Regional assessment of forest effects on watershed hydrology: Slovakia as a case study

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ABSTRACT: Recently, the importance of forest effect on watershed hydrology has been increasingly recognized due to an elevated threat of floods and expected alterations of water regime in watersheds induced by climate change. We assessed the trade-off between natural conditions of 61 basic watersheds in Slovakia and expected water-regulatory capacity of forest in these watersheds. A multi-criteria decision-making scheme was proposed to calculate a coefficient for each watershed indicating the need to regulate its water regime as given by natural conditions, and another coefficient indicating the magnitude of forest water-regulatory capacity given by forest structure and distribution. Factors indicating the forest water-regulatory capacity were extent of forest cover, forest fragmentation and distribution in watersheds relative to the spring area, forest stand density and vertical structure, and tree species composition. The results indicate that the present structure and distribution of forests in Slovakia has potential to moderately regulate the water regime at the scale of basic watersheds. We identified critical watersheds where natural conditions imply the unfavourable water regime and/or the forest water-regulatory capacity is weak. Limits of forest effect on watershed hydrology and caveats for interpreting the presented findings are discussed.

Keywords: watershed hydrology; water-regulatory capacity of forest; forest stand structure; forest cover; forest fragmentation

Forests comprise the most important ecosystems regulating water yield and water quality (Tong, Chen 2002; Farley et al. 2005). Their management affects watershed hydrology (Stednick 1996), including the incidence of extreme events such as drought or flooding (e.g. Calder 2004; FAO, CIFOR 2005). Recently, as water availability for both humans and aquatic ecosystems has become a critical issue worldwide, the importance of research on watershed hydrology and interaction between hydrological cycles and ecosystems has been increasingly recognized (Lee 2005; Sun et al. 2001, 2005). Such demands lay additional stress on optimizing the forest and landscape structure (Committee on Hydrologic Impacts of Forest Management 2008) to ensure the optimal provision of all ecosystem services and functions (e.g. in terms of the Millennium Ecosystems Assessment Report 2005), including water provision and regulation.

The effect of forest management on water yield and water quality has long been studied (e.g. Buttle 2011). A comprehensive overview of early studies was published, for example, by Hibbert (1967) and by Boschl and Hewlet (1982). Earlier studies generally focused mainly on the empirical investigation of forest effects on water yield in watersheds rather than on thoroughly understanding

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the hydrological processes. Paired-watershed experiments became a common approach in such empirical research (e.g. Hewlett, 1971). A recent overview of developing debates on water and forest relationships was provided, for example, by Andréassian (2004) or Kostka and Holko (2006) and pointed out the disparity between the public and scientific perception of forest effect on water environment. This disparity was also commented upon by Calder (2004) and Calder et al. (2004). Recently, the forthcoming climate change has posed another challenge for research of climate-hydrology-ecosystem relationships, and various simulation experiments have appeared taking into account coupled changes in land use and climate (e.g. Sun et al. 2005; Hlavčová et al. 2008).

Forest management related changes in the forest tree species composition, such as replacement of deciduous forest with conifer species, as well as modifications of harvesting and silvicultural regimes, can remarkably affect water yield and timing (Swank, Crossley 1988). The infrastructure development, such as building roads or skidding trails, can also affect watershed hydrology (Smerdon et al. 2009) by modifying the water flow path and increasing the overland flow. Forest disturbances, such as forest fires, landslides, windthrows or insect outbreaks also remarkably modify watershed hydrology. To date, however, these effects have not been studied extensively (e.g. Uunila et al. 2006).

At a landscape scale, changes in the spatial distribution of ecosystems can affect watershed hydrology. Hence, the study of forest hydrology needed to adopt a landscape perspective, which means finding methods for scaling up stand-specific knowledge to the watershed level. Such relationships have rarely been studied, however, and empirical studies or simulation experiments (e.g. Band et al. 2001) are missing. From this viewpoint, riparian forests are of great importance as such forests protect streams from the input of sediments, nutrients and herbicides while providing habitats and supporting biodiversity (Risser 1995; Najman, Decamps 1997; Sweeney et al. 2004).

The effect of deforestation, or a change in landuse, in general, on watershed hydrology has been studied extensively (Fohrer et al. 2001, 2005; Bíba et al. 2009, Holko et al. 2009), mainly because of the worldwide occurrence of large-scale deforestations induced by humans or natural hazards. Deforestation generally causes an increase in streamflow and water yield immediately after an event. Such increase, however, is likely to occur during high precipitation events and is not likely to occur during dry periods, when water demand is high (Committee on Hydrologic Impacts of Forest Management 2008). In addition, deforestation is expected to increase the probability of flood incidence, although this concept has been questioned by many authors (e.g. Robinson et al. 1991; Beschta et al. 2000); promotes soil erosion; and compromises water quality (e.g. Pimentel, Kounang 1998). Specific information as to the effect of afforestation on water yield has been provided by Farley et al. 2005.

This study proposes a methodology for the assessment of a relationship between forest effect on the water regime in watersheds and natural conditions of those watersheds. Such a methodology can be used for evaluating forest effects on water supply and regulation in terms of ecosystem services and functions (Millennium Ecosystems Assessment 2005), as well as for identifying critical watersheds where actions should be taken to optimize forest and landscape structures. The methodology is demonstrated on a country-wide scale, and such assessment is performed for 61 so-called basic watersheds of Slovak Republic. The paper also describes how forestry and other environmental databases can be used for such assessment. In particular, the paper focuses on:

– proposal of a methodology for assessing the extent up to which present forests affect the water regime of watersheds,
– evaluation of watershed natural conditions relative to their water regimes using publicly available environmental databases, and assessment of forest capacity to regulate the water regime of a watershed,
– identification of critical watersheds where the water regime could be improved by altering forest distribution and stand structure.

