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Original Articles

# Modelling long-term water yield effects of forest management in a Norway spruce forest

## Modélisation des effets de la gestion forestière sur le rendement en eau à long terme d'une forêt d'épicéa de Norvège

Xuan Yu, Anna Lamačová, Christopher Duffy , Pavel Krám, Jakub Hruška, Tim White & ... show all

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scenarios of the hydrological consequences of changing land cover. Stand-age-adjusted LAI (leaf area index) curves were generated from an empirical relationship to represent changes in seasonal tree growth. By consideration of age-adjusted LAI, the spatially-distributed model was able to successfully simulate the integrated hydrological response from snowmelt, recharge, evapotranspiration, groundwater levels, soil moisture and streamflow, as well as spatial patterns of each state and flux. Simulation scenarios of forest management (historical management, unmanaged, clear cutting to cropland) were compared. One of the critical findings of the study indicates that selective (patch) forest cutting results in a modest increase in runoff (water yield) as compared to the simulated unmanaged (no cutting) scenario over a 29-year period at Lysina, suggesting the model is sensitive to selective cutting practices. A simulation scenario of cropland or complete forest cutting leads to extreme increases in annual water yield and peak flow. The model sensitivity to forest management practices examined here suggests the utility of models and scenario development to future management strategies for assessing sustainable water resources and ecosystem services.

Editor D. Koutsoyiannis

## Résumé

La gestion intensive des forêts a induit l'un des principaux changements d'occupation des sols forestiers, entraînant des impacts significatifs sur les processus hydrologiques et les services écosystémiques. Dans ce cadre, un modèle hydrologique distribué a été développé et validé à long terme pour évaluer les impacts de différents scénarios de gestion forestière sur les niveaux de précipitation, les niveaux de sol, les flux de parcelles et les changements de débit. Les scénarios de gestion forestière examinés incluent la coupe sélective (patch), la coupe à blanc et la conversion en terres agricoles. Les résultats indiquent que la coupe sélective entraîne une augmentation modeste du ruissellement (rendement en eau) par rapport au scénario simulé non géré (pas de coupe) sur une période de 29 ans à Lysina, suggérant que le modèle est sensible aux pratiques de coupe sélective. Un scénario de terres agricoles ou de coupe à blanc entraîne des augmentations extrêmes du rendement annuel en eau et du débit de pointe. La sensibilité du modèle aux pratiques de gestion forestière examinées ici suggère l'utilité des modèles et du développement de scénarios pour évaluer les stratégies de gestion futures visant à assurer des ressources en eau durables et des services écosystémiques.



chaque état et flux. Les scénarios de simulation de gestion forestière (gestion historique, absence de gestion, coupe à blanc) ont été comparés. L'une des conclusions essentielles de l'étude suggère que la coupe sélective (par lot) de la forêt montre une augmentation légère du ruissellement (rendement en eau) par rapport au scénario simulé d'absence de gestion (pas de coupe) sur une période de 29 ans à Lysina, indiquant que le modèle est sensible aux pratiques de coupe sélective. Un scénario de simulation de terres arables ou de coupe forestière complète conduit à des augmentations énormes du rendement annuel en eau et du débit de pointe. La sensibilité du modèle aux pratiques de gestion forestière examinées ici souligne l'utilité de développer des modèles et des scénarios pour évaluer des ressources en eau et des services écosystémiques durables dans le cadre de futures stratégies de gestion.

Q Key words: [Lysina Critical Zone Observatory](#) [PIHM](#) [Norway spruce](#) [forest management](#)

Q Mots clefs: [Observatoire de la zone critique de Lysina](#) [PIHM](#) [épicéa de Norvège](#) [gestion de forêt](#)

## 1 INTRODUCTION

Catchment hydrological behaviour has important linkages and feedbacks that influence forest growth and health, although spatially-distributed quantitative hydrological assessments are challenging. This study uses the PIHM model to assess the impact of forest management on hydrology, climate, and water quality in a catchment in the Lysina Critical Zone Observatory. The model is used to simulate the impact of different forest management scenarios on hydrology, climate, and water quality. The results show that forest management has a significant impact on hydrology, climate, and water quality. The model is used to simulate the impact of different forest management scenarios on hydrology, climate, and water quality. The results show that forest management has a significant impact on hydrology, climate, and water quality. The model is used to simulate the impact of different forest management scenarios on hydrology, climate, and water quality. The results show that forest management has a significant impact on hydrology, climate, and water quality.



[1996](#)). The role of forest management in watershed hydrology has been the subject of several discussion papers and review articles (e.g. Bosch and Hewlett [1982](#), Stednick [1996](#), Andréassian [2004](#), Brown et al. [2005](#)). The general conclusions are that paired catchment experiments can qualitatively explain annual water yield differences; however, spatial details of hydrological forest management practices on hydrological flow patterns are difficult to assess quantitatively with this approach. Spatially-distributed hydrologic models provide an independent means of evaluating the impact of managed land-cover changes on water resources within a catchment. Hydrologic modelling studies explicitly driven by land-cover change scenarios offer a quantitative approach to assessing the impact of forest management on hydrological processes (Eisenbies et al. [2007](#), Thanapakpawin et al. [2007](#), Wijesekara et al. [2012](#)).

Soil-vegetation-atmosphere transfer schemes in general circulation models (GCMs) are now widely used to assess large-scale hydrological impacts of forest management. The strategy provides an integrated response of vegetation water use for a GCM grid cell using leaf surface area to scale land surface energy and water budgets, including the functions of soil moisture (Arora [2002](#)). Wattenbach et al. ([2007](#)) simulated the annual sub-grid water balance and seasonal pattern of impacts using the percentage of afforestation. Wijesekara et al. ([2012](#)) linked a land-use change model to a physically-based distributed model and predicted hydrological responses to the percentage of each land-use type. Studies have found that considerable variation in the hydrological regime of

However, this is not a sufficient hydrology component, without the soil hydrology component, and thus the current hydrology component, and thus the current hydrology component, is often insufficient to assess the impact of forest management on hydrology (Wijesekara et al. [2012](#)).

