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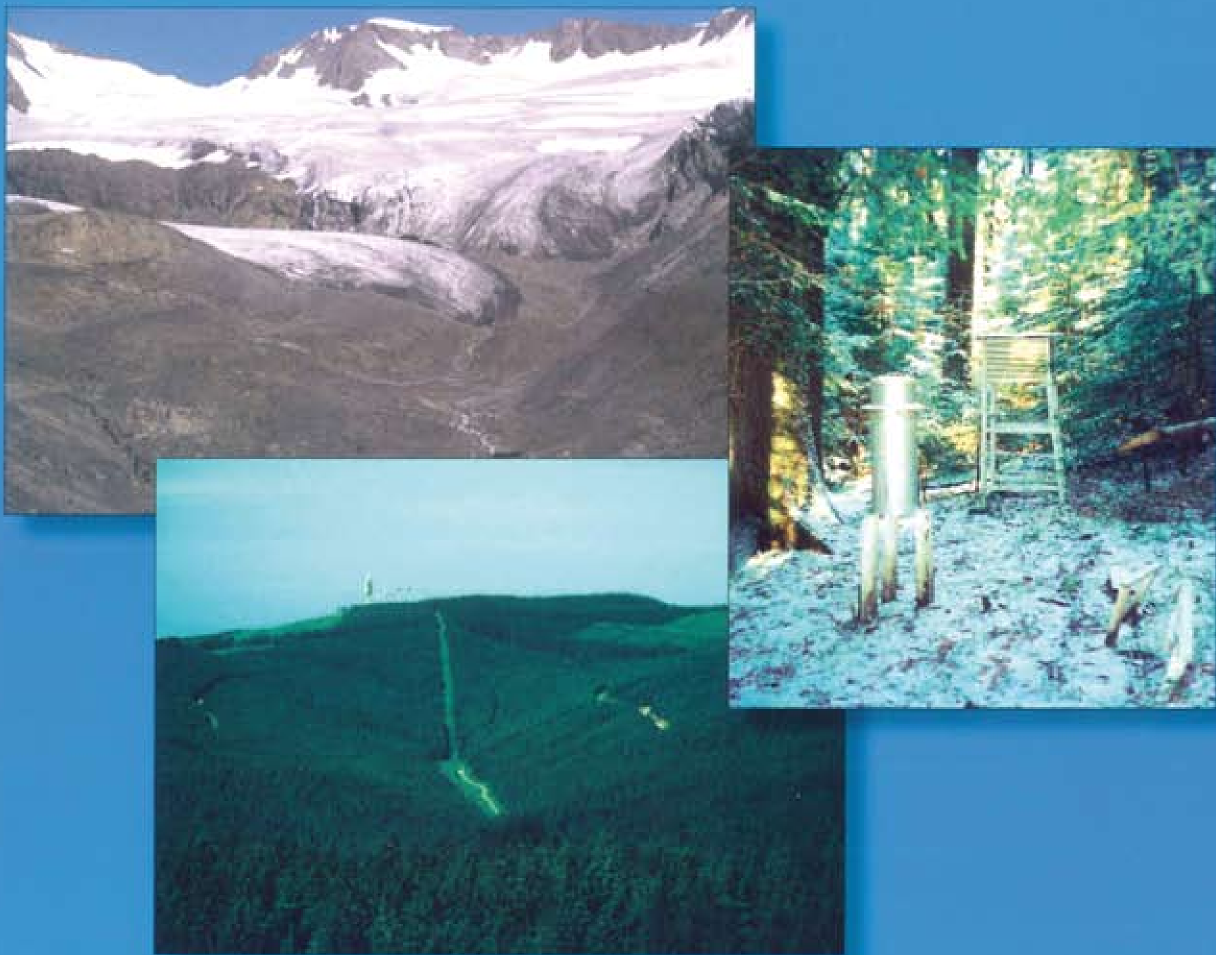
Studies in Mountain Hydrology



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HWRP – HYDROLOGY AND WATER RESOURCES PROGRAMME OF WMO

Studies in Mountain Hydrology

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A. Herrmann and U. Schröder

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Foreword

Mountainous regions take up a major part of the area of Central Europe. Their significance, however, is due not only to the impact of the area they occupy but also to the fact that they are an essential constituent of regional and supraregional climate systems. Changes in temperature and precipitation have in recent years led to the retreat of glaciers. Climatic changes do not only affect glaciers or the nival zone; a change in climatic conditions also has an impact on the entire hydrological and biogenous system of mountainous environments.

