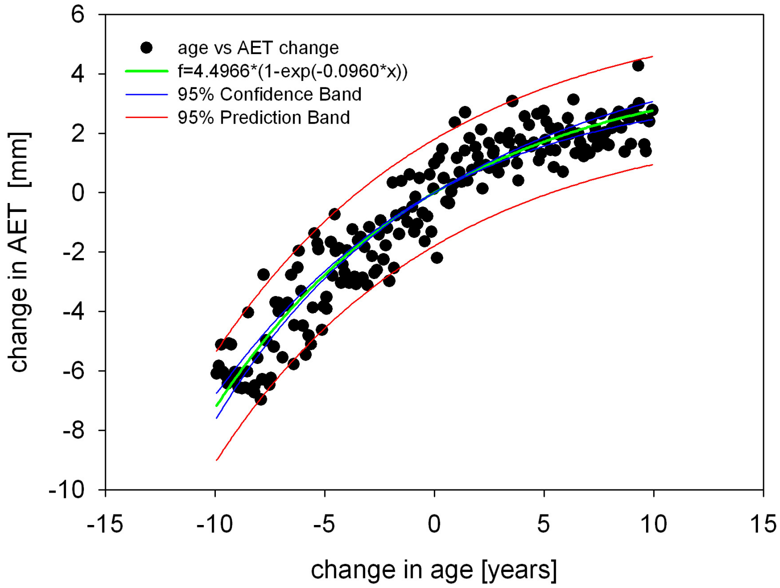

Fig. 37 Scatter plot of age change versus the average change in annual AET after ten years. The exponential function fitted to the values has a coefficient of determination (R^2) of 0.91 explaining the dominant part of the variance in the results.

The variation in the other factors also contributes to the variation in the results, but these have only relatively small influence on the change in AET. Figure 38 shows four contour plots that illustrate the combined effect of change in age and the other factors on the change in average annual AET after 10 years. To identify the influence of each parameter on the uncertainty in the AET prediction, the contribution index was calculated. The uncertainty is expressed in radar plots in Fig. 39 for year one and year ten of the simulation time period as the relative contribution of each factor to the global uncertainty of the result.

As already identified, more than 90% of the variance can be attributed to the change in age (94.6 % year one and 96.9 in year ten). However, if we look at the less important factors in plot 39 b and d, we can identify a shift of the importance from initial biomass in year one to the phenological factors in year ten. The base temperature is the second most important factor contributing to the global uncertainty after ten years. As the variation attributed to the factor was only one degree Celsius, the model is clearly sensitive to changes in the factor after ten years.