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Recently, the European Union initiated a programme of research using Earth's Critical Zone Observatories (CZOs) (Banwart et al. [2011](#)). The Lysina CZO is an experimental catchment to study the resilience of soil functions to acid deposition and other impacts in a heavily managed forest catchment used for timber production. Under the outline of the research framework of European CZOs (Banwart et al. [2012](#)), an effort was undertaken to compile and digitize extensive historical forest management data of stand age, soil and hydrogeological characterization within a mathematical modelling framework for the Lysina catchment. The aim of this study was to test how well a physics-based, meso-scale distributed model, PIHM (Penn State Integrated Hydrologic Model; Qu and Duffy [2007](#), Kumar [2009](#)), can simulate the intensive management practices and impacts on hydrological processes at the Lysina catchment using a simple representation of the historical record of forest growth based on biomass and leaf area index (LAI). Here PIHM is referred to as a meso-scale model with mesh sizes intermediate to plot- or micro-scale models (Dooge [1988](#)) and regional-scale climate or ecohydrology models. Using PIHM allowed the spatial structure of forest management units within the watershed to have independent growth (LAI) histories. The average mesh size in this case is around 20 metres. Calibration and validation of the model for the entire watershed was constrained by observed streamflow at the outlet, groundwater levels at several monitoring sites and the historical LAI/growth history information for each management unit. Climate/weather forcing was available at two nearby s

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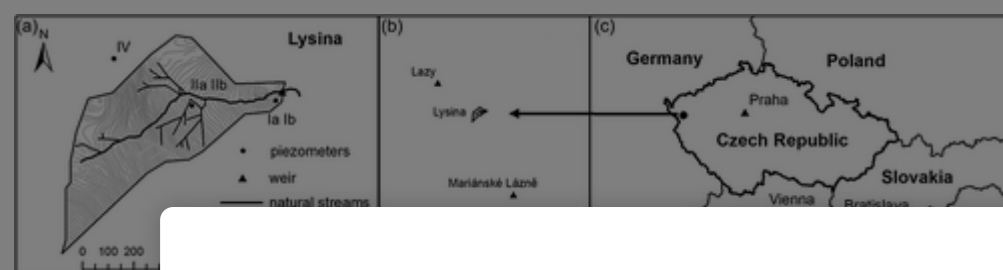
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mountainous region with an area of 610 km<sup>2</sup>. Lysina catchment has been continuously monitored since 1989, with the primary focus on the effects of anthropogenic atmospheric deposition on stream water chemistry (Krám et al. [1995](#), [1997](#), Hruška et al. [2009](#)). The study site belongs to the Czech Republic national network GEOMON (GEOchemical MONitoring) of small forest catchments (Oulehle et al. [2008](#)), and the Lysina catchment is one of two Czech sites within the international network of forest sites comprising the International Cooperative Program – Integrated Monitoring (Holmberg et al. [2013](#)), organized under the Economic Commission for Europe of the United Nations. The Lysina catchment also belongs to the Long-Term Ecosystem Research (LTER) network and recently became one of the European CZOs within the SoilTrEC (Soil Transformations in European Catchments) project (Banwart et al. [2011](#), [2012](#)).

Fig. 1 (a) Lysina catchment sites I and II each have two piezometers. Topographic contours are shown at 1-m intervals. (b) Two Czech Hydrometeorological Institute (CHMI) weather stations were available at Lazy and Mariánské Lázně (ML). (c) Location of the Lysina catchment.