The starting point for research are representative and more or less small-scale areas at different altitudes. Because of the very low network density, data of mountainous regions are rather rare, thus rendering these study areas all the more important. This publication addresses issues concerning the water balance in mountainous regions and its modelling. Further subjects are the impact of land use on runoff and erosion, the sediment discharge and the chemism of mountain streams. Long time series are necessary in order to determine and quantify the long-term effects especially of climate change. The scientific need to encourage the establishment of such study areas is of great significance. The functional relationships induced by climate and the changes in the ecosystem have a considerable socio-economic relevance – one just has to consider winter as well as summer tourism – so research in these fields is of particular importance.

With this publication the German IHP/HWRP National Committee contributes to the determination of hydrological parameters and processes in mountainous environments as well as to the clarification of the significance of climatically induced variations. My sincere thanks are extended to the authors of the papers for their contributions and to the editors Andreas Herrmann and Ulrich Schröder.

Professor Dr S. Demuth
Director of the German IHP/HWRP Secretariat

Preface

Mountain hydrology is by tradition a standard element of the International Hydrological Programme (IHP) of UNESCO. This is a rather impressive fact because continuing concern for a single topic over decades is unique, at least for international scientific hydrological programmes. Mountain hydrology is presently incorporated in the UNESCO IHP Phase VI, Theme 3 *Land Habitat Hydrology*, Focal Area 3.3 *Mountains.* Already some time ago, the growing interdisciplinary orientation of research on the hydrology of high mountain areas called for its inclusion in the Project 2.4 *Comprehensive assessment of the surficial ecohydrological processes* of IHP Phase V. To meet the requirements of other UNESCO scientific programmes, the hydrology of mountain environments is also included in a joint IHP/MAB (Man and the Biosphere Programme) activity under the Main Line of Action II.2.3 *Joint IHP/MAB: Land-water interactions.* In its Hydrology and Water Resources Programme (HWRP), WMO addresses, especially in the sub-programme *Sustainable Development of Water Resources*, several aspects of ecohydrological processes.

Mountainous regions are also integrated into FRIEND, the cross-cutting programme component of IHP Phase VI, and in particular the Northern European FRIEND Project 5 *Catchment Hydrological and Biogeochemical Processes in a Changing Environment.* In this context, the leading roles of UNESCO and WMO in enhancing mountain hydrology and developing regional databases such as HKH-FRIEND and regional observation systems such as HKH-HYCOS are worth mentioning.

Apart from the IHP, the theme of the IGBP's (International Geosphere-Biosphere Programme) core project, Biospheric Aspects of the Hydrological Cycle (BAHC), within the Mountain Research Initiative (MRI), directly related to mountain hydrology in which climate change impacts on hydrological processes and the redistribution of water resources play a role. Finally, the European Network of Experimental and Representative Basins (ERB) contributes considerably to scientific mountain hydrology activities in Europe.

Two years after the International Year of Mountains in 2002 and one year after the International Year of Freshwater in 2003, during which mountains were acclaimed for their function as the water towers of the world, the International Conference on Hydrology of Mountain Environments took place in Berchtesgaden, Federal Republic of Germany from 27 September to 1 October 2004. The conference was a contribution by Germany to IHP Phase VI and was jointly convened by the German National Committee for the IHP of UNESCO and the HWRP of WMO, the Technical University of Braunschweig and the Berchtesgaden National Park Authority.

The Berchtesgaden conference aimed at facilitating the exchange of scientific knowledge by bringing together scientists involved in the hydrology of mountainous areas with special emphasis on physical processes and regional aspects. The conference defined deficits and future needs in the field of hydrology and water resources management for regional study concepts for the mountains of the world with respect to regional infrastructure and scientific potential. It addressed various disciplines, agencies and administrative bodies covering hydrological and water management aspects of mountain environments.