MATERIAL AND METHODS

The 61 so-called basic watersheds of Slovak Republic with average size of 810 km^2 comprise the spatial scale upon which this paper focuses (Fig. 1). Data from various environmental databases are used for evaluating natural conditions of watersheds as well as for the description of forest structural and distributional parameters in relation to water regimes of watersheds (Table 1). The following variables require more detailed explanation:

Integrated flood risk map was taken from Solín (2011), who classified small watersheds of Slovakia (up to 150 km^2) by their flood risk on the basis of re-

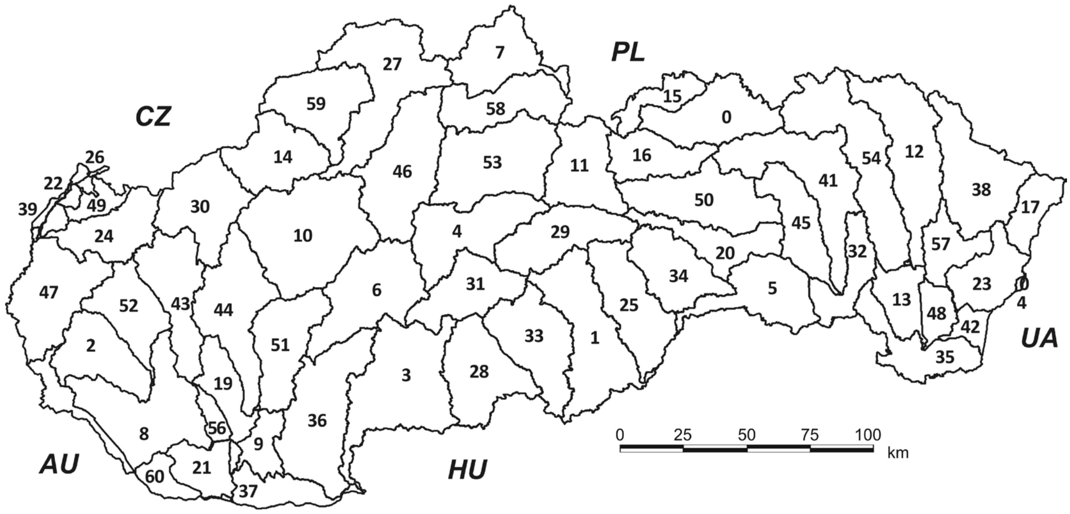

Fig. 1. Boundaries of 61 basic watersheds of Slovakia used as the spatial framework for the assessment of forest effect on watershed hydrology. Watershed codes used for the unique identification of watersheds are also given

cords on flood occurrence from national statistics for the period 1996–2006. The watersheds were grouped to risk categories by soil permeability and forest cover. Forest distribution describes the position of a forest relative to the headwater area of a watershed. The higher the value a watershed received, the larger the proportion of a forest that was distributed in the headwater area (better state). Watersheds with fragmented forest cover received lower scores as compared to those with contiguous forest cover. Fragmented forest cover was expected to regulate the overland water flow less efficiently. Stand density describes how well a forest stand is occupied by trees. The stand vertical structure describes the number of vertical layers in which trees are arranged within a stand. In the cases of both these variables we presume that denser and multi-layered stands provide higher evaporative surface, increase interception, and modify the runoff and hydrological parameters of soil more intensively. Therefore, watersheds containing denser and multi-layered forest stands received higher values.

Considering the spatial scale upon which this study focuses and the fact that there is generally very little knowledge allowing for the classification of individual tree species according to their effect on stand or watershed hydrology, forest tree species have been classified only as coniferous or broadleaved. Coniferous species were considered to modify the water regime of a watershed more intensively on an annual basis, as they slow the spring snow melt by protecting the ground from direct solar irradiation. Therefore, watersheds containing forest stands with a higher share of conifers were regarded as having a stronger effect on watershed hydrology, and thus those watersheds received higher values.

Methods

Reasoning behind the forest effect on water regulation

Forest water regulation addressed in this study contains diverse effects such as water flow retardation, which is the pronounced function for example in watersheds with low permeable soils and high slopes; water accumulation, which is pronounced in watersheds with the high water-holding capacity of soils; or flood mitigation function the need for which may depend on the complex environmental setting of watersheds inducing an increased flood incidence. This means that even the contrasting watersheds, e.g. those with flysch and karst bedrocks, can be classified as requiring the forest water regulatory effect, though the reasons for this need can be different. Such contrasting reasons can be for example retardation of intensive overland flow, or prevention of water losses due to water penetration through soil to the porous bedrock.

Data analysis and multi-criteria decision making

Spatial averages for each input variable presented in Table 1 were assigned to each watershed. In the cases of ordinal variables, weighted averages were used instead, with the relative extent of a given category in a watershed used as the weight. In this manner, the ordinal categories, such as soil permeability or forest fragmentation, were transformed onto a continuous scale.

Multi-criteria decision making (e.g. Massam 1988; Kangas et al. 2000; Malczewski 2006) was

Table 1. Variables used for the description of watershed natural conditions related to the water regime, and variables used for assessing the expected forest effect on watershed water regimes

Variable	Scale (units)	Source of data and reference
Bedrock permeability Soil permeability Soil water-holding capacity	ordinal (1–5)	Landscape Atlas of the Slovak Republic (2002)
Climatic water balance	ratio (mm)	Hlásny and Baláž (2008)
Integrated flood risk	ordinal (1–5)	Solín (2011)
Average slope of watershed	ratio (degrees)	Digital Elevation Model of Slovakia, Geodetic and Cartographic Institute in Bratislava
Forest stand density	ratio (0–1)	National Forest Centre, Slovakia Forest Management Plans
Forest stand vertical structure	ordinal (1–3)	
Forest stand species composition (proportion of conifers)	ratio (%)	
Forest cover in watershed	ratio (%)	
Forest fragmentation	ordinal (1–3)	
Forest distribution	ordinal (1–3)	

used to evaluate the relationship between natural conditions of watersheds and the expected capacity of forests to regulate the water regime.