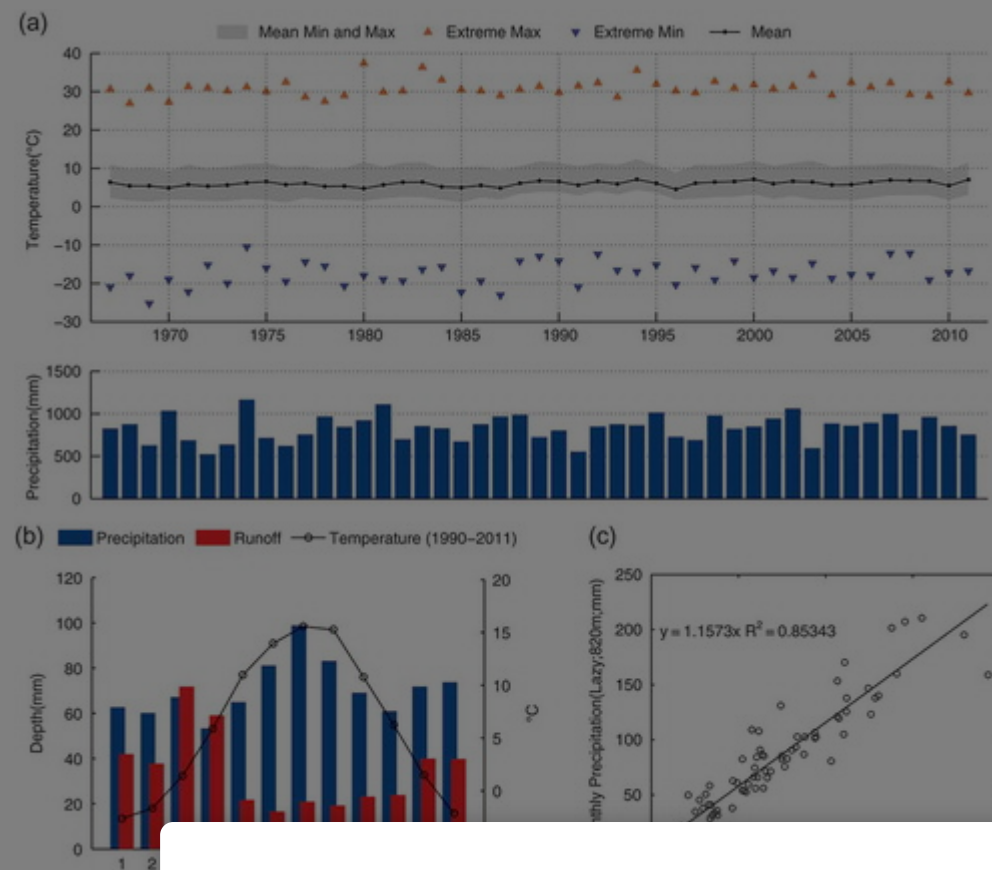


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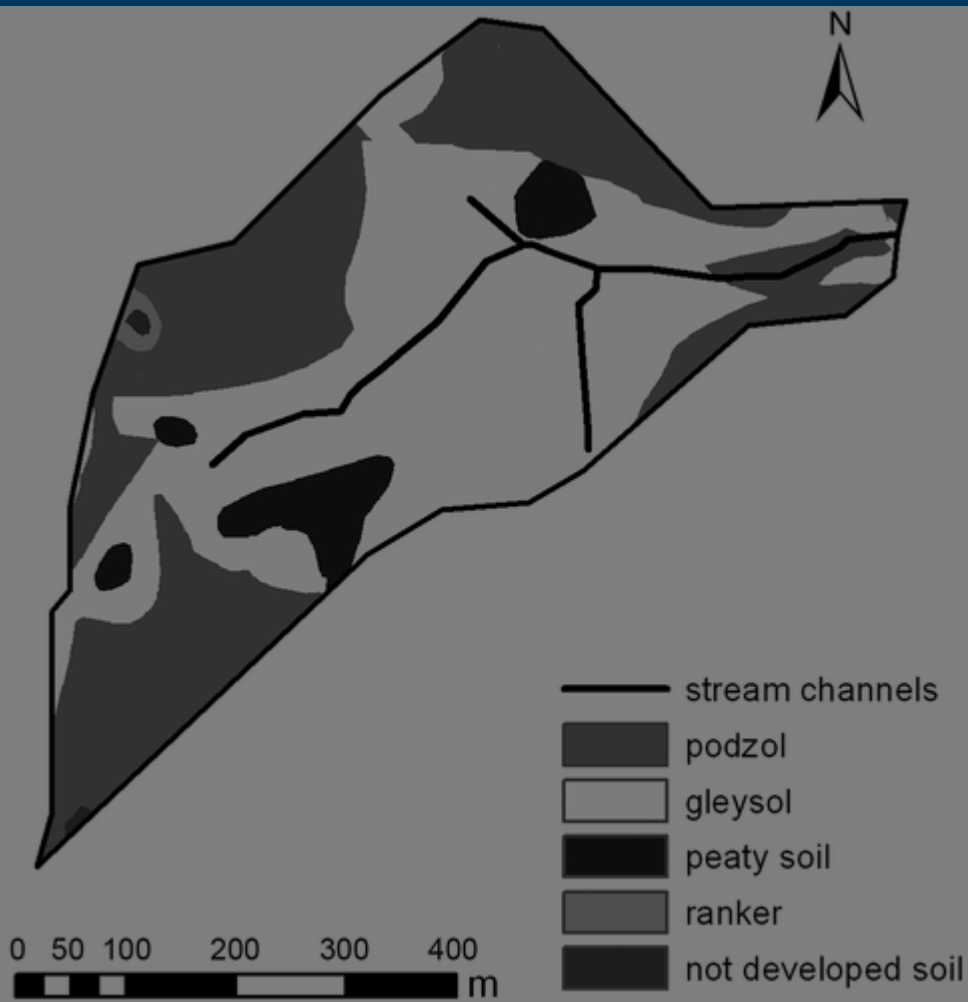
Fig. 2 (a) Annual temperature and precipitation at the base climate station (ML; elevation 691 m). (b) Monthly mean temperature, precipitation and runoff during the last two decades (1990–2011) at climate station ML. (c) Scatterplot of monthly precipitation at raingauges ML and Lazy, from 2006 to 2011.



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Fig. 3 Soil... podzol... develop... (%) and... (%) and not





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## 2.2 Field measurement and data collection

Precipitation was measured at the Lysina Institute (691 m a.s.l.) where average precipitation was 1060 mm for the period 1967–2017. Average annual precipitation at the Lysina Institute (691 m a.s.l.) was 1060 mm for the period 1967–2017. Average annual precipitation at the Lysina Institute (691 m a.s.l.) was 1060 mm for the period 1967–2017.



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The streamflow was calculated using a standard rating curve method developed for the weir. The 20-min discharge values were aggregated to hourly and daily runoff in cubic metres.

Groundwater patterns were monitored in five piezometers by manual measurements at weekly intervals from September 2011. The piezometers are located at three different places, two in pairs and one single piezometer (Fig. 1). The depths of piezometers Ia and Ib are 3.58 and 3.92 m below ground surface (b.g.s.); those of IIa and IIb are 1.2 and 2.59 m b.g.s.; and that of IV is 2.89 m b.g.s; the latter site is just outside the watershed. Observation well lithology was used to estimate the lower bound of active groundwater flow.

Daily snow depth observations were collected from ML. The snow water equivalent (SWE) was estimated using the equation from Jonas et al. (2009). The SWE was used for the melt factor calibration:

$$(1)$$

where SWE is in  $\text{kg/m}^2$ , and HS is snow depth in m.

## 2.3 Geospatial watershed information

Topography was obtained from a traditional topographic survey done in 1989 with 1 m contours and a final map scale of 1:1000. These data were digitized and converted to a

1-m resolution. The topographic data were compared with recent digital elevation data derived from airborne laser scanning (ALS) data. The stream network was derived from the ALS data using the stream power index (SPI) method (Tarboton et al. 1992). The stream network was derived from the ALS data using the stream power index (SPI) method (Tarboton et al. 1992).

The high-resolution topographic data were used to define the watershed boundary as

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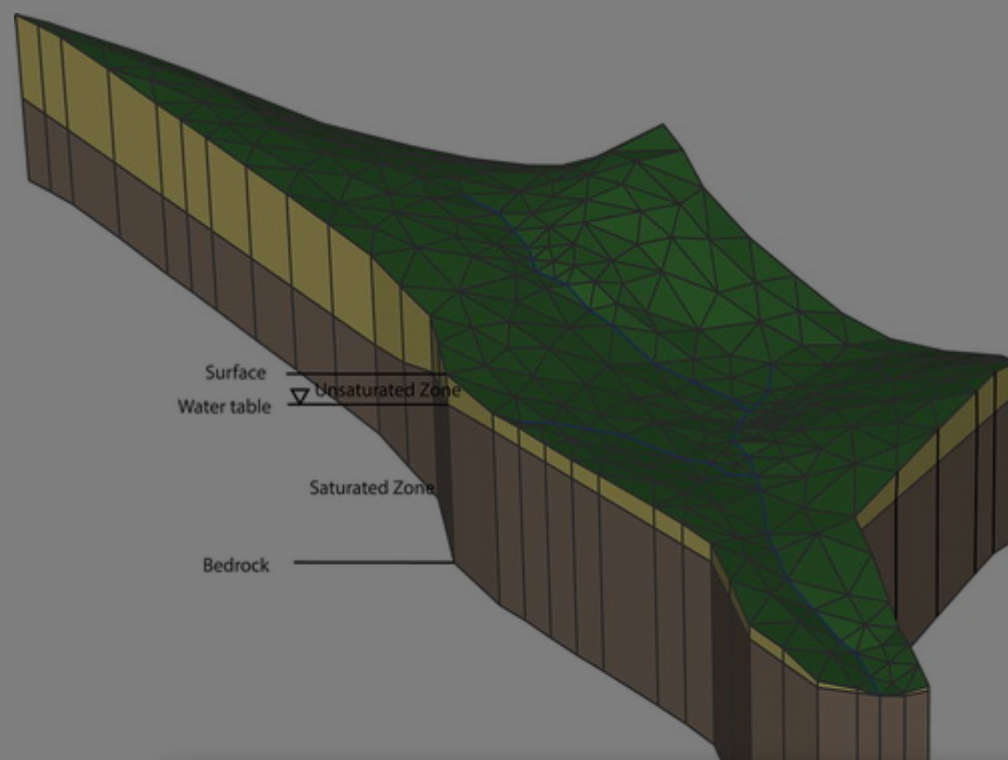
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estimated from the borehole data to be approx. 4 m below the land surface and this was used in the model.