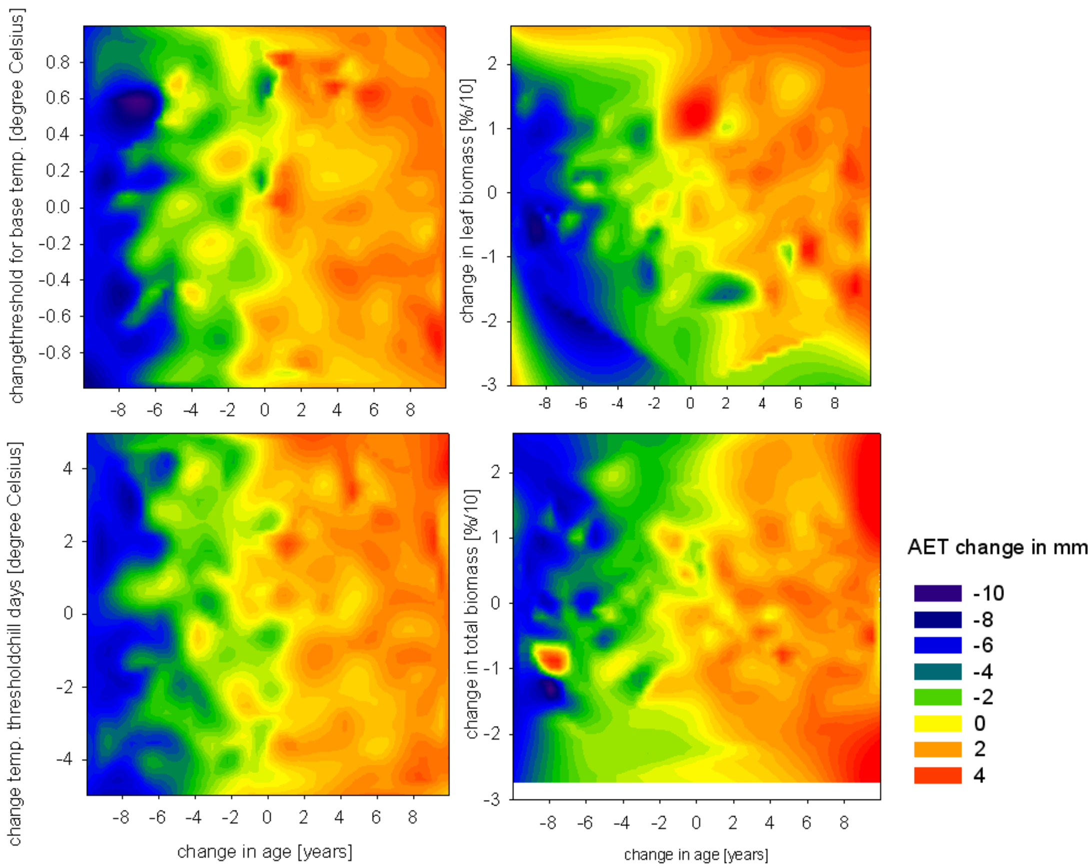

Fig. 38 Contour plots of AET for a selection of different parameter combinations.

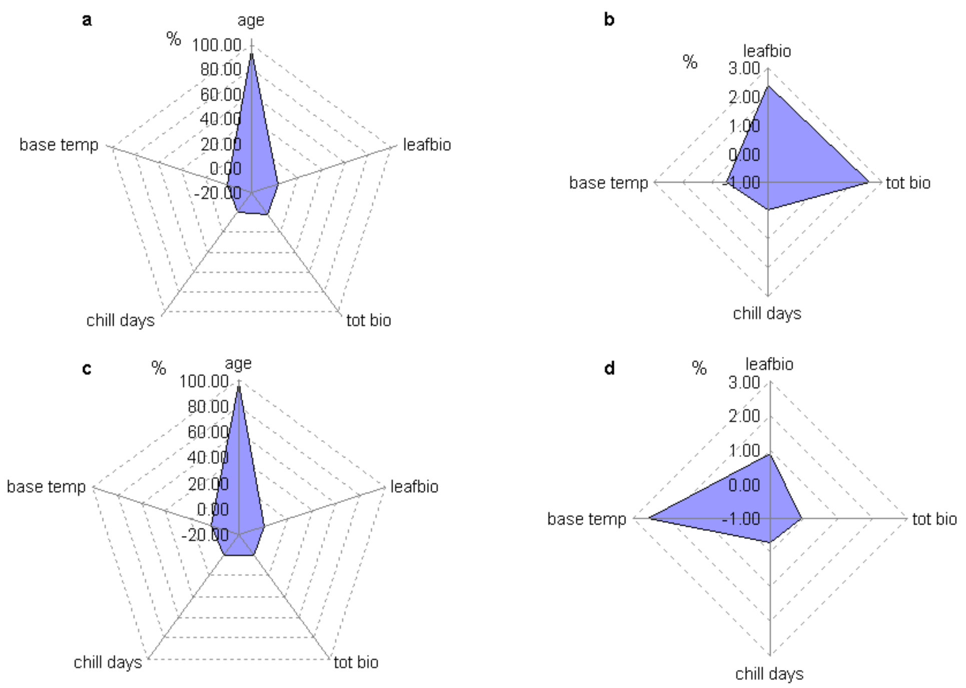

Fig. 39 Relative contribution of the five factors to the global uncertainty in AET. Plot a, b: year one, plot c, d: year ten of the simulation. age – factor to change the initial age, leafbio - factor to change the leaf biomass, tot bio- factor to change the total biomass, chill days – factor to change the chill day temperature threshold, base temp – change to the temperature threshold for the heat sum accumulation.