Two groups of criteria were developed using the input variables in Table 1: external criteria, which represent the natural conditions of watersheds in terms of their expected need for water regime regulation; and internal criteria, which represent forest structure and distribution in terms of the expected capacity of forest to regulate the water regime. Such criteria have been developed by rescaling (standardizing) the ranges of input variables, averaged within the watersheds, into the unit range (Table 2) so as to represent either the relative magnitude of forest effect on the water regime or relative magnitude of need for the water regime regulation.

Two types of transfer function have been applied to input variables to obtain the aforementioned criteria: unimodal and linear. A unimodal function is used when the effect of a given variable peaks in a certain part of the gradient, while a linear function is used in the case of monotonically increasing or decreasing response. Climatic water balance represents the former case, in which we presume that dry or moist watersheds need more regulation as compared with watersheds with even climatic water balance (i.e. the difference between precipitation and potential evapotranspiration ranges around 0), while the latter case is represented, for example, by forest fragmentation or flood risk (the higher the poorer). Values for inflection points of those transfer functions are given in Table 2 (columns C, D, E).

Further, weights representing the preference given to the criteria were set. This was done independently for external and internal criteria so that the weights for each group of criteria sum to 1. In order to reduce the subjectivity of setting weights, the weights were proposed using an expert-panel approach, i.e. 5 forestry and hydrology experts were asked to weight the criteria (as suggested for example by Sierra et al. 2002, or Phua, Minowa 2005). Experts' background was hydrology (2 experts), forest bioclimatology (2 experts) and hydropedology (1 expert). The weights obtained in this way were averaged to achieve a more robust set of weights as compared with a single expert assignment (Table 2, column B).

To assess the integrated effect of external and internal criteria, those criteria have been synthesized using the following equations:

$$A = \sum_{e=1}^{n} EC_e w_e \text{ subject to } \sum_{e=1}^{n} w_e = 1 \quad (1)$$

$$B = \sum_{i=1}^{m} IC_i w_i \text{ subject to } \sum_{i=1}^{m} w_i = 1 \quad (2)$$

where:

A – indicator of need for the water regime regulation in a given watershed,
B – indicator of expected forest water-regulatory capacity,
EC_i – external criteria,
n – number of external criteria,
w_e – weights of external criteria,
IC_i – internal criteria,
m – number of internal criteria,
w_i – weights of internal criteria.

Table 2. Scheme for the multi-criteria assessment of forest effect on the water regime of watersheds as given by forest structure and distribution, and for the assessment of watershed need for the water regime regulation as given by watershed natural conditions. The weights in column B were proposed using an expert-panel approach. Columns C to E contain inflection points of a function used to transfer the input variables into the water regime related criteria.

		A	B weight	C	D	E
				scale and transfer function inflection points		
External factors	Natural conditions (climate, hydrology, geology, relief and soil related factors)	bedrock permeability	0.08	karst and fissure-karst 1	porous 0	fissure 0
		soil water-holding capacity	0.37	low 1	middle 0.5	high 0
		soil permeability	0.16	low 1	middle 0	high 1
		climatic water balance	0.11	negative 1	balanced 0	positive 1
		flood risk	0.15	high 1	middle 0.5	low 0
		average slope of watersheds	0.13	high 1	— —	low 0
Internal factors	Factors related to stand structure	stand density	0.02	max 1	— —	min 0
		stand vertical structure	0.03	max 1	— —	min 0
		species composition	0.08	coniferous > 75% 1	— —	coniferous < 25% 0
	Factors related to forest spatial distribution	forest cover	0.47	max 1	— —	min 0
		forest fragmentation	0.16	low 1	moderate 0.5	high 0
		forest distribution	0.24	> 50%* 1	< 50%* 0.5	< 20%* 0

– indicates that the values change continuously between the border values

In the case of variable *A* (given by synthesis of external factors), higher values indicate a higher need for the regulation of the watershed water regime, while in the case of variable *B* (given by synthesis of internal factors), higher values indicate the higher capacity of forest to regulate the water regime.

The relationship between the watershed need for the water regime regulation and forest water-regulatory capacity has been investigated as a difference between variables *A* and *B*:

$$C = A - B = \sum_{e=1}^{n} EC_e w_e - \sum_{i=1}^{m} IC_i w_i \quad (3)$$

where:

C – indicator of the relationship between variables *A* and *B*. Higher values denote those watersheds where natural conditions do not correspond to the desirable water-regulatory effect of forest. In addition to Eq. (3), a correlation between variables *A* and *B* was evaluated to describe the investigated relationship in greater detail.

RESULTS

Classification scheme and weight assignment

The proposed classification scheme (Table 2) encompasses all criteria divided into internal (forest-related) and external (related to watershed natural conditions) ones, weights of those criteria, and description of the inflection points of transfer functions which are used to transform the input variables into criteria. As can be seen, in the case of external criteria, soil water-holding capacity, soil permeability and integrated flood risk received the highest weights. These criteria received 68% of the total unit weight. In the case of internal criteria, the largest weights were assigned to criteria pointing out the spatial arrangement of forest within a watershed – forest cover, forest fragmentation and forest distribution. These criteria received 87% of the total unit weight. Stand structure-related parameters generally received low weights, which relates to the spatial scale at which the assessment was performed.