Fig. 4 Mesh and boundary of the Lysina catchment model. The elevation of the lower limit of impermeable bedrock was set to a uniform 4 m below the surface. The groundwater flow in the catchment is within the soil (0–1.5 m) and weathered bedrock (1.5–4 m). Solid (blue) lines represent the stream channels, and (green) triangles represent the catchment domain.



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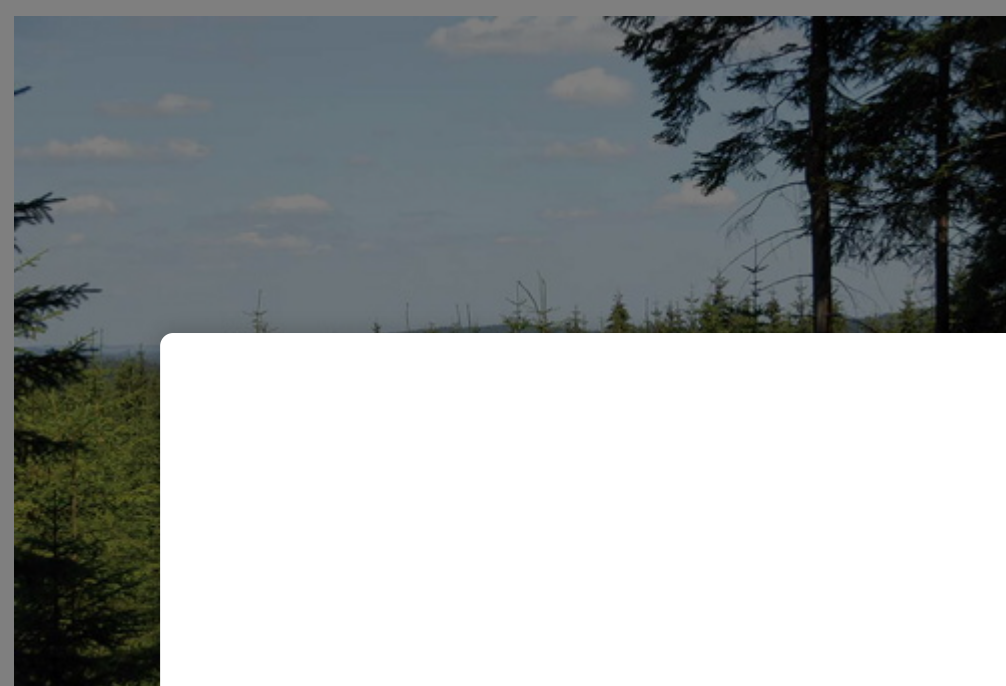
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practices. At the so-called rotation age of 100–130 years, even-aged stands were harvested, with areas of one or more hectares clear-cut. Silvicultural management at Lysina in the 20th century was based entirely upon cutting around 5 ha of even-aged spruce stands until the 1970s, and relatively small units (up to 2 ha) to the present. This type of block cutting produces an uneven age distribution of the forest and limits adverse effects of large-scale single-age timber management such as soil erosion and lost ecosystem services (Swanson and Dyrness [1975](#)). Soon after harvesting, spruce seedlings were planted. Trees are almost always cut after the rotation age following the Czech Forest Law (approx. 100 years for Norway spruce), although harvesting may be accelerated due to the poor health of trees (Krám et al. [1999](#)) due to wind damage, snow damage, bark beetle attack, acid rain or ozone injuries. [Figure 5](#) is a photograph of typical multi-age forest in the Slavkov Forest.

Fig. 5 A photograph taken in the Lysina catchment shows a boundary between the two even-aged Norway spruce stands.



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catchment, 20% was covered by 20–40-year-old spruce forest, and the rest of the catchment was covered by young spruce (0–20 years old). In 1984 approximately 30% of the 100-year-old trees were logged, and the areas replanted with spruce. In 1994, 90% of the trees older than 100 years were harvested, and the areas replanted with young spruce plantation. Forest stands at Lysina ([Table 1](#)) represented typical central European mountainous managed forest. The rooting zone of spruce trees is extremely shallow. The majority of the roots are situated in the organic horizon, immediately above the nutrient-poor eluvial horizon.

Table 1 Stand characteristics for Norway spruce at Lysina catchment (unpublished data from the Forests of the Czech Republic, State Co. and Černý et al. [1996](#) ).



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Table 2 Model evaluation criteria for the calibration and validation period.

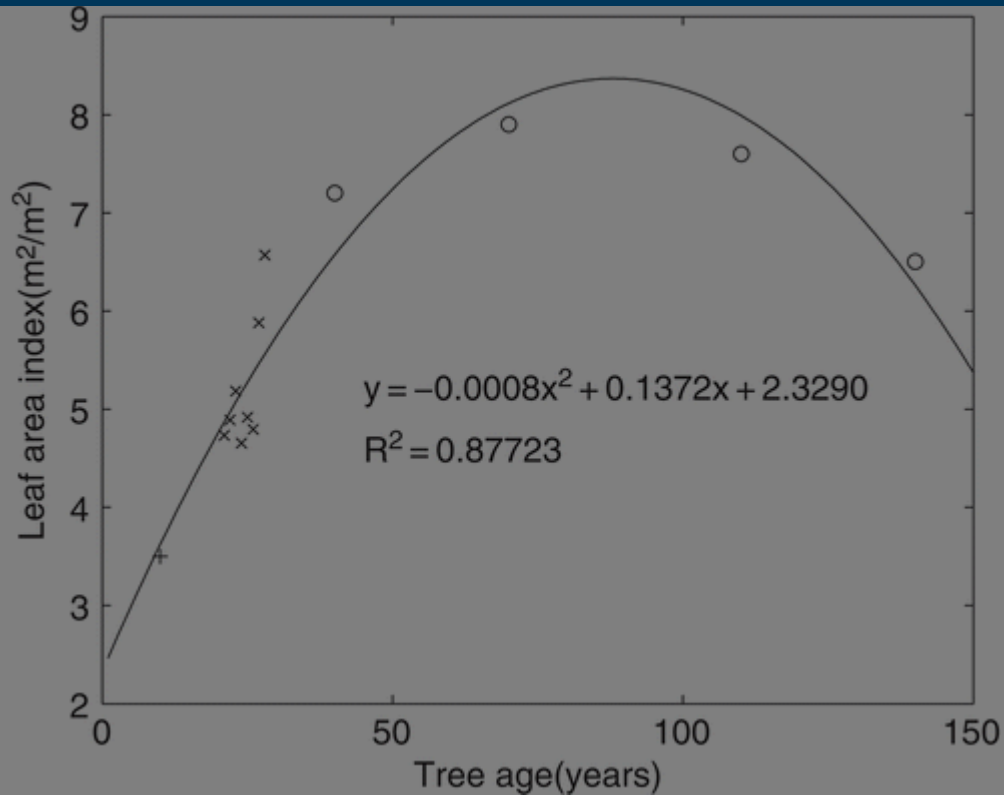


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According to the forest management history (Pokorný et al. 2008) and tree age maps of 1984 and 2004 (Czech forest administration), selective cutting management for the watershed was divided into 10 patches representing stands with unique plantation histories (Fig. 7). It is worth mentioning that Czech forest management is usually very continuous, and cutting of young trees rarely happens. Here, the deduced selective cutting h... not be precise enough... curves n... ment patches and their... od 1984-2012.