The negligible contribution of chill days to the overall uncertainty is notable. Schaber (2002) conducted a Germany wide analysis of phenological data, which identified the temperature threshold for chill days as unimportant for the prediction of leaf emergence, and this is in agreement with the forest module results. The uncertainty of the simulation results for the Brandenburg study arising from the forest growth parameterisation seems to be low. The effect of the scenario analyses in the Brandenburg study yielded a maximum change in AET of 3.7% and 3.4% for the liberalization scenario and the forest species scenario, respectively, when compared to no change in land-use.

The uncertainty ranges, defined as standard deviation, are between 0.6% for the mean overall years and 0.7% in the first year of the simulation in relation to the run with no change in any factor. However, as we only compare the annual mean over the total state area, the uncertainty might be underestimated. The related factor that might contribute to an underestimate is the shape of the age class distribution as this may change the response to a shift in age, as discussed in the start of this section. Finally, the result of the scenario analysis showed a seasonal and spatial heterogeneity in the results that may also apply to the uncertainty ranges. In addition, it must be borne in mind that any interactions arising from the uncertainties in the calibration parameters were not considered.

4. Conclusions

4.1 Forest model approach

The forest module has demonstrated that it can clearly provide satisfactory simulations of Scots Pine, and to some extent of Common Oak growth, together with their effects on: effect on hydrological properties, discharge at the basin outlet and the landscape water balance within the SWIM model framework. A reasonable description of forest growth (LAI and phenology) and forest-related hydrological processes (interception, transpiration, and root water uptake) is crucial in catchment modelling, because changes in land-use as well as in climate will also affect the forest distribution and tree species composition. This, in turn, impacts on the regional water balance (Bäumler and Zech, 1999; Crockford and Richardson, 1999; Engel et al., 2002; Finch, 2001; Fohrer et al., 2001) and has to be considered in relevant model applications such as integrated assessments. The approach also provides the possibility of a multi-criteria model evaluation in cases where forest data are available. The European-wide available Level II network is a good basis for evaluation as shown in this study. The overall performance of the forest extended SWIM model has proved to be satisfactory as shown in the results section. In addition, the model agrees with the criteria of Lindström et al. (1997) as mentioned previously in the introduction section. To recap, these criteria are as follows:

- the model shall be based on a sound scientific foundation:

  The approaches that are used in the forest module are approved methods that are widely validated. This could be confirmed for Brandenburg conditions as it was possible to reproduce the biomass on Level II stands in this federal state. The computation of intercepted rain was good in regard to the summer season. Transpiration was modelled for the year 1998 with a good agreement with measured data as well as with acceptable results for the year 1999.

- data demand must be met in typical basins:

  The parameters for the core function of biomass allocation and initial data for biomass and age can be obtained from long-term measurements as e.g. in Burger (1947) and Burger (1948). For applications in other regions, Bugmann (1994) gives a compilation of parameters to calculate leaf biomass based on

DBH. Forest inventory data incorporating DBH and standing volume are available in most European countries (Zianis et al. 2005). If there is no detailed spatial information for age class distribution the use of local statistics and land-use maps is possible as shown in the regional study for the federal state of Brandenburg. For the calculation of the phenological events, Menzel (1997a) and Schaber (2002) published the parameters of the Cannell and Smith (1983) model for a number of tree species for Europe and Germany, respectively.

- the model complexity must be justified by model performance:

    The model uses a simplified but physically/physiologically based approach to calculate forest growth and the related hydrological fluxes. Due to this approach, the model can be applied on the regional scale, the scale relevant to calculate the water and nutrient balance of river basins.

- the model must be properly validated:

    The evaluations shown in this thesis are a first step towards the validation of the model with promising results. Additional applications are required to investigate the models performance in different regions and for other tree species.