The designated scheme (Table 2) allows for synthesizing the criteria using Eqs (1) and (2), as well as investigating the distributions of variables *A* and *B*. Distribution of watersheds within the categories of variable *A* is relatively equal, with prevalence of lower values (Fig. 2a). Those lower values are typical of watersheds where natural conditions do not imply a critical need for the water regime regulation. By contrast, there is a high prevalence of watersheds reaching low (or approaching zero) values of variable *B* (Fig. 2b). These are watersheds with the low regulatory capacity of forest. Mainly sparsely forested watersheds with fragmented forest cover, which are intensively exploited for agriculture in most cases, belong to this category.

The values of variables *A* and *B* were further assigned to the map of Slovak Republic's basic watersheds (Fig. 1). The maps produced in this way describe the spatial distribution of watersheds according to their need for water regulation as given by their natural conditions (Fig. 3a) or by forest water-regulatory capacity (Fig. 3b).

As can be seen in Fig. 3, watersheds with high values of both variables form a cluster in the central part of Slovak Republic. In the case of variable *A*, a combination of higher soil permeability, higher soil water-holding capacity and higher flood risk mainly due to steep slopes in central mountain ranges of the West Carpathians affected high values received by these watersheds. In the case of *B* variable, higher values are associated mainly with watersheds situated in large mountain massifs (e.g. Nízke Tatry Mts., Slovenské Rudohorie Mts.), which are forested extensively and forest cover is compact (watershed codes 4, 11, 20, 29, 34, 53, etc.). The lowest values of both variables are assigned mainly to sparsely forested catchments in the Pannonian basin with flat relief.

Relationship between watershed natural conditions and forest regulatory capacity

Distribution of values taken on by variable *C* from Eq. (3) (Fig. 4) suggests that the need for forest regulatory capacity (variable A) is moderately well reflected by forest structure and distribution (variable B) on the scale of basic watersheds in Slovak Republic. This is indicated by the large proportion of values clustered around zero, although the frequency of positive values is relatively higher. These values are associated with watersheds where the forest water-regulatory capacity is low in comparison with the watershed need for the water regime regulation.

A map of variable *C* (Fig. 5) indicates that the water regime-related natural conditions of most watersheds in central and northern Slovak Republic (for example the upper part of the Hron river catchment, watershed codes 4 and 29) can be thought of as corresponding well with the expected water-regulatory effect of forest.

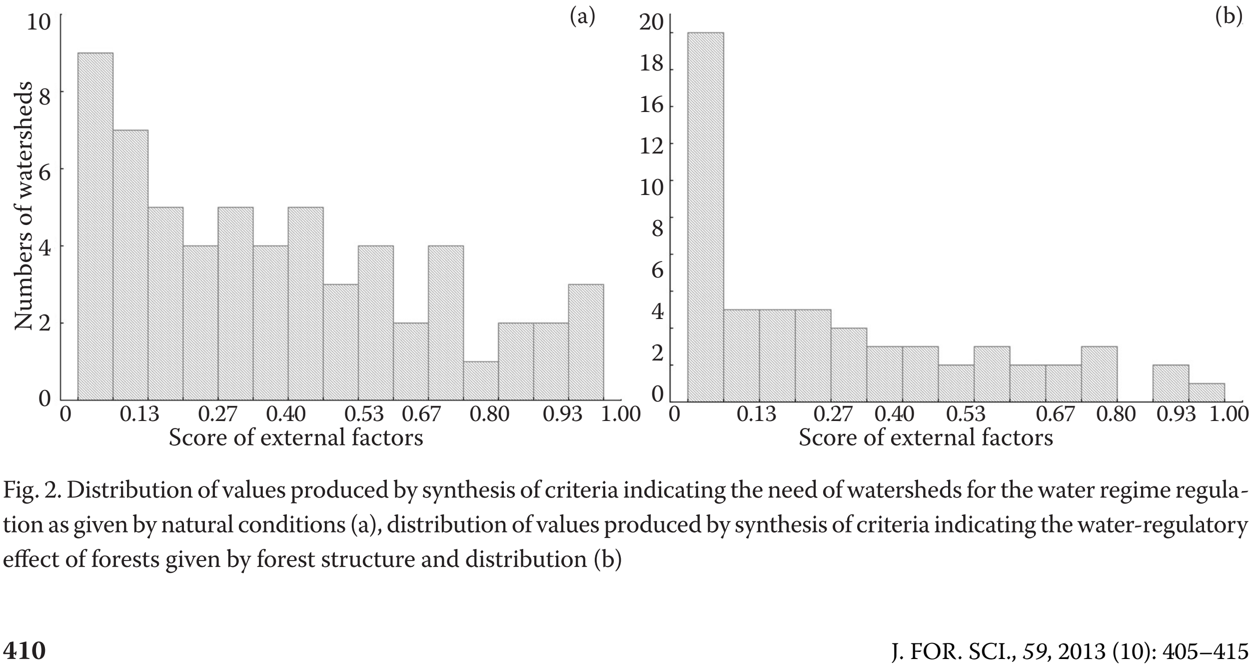

Fig. 2. Distribution of values produced by synthesis of criteria indicating the need of watersheds for the water regime regulation as given by natural conditions (a), distribution of values produced by synthesis of criteria indicating the water-regulatory effect of forests given by forest structure and distribution (b)