Fig. 7 (a) ... 0 patches: the bar... e watershed; (c), ... 84, 1994, 2004, re



Calibration of parameters is based on the partition calibration strategy and evolutionary algorithm (Yu et al. [2013](#)). The initial soil and subsurface hydrologic parameters were estimated based on soil textural properties (Wösten et al. [2001](#)). The hydrologic parameters were then optimized through an evolutionary algorithm (Yu et al. [2013](#)) using streamflow observation data from several precipitation events during the spring of 2006. Snow accumulation and melting processes were determined by the temperature index model, where melting rate is a product of melt factor (MF, seasonal variable) and positive air temperature (Kumar [2009](#)). The melt factor is adjusted to match the simulated SWE to the SWE estimated from snow depth observations. Energy parameter estimation (Yu et al. [2013](#)) is based on seasonal LAI, air temperature, relative humidity and wind data for the year 2006. The spatial groundwater table was matched by locally nudging soil hydraulic parameters and soil porosity to match the field data.

### 3 RESULTS AND DISCUSSION

As an integrated model, PIHM simulated results were compared with multiple observed variables, including SWE, streamflow and groundwater table depth. We used the relative error (E), Pearson product-moment correlation coefficient (R), and Nash-Sutcliffe performance index (NSE) to evaluate the model performance.

where  $t$  is the time,  $o$  is the observed value, and  $s$  is the simulated value.

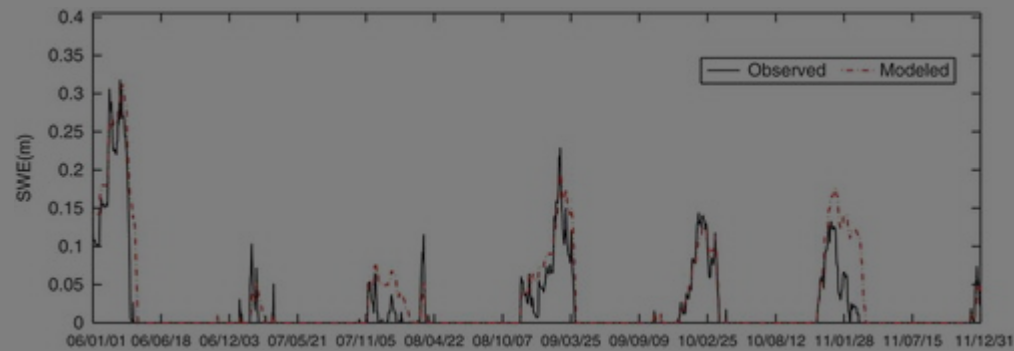
#### 3.1 Streamflow

The default parameters were used for the simulation. The maximum value of the MF results on 21 July 2006 were 0.2 degree-celsius. The results in the model agreed with the observed results.



the spring melt years of 2008 and 2011 when the fit is poorer but still satisfactory for scenario development.

Fig. 8 Comparison between observed and modelled snow water equivalent (SWE) for the period 2006–2011. Observed SWE was estimated from snow depth.



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### 3.2 Streamflow

Agreement between modelled and measured daily streamflow indicated satisfactory performance of PIHM for the seasonal water yields of the Lysina catchment over the 2006 calibration period (Fig. 9, Table 2). Comparison of simulated and observed hydrographs shows that the spring snowmelt runoff events were adequately simulated in the model. The summer drought was also well represented in the simulation responding to the overall vegetation water use.

Fig. 9 Comparison between observed and modelled daily streamflow for the 2006 calibration period (2006-01-01 to 2006-06-15).



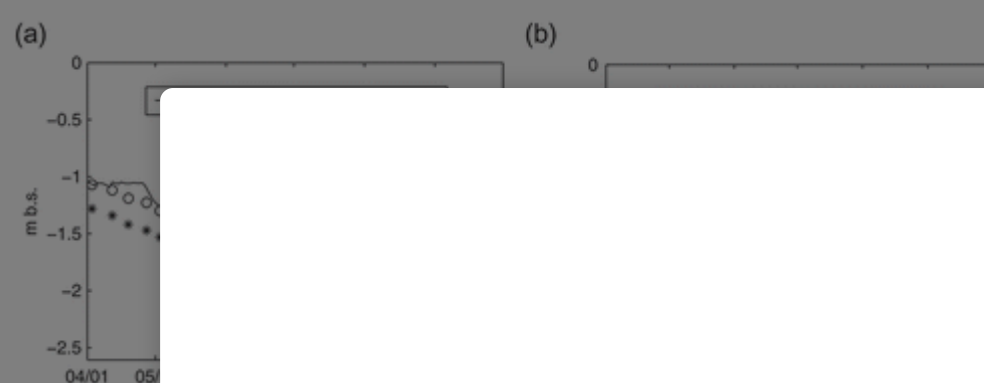
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### 3.3 Gro



Despite the short period of groundwater observations, the results showed significant differences in groundwater level fluctuations between the sites. Piezometers Ia and Ib, located in the same grid cell, show a similar groundwater table pattern with the lowest elevation in autumn (September and October) and high water levels after snowmelt (April). The water level range for the period was 0.8 m and the average depth to the water table was 1.5 m b.g.s. (Fig. 10). The groundwater levels in IIa and IIb were also located in a single grid cell. The records were averaged since they show the same seasonal trend but with an offset of approx. 1 m of depth to groundwater. The averaged data and model results (Fig. 10) had a below ground depth of around 1–2 m. The shallowest depth to groundwater in the model occurred for gleysols (higher clay content). The model-simulated groundwater table elevations were consistent with observations (Table 2).

Fig. 10 Modelled and observed groundwater table depth below surface in 2012: (a) Site Ia and Ib piezometers were located in the same mesh triangle. (b) Site IIa and IIb piezometers were also located in the same grid cell and show the same trend, but with an elevation difference of  $\sim 1$  m, so the data were averaged and then compared with the model result for the corresponding triangle. The x-axis values are in date format: mm/dd.