- the model must be understandable by users:

    The parameters used in the module have a physical or plant-physiological background making it easy to adapt the calculations to specific regional conditions and other tree species. This thesis gives an overview of the approaches used and enables the reader to apply these if necessary.

4.2 The Brandenburg study

In general, it can be concluded that the situation in Brandenburg is comparable to other regions with low climatic water balance (Brown et al., 2005). In such regions, precipitation and evapotranspiration are highly correlated (Zhang et al., 2001) and water is a limiting factor for growth. Most of the water is lost to the atmosphere by transpiration, and only a small amount contributes to runoff and groundwater recharge (Badeck et al., 2004). Based on this environmental condition, any land-use change that increases the forested area will increase evapotranspiration and decrease groundwater recharge. This needs to be considered if subsidy systems are changed in the way outlined in the “partial liberalization” scenario. In the study presented, no cross-compliance is assumed, which implicitly showed the necessity of such measures. Currently, in accordance with the specific conditions in the federal state of Brandenburg, a strictly economically oriented scenario leads to a very high percentage (up to 47.3% of the agricultural land) of abandoned land. If no monetary support is allocated to keep this land managed (cross-compliance is such a support system), the probability of a gradual afforestation as assumed in the “partial liberalization” scenario is very high. As the low amount of rain, which limits agricultural production, is one of the main reasons for the high percentage of abandoned land, this conversion from agriculture to forest can interact with the environmental conditions and lead to a positive feedback mechanism such as we see a decrease in groundwater recharge caused by the interaction of forested areas with low precipitation.

Groundwater recharge is an important environmental service as the groundwater levels in the state are either already decreasing (Landgraf and Krone, 2002; Zebisch et al., 2005) or are at risk to decrease in future (Gerstengarbe et al., 2003; Zebisch et al., 2005). Therefore, it can be concluded that cross-compliance is a necessary measure in such a region where agricultural production is at the limits of environmental capacity.
If we consider future Climate Change effects, the picture becomes even more evident. The predictions for the federal state are a further increase in summer dryness (Gerstengarbe et al., 2003; Zebisch et al., 2005) and, therefore, any decrease in agriculture will enforce the above-mentioned feedback, by increasing the percentage of abandoned land, which will, in turn, increase forest areas that decrease groundwater recharge. In particular, the regional patterns of changing land-use needs to be closely monitored when considering the allocation of cross-compliance funding, as areas which already have high percentages of forest and/or with high groundwater levels could be vulnerable. This indicates a necessity to direct the subsidies within such regions to prevent a further enforcement of the previously outlined feedback. If we take into account that these regions have already low population density with the prospect of a further decline (LDSP, 2005a), cross-compliance could be an important way to provide income for the rural community to maintain the current landscape pattern.

A further important aspect is related to the Kyoto Protocol as it allows the use of forestry related activities to meet the carbon sequestration commitments (Noss, 2001). If we assume that afforestation of abandoned arable land would be counted as a potential carbon sink (Post and Kwon, 2000), then the probability of the scenario assumption of “more forested area” increases. However, as it was demonstrated, the result would be a loss in groundwater recharge that might contradict the sink function by causing groundwater levels to fall which would lead to the exposure of organic soils to decomposition. Therefore, the creation of a balance of the two forest functions is necessary (Jackson et al., 2005).

The second scenario “forest species change” provides us with the second important conclusion. The scenario clearly shows that legal measures introduced by regional forest authorities to support natural tree species composition can also improve an essential public service like groundwater recharge. This service is especially important in relation to the specific environmental conditions of Brandenburg. As outlines earlier it becomes even more important if we look at the probable future climatic development, where groundwater recharge becomes more important as the climatic water balance gets smaller (Gerstengarbe et al., 2003; Zebisch et al., 2005). The effect of the “partial liberalization” scenario could be partly compensated by a change in tree species composition. However, as shown in this thesis, the spatial distribution may contradict some of this compensating effect, as the areas of the greatest change in response to the two scenarios do not necessarily match each other. With regard to the Kyoto protocol, we can also assume that we may derive a benefit from this scenario in storing more carbon as the sequestration is higher in more natural forests because they are less vulnerable to Climate Change (Noss, 2001).