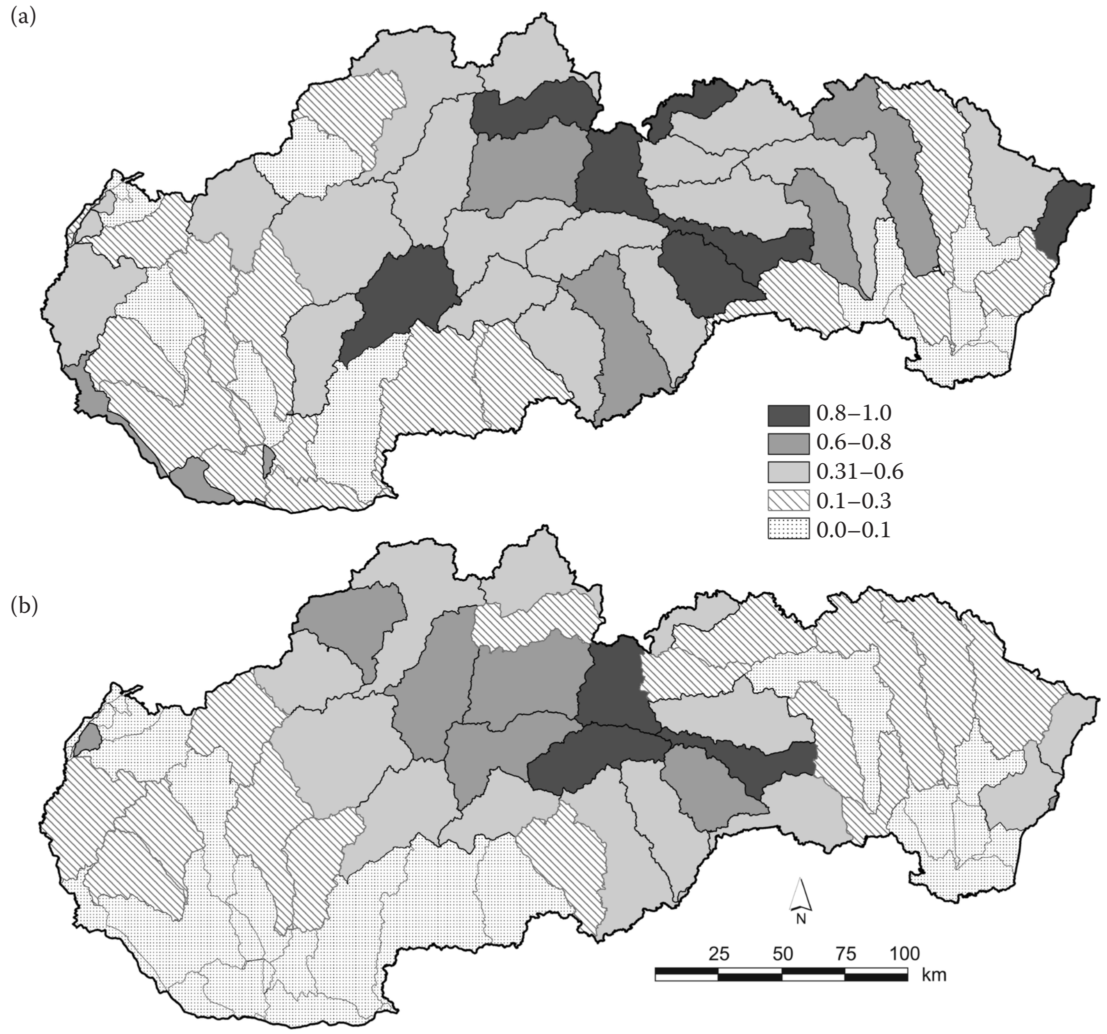

Fig. 3. Result of multi-criteria assessment of the need of watersheds for the regulation of water regime relative to their natural conditions (the higher the value, the higher the need) (a), and result of multi-criteria assessment of expected forest effect on watershed water regimes given by forest structure and distribution (the higher the value, the higher the effect) (b)

In contrast, most watersheds in southern Slovak Republic, having large proportions covered by agricultural land (for example the lower part of the Váh or Rimava river catchments, watershed codes 43, 1), exhibit high positive differences between variables *A* and *B*, thus suggesting the low water-regulatory capacity of forests and/or natural conditions implying a higher need for such regulation; this is of course the effect of low forest cover, which receives the highest weight in this evaluation. The watersheds associated with the highest values of variable *C* form a cluster in the south-western, southern and eastern parts of Slovakia (watershed codes 0, 1, 3, 6, 8, 11, 13, 15, 16, 17, 21, 22, 24, 28, 30, 31, 33, 34, 37, 38, 41, 43, 45, 47, 54, 58, 60).

The correlation chart between variables *A* and *B* and the square of the linear correlation coefficient r^2 = 0.28 suggest a positive relationship between the forest water-regulatory capacity and water-

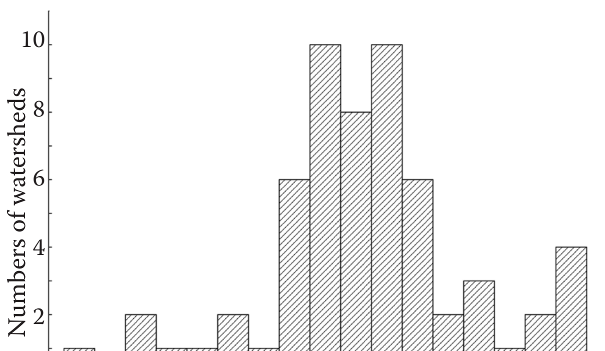

Fig. 4. Distribution of differences between the synthesis of criteria indicating the need of watersheds for the water regime regulation as given by natural conditions and criteria indicating the forest regulatory effect as given by forest structure and distribution