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### 3.4

#### 3.4.1 U

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meant to be comparative and as the same inputs are used in each scenario it should not drastically influence the conclusions.

### 3.4.2 Snow accumulation and melting processes

The temperature index model simulated slower melting processes during spring of 2008 and 2011, which led to underestimated runoff in winter of 2007 and 2010, and overestimated runoff in spring of 2008 and 2011. The snow-melt modelling component could be improved by a distributed modelling scheme and by incorporating more variables, such as radiation or vapour pressure (Hock [2003](#)).

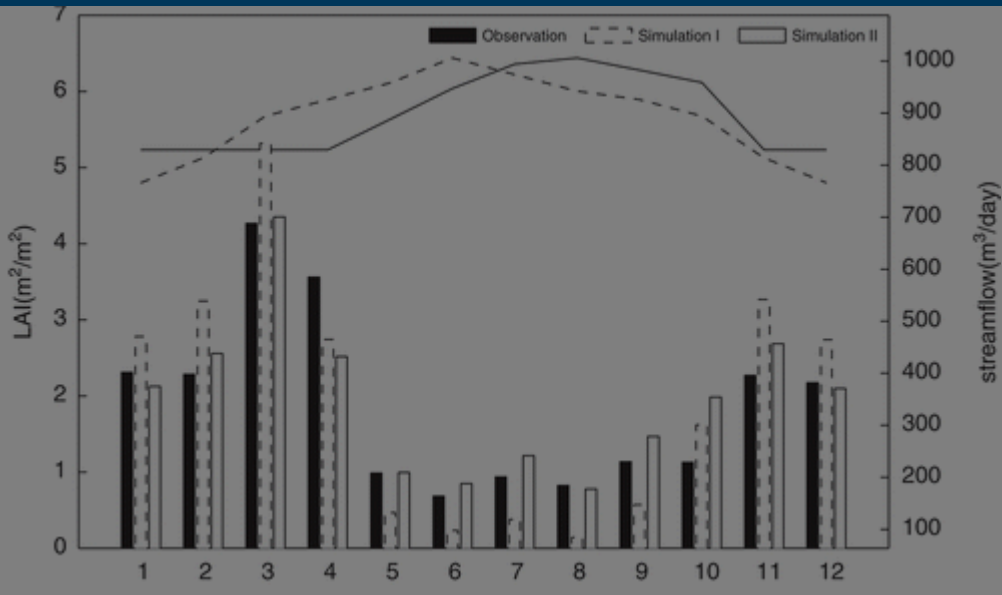
### 3.4.3 Vegetation dynamics

The lifetime growth vegetation dynamics were related to age using the published relationship between age and ET (Murakami et al. [2000](#), Kostner et al. [2002](#)). Here, a simple polynomial was fitted to the LAI-age data to represent forest growth in the model. Although the estimated LAI is an approximation, the sensitivity of the model suggested the importance of forest growth (age) on catchment water budgets. Another model uncertainty is the length of growing season for Norway spruce, which Pokorný et al. ([2008](#)) estimate ranges from 173 to 226 days. The phenology of Norway spruce was assumed to be the same every year, with LAI growing season beginning in April, and senescence in October. LAI reaches maximum values in August (Pokorný et al. [2008](#)).

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### 3.5 Long-term simulations: 1984–2012

Based on the performance of PIHM through the validation step, the impact of land-use changes under the actual forest management was simulated. In order to assess the hydrological impacts of forest management, three separate scenarios were developed: (1) actual historical forest management practices (referred to as ‘managed’); (2) no forest cutting for the period 1984–2012 (unmanaged); and (3) conversion of forest to cropland for 1984–2012 (cropland). All scenarios are initialized from the forest data in the year 1984.

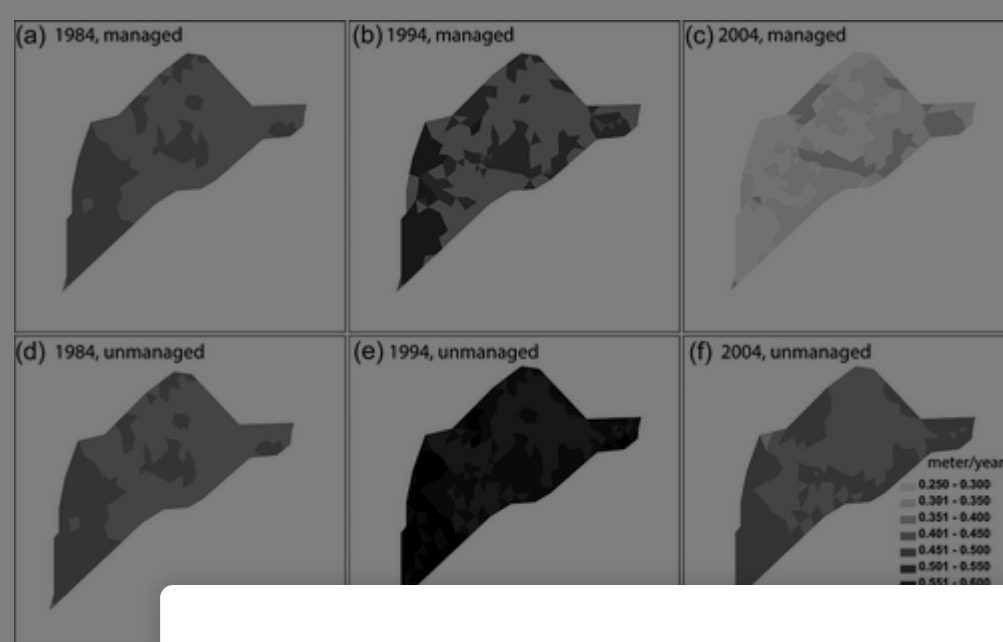
To simulate the observed annual evapotranspiration as a function of changing climate budget. The representation means years in

derived from maximum percent to LAI of available water content growth curve for all

Figure 1. Comparison of forest management practices from 1984 and 2004. Comparison of forest management practices, with managed

impact on ET for the managed cutting case are clearly different or the model is sensitive to the spatial pattern of cutting (non-cutting). Often hydrological models are criticized for oversimplifying vegetation/evapotranspiration processes, which typically prescribe seasonal LAI to be constant from year to year (Arora [2002](#)). Thus longer time scales of change in the water use as a function of tree age are important in the hydrologic model. Clearly, these simulations demonstrate that long-term tree growth does affect the spatial patterns of tree water use.

Fig. 12 Simulation scenarios for managed forest cutting, and unmanaged or no-cutting, showing their impact on the mean annual spatial pattern of evapotranspiration. Note that the unmanaged case has no forest cutting after 1984.