4.3 Uncertainty analysis

4.3.1 Sensitivity and Uncertainty analysis in the Stöbber and Elbe catchment

The sensitivity/uncertainty analysis in the Stöbber and Elbe basin demonstrated that the reproduction of evapotranspiration was one of the main sources of uncertainty. It did so by identifying the calibration factor for the radiation term, *rad,* as one of the most sensitive input factors. The true value of this parameter is unknown and its probability space is very wide due to its high uncertainty. Radiation is, however, the main driver for the calculation of evapotranspiration. Thus, a more certain value for the evapotranspiration calculated in the model would reduce the probable range of the calibration parameter *rad.* The range of the parameter would be reduced by constraining the probability space for evapotranspiration results, because the range of radiation values that would produce this reasonable evapotranspiration becomes smaller, thus reducing the range for the calibration parameter *rad*. In this thesis, forest hydrological properties were implemented and an evaluation of these was carried out, in the consequence the calculation of evapotranspiration for this important land-use class became more certain. This constrained the calibration range of the parameter *rad* and as a result reduced the uncertainty in the model results. As an example, the results of the Nuthe basin study are more certain model outcomes because they achieved an efficiency and water balance comparable to other studies without using the calibration factor *rad*.

4.3.2 Uncertainty analysis of the forest module

The main finding from the forest module uncertainty analysis shows that the contribution of the parameters involved in the forest growth calculation is relatively small when compared to the effect of calibration parameter uncertainties of the original SWIM model in the Elbe Basin case study. The results of the study also indicate that the implemented forest growth approach did not considerably increase the uncertainty of the model by an increase in conceptual uncertainty (see chapter 2.2 for a definition). We can therefore conclude that the implemented approach did increase the quality of the model results, by reducing the probability range of a highly uncertain calibration parameter (*thc*) and, at the same time, allowing the introduction of multi-criteria evaluation options through an improved forest growth description with a low conceptual uncertainty.

4.4 Final conclusion of this thesis

It is a key consideration of this thesis that environmental impact assessment procedures ensure that the environmental effects of a proposed development are fully understood and taken into account. In this thesis the **DPSIR** approach has been successfully implemented to achieve this aim by identifying **D**riving forces for environmental change in form of the two scenarios. The driving forces are translated into **P**ressure on the environment in this case; the change in land-use as a result of legislative decisions. The **S**tate of the environment has been taken into account, by the use of an eco-hydrological model which explicitly simulated the specific environmental conditions of the state such as sandy soils and negative water balance in summer. The **I**mpacts on ecosystem level have been investigated by analysing the land-use change effects on the components of the water balance. Based on the model results, it has been possible to discuss potential **R**esponses of society by maintaining the current forest area and continuing with the transition to a more natural forest species composition.

To summarize, the implemented forest module proved to be applicable for an assessment of this kind, not only reproducing the specific effect of forested surfaces in the model, but also by reducing the uncertainty in the model results. The analysis shows the general interaction of policy induced land-use change with other environmental services such as that of the landscape water balance. This provides a clear indication of the need for Environmental Assessment procedures to evaluate the full spectrum of impacts of decisions that influence these aspects of land management. This evaluation should include scrutiny of interactions of decision making made at different levels of administration. In order to further develop the Strategic Environmental Assessment Directive (2001/42/EC) the results of this thesis suggest that integrated spatial explicit modelling is an appropriate tool to understand the complex landscape scale pattern of interaction. It may be concluded that it is essential to focus on “win win” strategies (Lal et al., 1998) as demonstrated in the “forest species change” scenario. In this scenario a change from evergreen to deciduous species combined an increase in groundwater recharge with a potential increase in carbon storage.

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Tables and Figures

Tables:

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