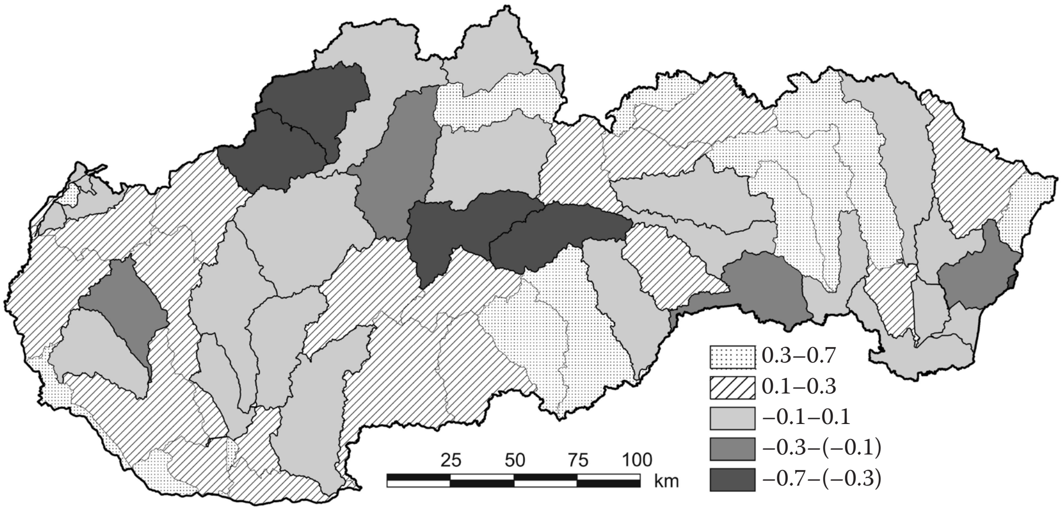

Fig. 5. Map of differences between the synthesis of factors indicating the need of watersheds for the water regime regulation and factors indicating the forest water-regulatory effect (the higher the values, the poorer the status)

shed need for the water regime regulation (Fig. 6). This indicates that the structure and distribution of forests in Slovakia can be thought of as corresponding moderately well with watershed natural conditions in terms of their need for the water regime regulation on a country-wide scale.

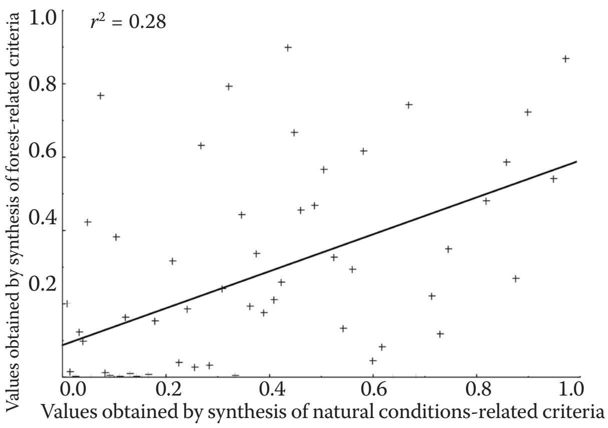

Fig. 6. Correlation between the scores from synthesis of factors indicating the need of watershed for the water regime regulation and factors indicating the forest water-regulatory effect

DISCUSSION AND CONCLUSIONS

Forests comprise ecosystems with remarkably high capacity to regulate the water regime, albeit at various scales. Therefore, the optimization of forest structure and distribution should be regarded as an important concept in integrated watershed management (Naiman 1997; Heathcote 2009). This approach assigns importance to the forestry community also from the viewpoint of increasing efforts to establish a system of payments for environmental services (Kosoya et al. 2007), where water provision and regulation represent an important forest-related ecosystem service. The forest effect on watershed hydrology tends to be overestimated, however, and especially in the perceptions of the public and of policy-makers (e.g. Andréassian 2004; Calder 2004; Calder et al. 2004). Empirical studies suggest that the water-regulatory effect of forest should be thought of as highly variable and general conclusions on forest effects are difficult to draw. Therefore, some experts (e.g. Calder et al. 2004) call for addressing this disparity before devising and developing land and water policies.

To contribute to this field, we made a country-wide investigation of the relationship between estimated effects of forest on watershed hydrology in relation to their natural conditions. We proposed a methodology for such assessment and demonstrated its use in the watersheds of Slovak Republic. To reduce the subjectivity of decisions concerning selection and preferences of input criteria, several experts' inputs can be used, and thus one can arrive at the selection of more robust criteria and weight assignment (e.g. Sierra et al. 2002; Phua, Minowa 2005), as has been presented in this study. Sophisticated approaches to coping with subjective judgement in multi-criteria decision making have been proposed, for example, by Yeh and Chang (2009) or Anisseh and Yusuff (2011). Such techniques can be used as extensions of the proposed methodology.

Preferences to forest-related input criteria corresponded with the spatial scale upon which the present study was conducted. The forest effect on the water regime is generally scale-dependent (Thompson et al. 2011). This means, for example, that while the effect of species composition and stand structure takes on greater importance at a stand (or patch) scale, these diminish in importance towards the watershed scale. At a watershed scale, the effect of lateral hydrological connectivity (which is affected, for example, by ecosystem distribution) becomes prevailing. Hence, total forest cover and forest distribution were preferred at the scale of the present study over stand parameters. In the case of criteria on natural conditions of watersheds, the distribution of weights was more uniform as compared with the forest-related criteria. Presumably, the reason for this lies in the fact that the relative effect of those criteria can vary between watersheds, and therefore averaging the experts' inputs yielded such a balanced weight distribution.