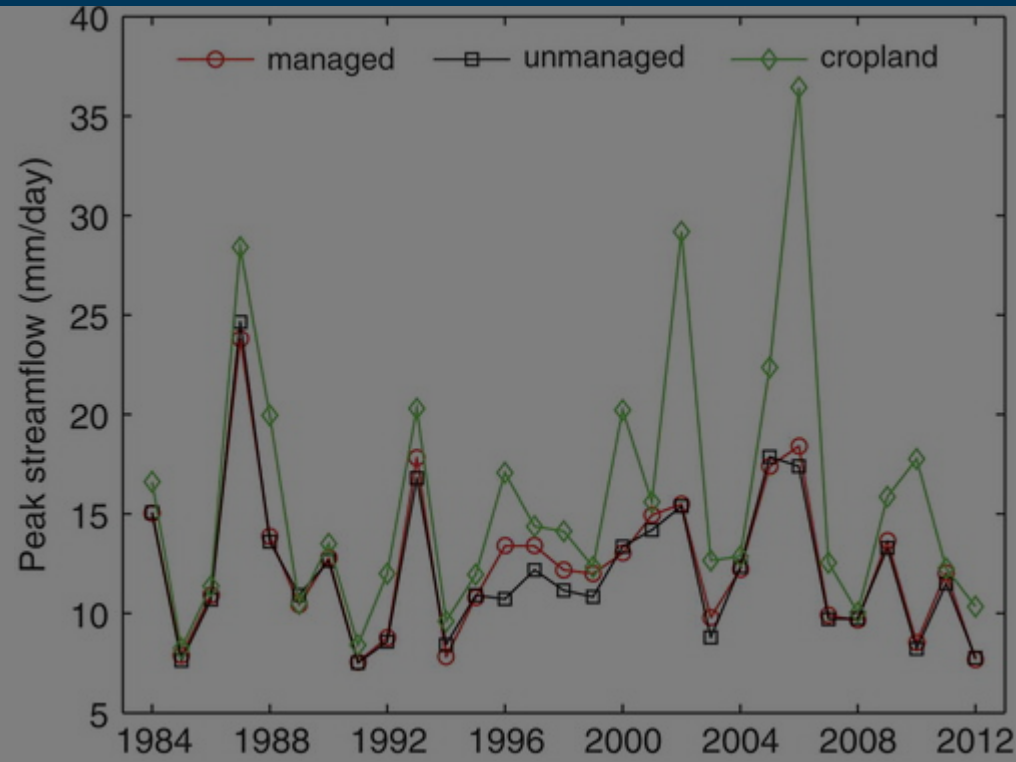
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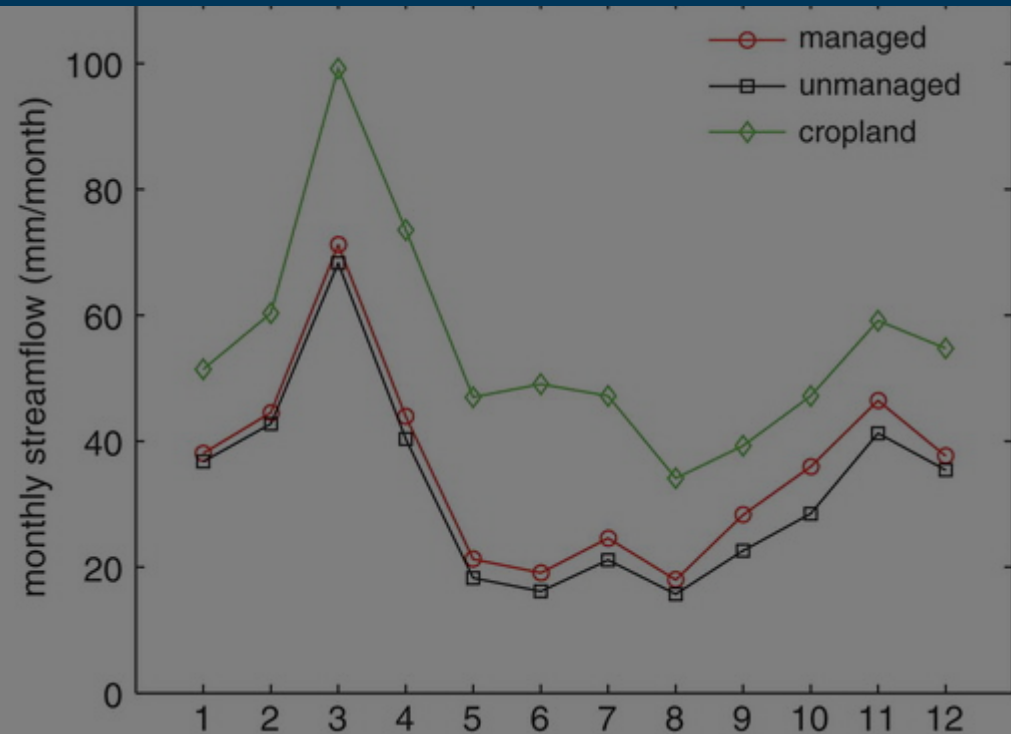


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Figure 14 illustrates the monthly mean runoff (January–December) for all three scenarios, for the period 1984–2012. The managed and unmanaged scenarios are again similar, with the autumn season showing a larger increase in streamflow compared to other seasons (see Appendix Tables A1–A3 for details). Under unmanaged conditions, the greater percentage of older trees consume more water than for the managed case with younger trees. The impact of selective cutting on the water balance is to increase groundwater and autumn streamflow, and to reduce spring and summer streamflow and drought risk. The impact of selective cutting on the water balance is to increase groundwater and autumn streamflow, and to reduce spring and summer streamflow and drought risk. The impact of selective cutting on the water balance is to increase groundwater and autumn streamflow, and to reduce spring and summer streamflow and drought risk.