We found out that forest structure and distribution moderately well correspond with the need for the water regime regulation given by natural conditions of basic watersheds in Slovak Republic. The good degree of match between the need for water regulation and expected water-regulatory capacity of forests may imply that negative water-related events are not likely to occur in watersheds for which such match was identified, and that the forest water-regulatory capacity is sufficient to regulate the water balance. Such degree of match, however, only means that either forests are well structured and distributed (and thus there is very little that can be done to improve water regulation by forest) or that the natural conditions of watersheds generally do not imply that negative water-related events are likely to occur. Watersheds with a good degree of match between the need for regulation and expected forest water-regulatory capacity must not, however, be thought of as watersheds that do not need any other actions for improving the water regime and preventing floods, drought or other events from occurring.

The final question which should be addressed is the anticipated effect of climate change on our analysis, and generally on the role of forests in water regulation. While most of the variables used in the analysis, such as relief, soil and bedrock remain invariant under climate change, the used indicator of flood risk can be seriously affected. Cameron et al. (2000) stated in this regard that climate change is expected to have serious implications for flood frequency. Bronstert (2003) is more reserved and he suggested that while in some areas there is evidence of increased flood risk from climate change, in other areas such evidence is missing and further development of hydrological catchment models and tools for incorporating stochastic components into such models is needed to complement our current knowledge. Moreover, as weight assignment used in this study was based on the expert panel approach, development in scientific opinions, and assumingly increasing frequency of floods in the future, may affect experts' perception and thus alter the outputs.

Finally, the current extent of deforestation due to various disturbances in Central Europe with adverse effects on environment (e.g. Hlásny et al. 2010, 2011a), which can be further amplified by climate change (Hlásny et al. 2011b,c), may pronounce the importance of regulatory functions of forest and increase the research effort in this field.

References

Andréassian V. (2004): Waters and forests: from historical controversy to scientific debate. Journal of Hydrology, ***291***: 1–27.

Anisseh M., Yusuff R. bt M. (2011): A fuzzy group decision making model for multiple criteria based on Borda count. International Journal of Physical Sciences, ***6***: 425–433.

Beschta R.L., Pyles M.R., Skaugset A.E., Surfleet C.G. (2000): Peakflow responses to forest practices in the western Cascades of Oregon, USA. Journal of Hydrology, ***233***: 102–120.

Bíba M., Oceánská Z., Vícha Z., Jařabáč M. (2009): Long-term effect of forest renewal on the water regime in the small experimental watershed Červík. Soil and Water Research, ***4*** (Special Issue 2): S59–S65.

Band L.E., Tague C.L., Groffman P., Belt K. (2001): Forest ecosystem processes at the watershed scale: Hydrological and ecological controls of nitrogen export. Hydrological Processes, ***15***: 2013–2028.

Bond B.J., Meinzer F.C., Brooks J.R. (2008): How Trees Influence the Hydrological Cycle in Forest Ecosystems. In: Wood P.J., Hannah D.M., Sadler J. P. (eds): Hydroecology and Ecohydrology: Past, Present and Future. Chichester, John Wiley & Sons: 7–35.

Bosch J.M., Hewlet J.D. (1982): A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, ***55***: 3–23.

Bronstert A. (2003): Floods and climate change: Interactions and impacts. Risk Analysis ***23***: 545–557.

Buttle J.M. (2011): The Effects of forest harvesting on forest hydrology and biogeochemistry. Ecological Studies, ***216***: 659–677.

Calder I.R., Amezaga J., Aylward B., Bosch J., Fuller L., Gallop K., Gosain A., Hope R., Jewitt G., Miranda M., Porras I., Wilson V. (2004): Forest and water policies. The need to reconcile public and science perceptions. Geologica Acta, ***2***: 157–166.

Calder I.R. (2004): Forests and water – closing the gap between public and science perceptions. Water Science and Technology, ***49***: 39–53.

Cameron D., Beven K., Naden P. (2003): Flood frequency estimation by continuous simulation under climate change (with uncertainty). Hydrology and Earth System Sciences, ***4***: 393–405.

Committee on Hydrologic Impacts of Forest Management, National Research Council (2008): Hydrologic Effects of a Changing Forest Landscape. Washington DC, National Academies Press: 168.

FAO, CIFOR (2005): Forests and Floods – Drowning the fiction or thriving on facts? Bogor, Center for International Forestry Research, Food and Agriculture Organization of the United Nations: 30.

Farley K.A., Jobbágy E.G., Jackson R.B. (2005): Effects of afforestation on water yield: A global synthesis with implications for policy. Global Change Biology, ***11***: 1565–1576.

Fohrer N., Haverkamp S., Eckhardt K., Frede H.G. (2001): Hydrologic response to land use changes on the catchment scale. Physics and Chemistry of the Earth (Part B) ***26***: 577–582.

Fohrer N., Haverkamp S., Frede H.G. (2005): Assessment of the effects of land use patterns on hydrologic landscape functions: development of sustainable land use concepts for low mountain range areas. Hydrological Processes, ***19***: 659–672.

Heathcote W.I. (2009): Integrated Watershed Management: Principles and Practice. Hoboken, John Wiley & Sons: 464.

Hewlett J.D. (1971): Comments on the catchment experiment to determine vegetal effects on water yield. Water Resources Bulletin, ***7***: 376–381.

Hibbert A. R. (1967): Forest treatment effects on water yield. In: Sopper W.E., Lull W.E. (eds): International Symposium of Forest Hydrology. Pennsylvania State University, 29. August–10. September 1965. Pergamon, Oxford: 527–543.

Hlásny T., Baláž B. (2008): The climatic water balance of Slovakia based on the FAO Penman-Monteith potential evapotranspiration. Geografický časopis, ***60***: 15–30.

Hlásny T., Kulla L., Barka I., Turčáni M., Sitková Z., Koreň M. (2010): The proposal of biotic hazard zones in selected spruce dominated regions in Slovakia. Journal of Forest Science, ***56***: 236–242.

Hlásny T., Křístek Š., Holuša J., Trombík J., Urbaňcová N. (2011a): Snow disturbances in secondary Norway spruce forests in Central Europe: Regression modeling and its implications for forest management. Forest Ecology and Management, ***12***: 2151–2161.

Hlásny T., Barcza, Z., Fabrika M., Balázs B., Churkina G., Pajtík J., Sedmák R.,Turčáni M. (2011b): Climate change impacts on growth and carbon balance of forests in Central Europe. Climate Research, ***47***: 219–236.

Hlásny T., Zajíčková L., Turčáni M., Holuša J., Sitková Z. (2011c): Geographical variability of spruce bark beetle development under climate change in the Czech Republic. Journal of Forest Science, ***57***: 242–248.

Hlavčová K., Szolgay J., Kohnová S., Hlásny T. (2008): Simulation of hydrological response to the future climate in the Hron river basin. Journal of Hydrology and Hydromechanics, ***56***: 163–175.

Holko L., Hlavatá H., Kostka Z., Novák J. (2009): Hydrological regimes of small catchments in the High Tatra Mountains before and after extraordinary wind-induced deforestation. Folia Geographica, series Geographica-Physica, ***40***: 33–44.

Kangas J., Store R., Leskinen P., Mehtatalo L. (2000): Improving the quality of landscape ecological forest planning by utilising advanced decision-support tools. Forest Ecology and Management, ***132***: 157–171.

Kosoy N., Martinez-Tuna M., Muradian R., Martinez-Alier J. (2007): Payments for environmental services in watersheds: Insights from a comparative study of three cases in Central America. Ecological Economics, ***61***: 446–455

Kostka Z., Holko L. (2006): Role of forest in hydrological cycle – forest and runoff. Meteorologický časopis, ***9***: 143–148.

Landscape Atlas of the Slovak Republic (2002): Available at http://mapserver.geology.sk/Atlas_krajiny_sk/mapviewer.jsf. Bratislava, Ministry of the Environment of the Slovak Republic.

Lee R. (2005): Forest Hydrology. Dehra Dun, Bishen Singh Mahendra Pal Singh: 349.

Malczewski J. (2006): GIS-based multicriteria decision analysis: a survey of the literature. International Journal of Geographical Information Science, ***20***: 703–726.

Massam B. H. (1988): Multi-criteria decision making techniques in planning. Progress in Planning, ***30***: 1–84.

Millennium Ecosystem Assessment (2005): Ecosystems and Human Well-Being: Synthesis. Washington DC, Island Press: 137.

Naiman R.J., Decamps H. (1997): The ecology of interfaces – riparian zones. Annual Review of Ecology, Evolution, and Systematics, ***28***: 621–658.

Phua M.H., Minowa M. (2005): A GIS-based multi-criteria decision making approach to forest conservation planning at a landscape scale: a case study in the Kinabalu Area, Sabah, Malaysia. Landscape and Urban Planning, ***71***: 207–222.

Pimentel D., Kounang N. (1998): Ecology of soils erosion in ecosystems. Ecosystems ***1***: 416–426.

Risser P.G. (1995): The status of the science examining ecotones. Bioscience ***45***: 318–325.

Robinson M., Gannon B., Schuch M. (1991): A comparison of the hydrology of moorland under natural conditions, agricultural use and forestry. Hydrological Sciences Journal, ***36***: 565–577.

Sierra R., Campos F., Chamberlin J. (2002): Assessing biodiversity conservation priorities: ecosystem risk and representativeness in continental Ecuador. Landscape Urban Planning, ***59***: 95–110.

Smerdon B.D., Redding T.E., Bckers J. (2009): An overview of the effects of forest management on groundwater hydrology. BC Journal of Ecosystems and Management, ***10***: 22–44.

Solín L. (2011): Regionálna variabilita povodňovej hrozby malých povodí na Slovensku. [Regional variability of flood threats to small water basins in Slovakia.] Geografický Časopis, ***63***: 29–52.

Stednick J. D. (1996): Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology, ***176***: 79–95.

Sun G., McNulty S. G., Shepard J.P., Amatya D.M., Riekerk H., Comerford N.B., Skaggs R.W., Swift L. W. Jr. (2001): Effects of timber management on wetland hydrology in the eastern United States. Forest Ecology and Management, ***143***: 227–236.

Sun G., McNulty S.G., Lu J., Amatya D.M., Liang Y., Kolka R.K. (2005): Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States. Journal of Hydrology, ***308***: 258–268.

Sweeney B.W., Bott T.L., Jackson J.K., Kaplan L.A., Newbold J.D., Standley L.J., Hession W.C., Horwitz R.J. (2004): Riparian deforestation, stream narrowing, and loss of stream ecosystem services. Proceedings of the National Academy of Sciences of the United States of America, ***39***: 14132–14137.

Thompson S.E., Harman C.J., Troch P.A., Brooks P.D., Sivapalan M. (2011): Spatial scale dependence of ecohydrologically mediated water balance partitioning: A synthesis framework for catchment ecohydrology. Water Resource Research, ***47***: 1–17.

Tong S.T.Y., Chen W. (2002): Modeling the relationship between land use and surface water quality. Journal of Environmental Management, ***66***: 377–393.

Uunila L., Guy B., Pike R. (2006): Hydrologic effects of mountain pine beetles in the interior pine forests of British Columbia: key questions and current knowledge. Streamline, ***9***: 1–6.

Yeh CH.H., Chang Y.H. (2009): Modeling subjective evaluation for fuzzy group multicriteria decision making. European Journal of Operational Research, ***194***: 463–473.

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