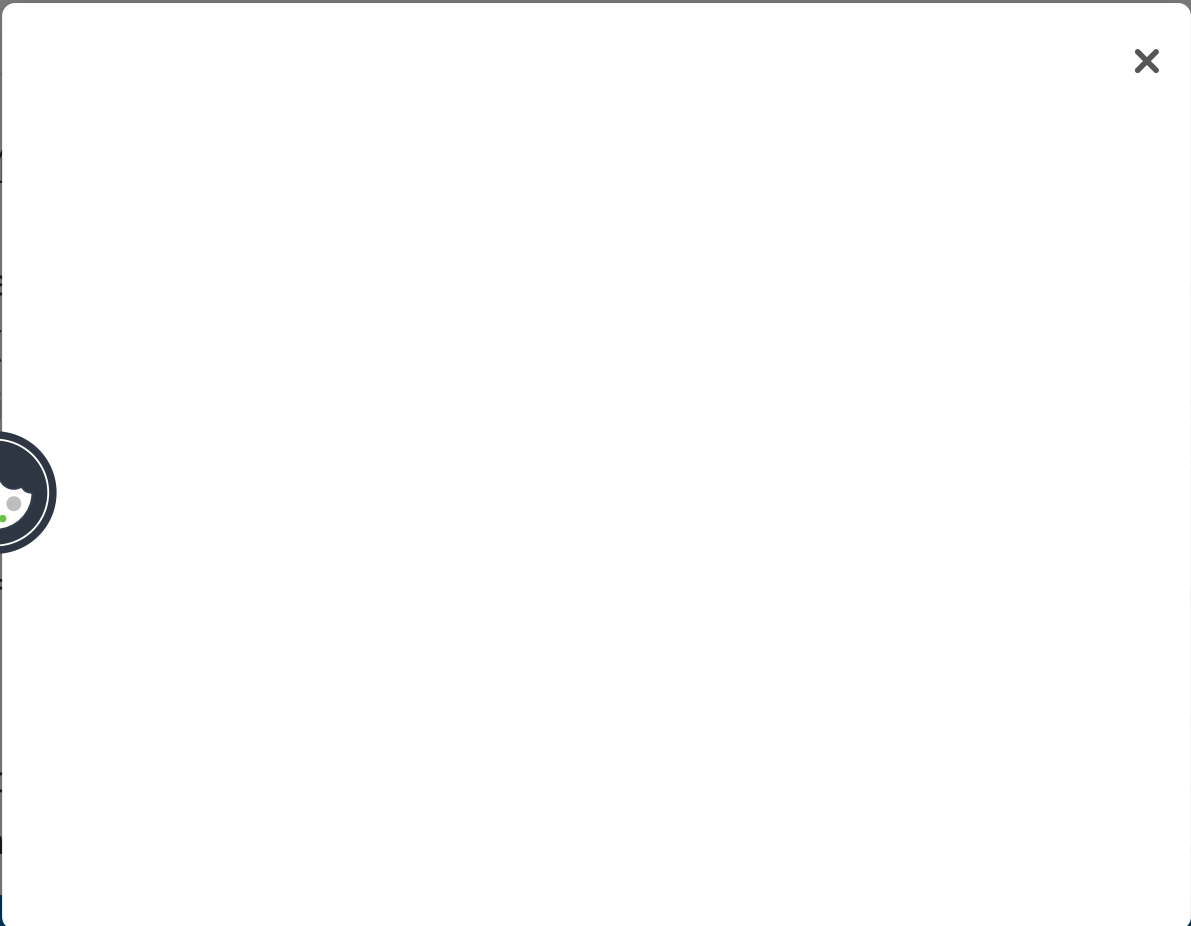
Fig. 14 Simulated monthly mean streamflow (mm/day) for the managed, unmanaged, and cropland scenarios from 1984 to 2012. The managed and unmanaged scenarios are again similar, with the autumn season showing a larger increase in streamflow compared to other seasons (see Appendix Tables A1–A3 for details). Under unmanaged conditions, the greater percentage of older trees consume more water than for the managed case with younger trees. The impact of selective cutting on the water balance is to increase groundwater and autumn streamflow, and to reduce spring and summer streamflow and drought risk.





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The simulated water budget scenarios demonstrate dramatic differences. For the management case, the net annual runoff is 441.2 mm, while the cropland scenario predicted annual runoff at 671.1 mm. The scenario of unmanaged growth predicted 399.0 mm annual runoff, which shows that the management practices in 1984 and 1994 have increased water yield by 9.5%. Detailed 29-year simulated annual water budgets for each scenario are listed in Tables A1-A3.



#### 4 SUMMARY

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scenario, peak flows are amplified in the latter case. There are definitely other factors that affect hydrological impacts of forest management, such as soil disturbance or compaction, the effect of local atmospheric conditions and plant physiological acclimatization (Van Dijk and Keenan [2007](#)), which are not examined here. Nonetheless, the physics-based hydrologic modelling in this study provides useful insights to the sensitivity of watershed hydrological response to tree cutting history and forest growth.

The study results have demonstrated the utility of physics-based distributed hydrologic modelling, such as PIHM, as a management tool for expanding our understanding of forest hydrological processes and spatially-explicit logging and replanting practice impacts over long periods of time. Compared with previous hydrological studies (Buzek et al. [1995](#), Krám et al. [1999](#), Benčoková et al. [2011](#)), the improvements include complete physics-based representation with observed data, localized age-related vegetation dynamics, multi-process integrated modelling of snow accumulation and melting processes, and distributed unsaturated-saturated dynamics. The model's performance was validated by multi-variables observed at different locations. Simulation of snow accumulation and melt processes was found to be sufficient to capture the spring runoff. The spatial groundwater-table dynamics were obtained using hydrological properties of spatial soil classes. The long-term dynamics of the forest were represented through observed age-LAI relationships. The integrated modelling approach can be useful in assessing the hydrological influence of the spatial

configurability of hydrological models to assess the impact of forest management on water resources and ecosystem services.

One series of future research is to integrate the framework with other datasets (e.g., remote sensing data) to assess the role that forest management practices play in droughts and flooding events. Future research should focus on the spatial variability of hydrological processes and the impact of forest management practices on the hydrological cycle.



Lysina represents a catchment influenced by intensive forest management, with research priorities that include nutrient leaching, water acidity, metal toxicity and atmospheric deposition (Banwart et al. [2011](#)). This study implemented a distributed integrated hydrologic model, PIHM, with explicit representations of forest management practices. The model combined historical records of land use, existing data and recent field measurements to provide a long-term resolution between available data and mathematical model results. It is interesting to note that, as the forest management-impacted flow pattern changed, the quantity and timing of water yield were observed to influence changes in stream water quality (Hruška and Krám [2003](#)) and soil solution chemistry (Navrátil et al. [2007](#)). This suggests that the model simulation could be applied in future studies on drainage water quality and solute transport. In addition, rapidly changing land use and climate have been found to threaten water resources at many places (Banwart et al. [2011](#)). The projected impacts of global climate change have been estimated with significant impacts likely on both runoff and evapotranspiration at Lysina (Benčoková et al. [2011](#)). The increase in annual evapotranspiration based on model projections was estimated to be 15 to 20%, and annual runoff will decrease by 10 to 30%. The high evapotranspiration changes during the growing season would result in extreme September drought. The scenarios presented here provide insight into the competing impacts of forest management on stream water resources. The hydrological impacts of future climate and forest





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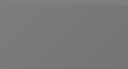
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## APPENDIX

Table A1 Water budget of the managed scenario at Lysina.



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