To prepare some of these aspects in more detail for the conference, the Workshop on Mountain Hydrology, organised jointly by the Northern European FRIEND Project 5, the Euromediterranean Network of Experimental and Representative Basins (ERB) and the Romanian National Institute of Meteorology and Hydrology, was held in Bucharest on 27 September 2003. The German IHP/HWRP National Committee was a main sponsor of the workshop. The programme was to some extent a thematic image of European hydrological research in mountain environments, although from the regional point of view some important mountainous regions were not represented. However, the mixture of regional case studies and country reports presented at the workshop and published here largely reflects the present focal points of mountain hydrological research activity within the cooperating groups of Northern European FRIEND Project 5 and ERB.

The themes of the papers range from the observation of runoff formation under the possible influence of climate change in various regions of the world, from studies of the impact of land-use changes in headwaters on the soil water balance, the presentation of national networks of small study and experimental areas, and the assessment of anthropogenic influences based on historical data, to the utilisation of hydrological models for socio-economic decision-making with respect to climate change.

Andreas Herrmann and Ulrich Schröder, editors

Runoff formation in mountain environments and possible effects of global warming

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Abstract

This paper shows how hydrological small-scale studies in mountainous basins have contributed to enlarge our knowledge about runoff formation which is considered an ecohydrological key process. A most efficient conceptual basis for such studies is the holistic and multilateral ICA (Integrated Catchment Approach) which combines traditional water balances with water tracing and GIS techniques, and mathematical modelling. Experimental results are taken from mountainous study basins in which the TUBS Department of Hydrology and Landscape Ecology has been active. The main findings are that the runoff formation process can be subdivided in three principal evolution stages, that the tracer technique is an indispensable purposeful tool on different scales and that climate warming is supposed to influence runoff regimes considerably, but runoff formation only gradually. Future research should concentrate on the extension of ICA applications preferably to subpolar, boreal and tropical mountain environments, prolonging the existing data series to allow evaluation of climate change impacts on ecohydrology, and upscaling and transferring hydrological information to the so-called ungauged areas.

1 Introduction

Runoff formation and runoff regime are specific responses of hydraulic and hydrologic system behaviour on environmental conditions. Hence, change in those conditions may modify runoff formation and behaviour of natural watersheds. Therefore, runoff formation is considered an ecohydrological key process. Depending on the systems' complexity, changes due to global warming will be more or less distinct, i.e. small and simply structured hydrological systems should respond more spontaneously and unequivocally.

To allow the determination and quantification of such effects, special experiments and long-term monitoring have to be carried out at a high level of accuracy. Due to the global change discussion, most relevant runoff formation concepts, as, for example, mentioned by Uhlenbrook and Leibundgut (1997), have, for several years, been revisited if they are purely formalistic, i.e. not taking into account from where the flood-generating water really originates, which are the pathways and how old it is.

To investigate runoff formation 19 small mountainous and hilly basins with sub-basins have been studied for 30 years under the umbrella of or in cooperation with the Department of Hydrology and Landscape Ecology at the Technical University Braunschweig (TUBS). On this basis, a new conceptual approach for runoff formation with its partial processes was proposed by Herrmann in 1994 and recently refined in Herrmann (2002). The main focus in this article is on summarising findings for runoff formation in mountains on a small basin scale, also with respect to possible effects of global warming on the regional runoff formation process pattern with conclusions for future research strategies.

2 Experiments

2.1 Study concept: Integrated Catchment Approach (ICA)

Hydrologic basin research at TUBS Department of Hydrology and Landscape Ecology is principally based on the holistic Integrated Catchment Approach (ICA) study concept in Figure 1 as developed and applied in cooperation with various disciplines (Herrmann et al., 2001a; Herrmann, 2002). An important tool which is used by ICA are natural and artificial hydrological tracers which allow the determination of hydraulic parameters like transit times, or the separation of event from pre-event water in total runoff.

The ICA concept was not established as such at the initiation of the early studies in Table 1, but it has grown successively according to the scientific needs or technical and financial possibilities of research projects. ICA is therefore never complete, but for each individual realisation an appropriate conceptual hydrological model forms the starting point of the investigation which should consider relevant features of an actual study system. Besides appropriate experimental facilities, mathematical models and some other tools like GIS (here: Arc/INFO and ArcView) are required. As to the environmental tracer approach, it aims at determining the proportions of event and pre-event water for single floods, at assessing the origin and pathways of the subsurface components and mean transit times of groundwater, and at estimating subsurface storage volumes of mobile water and effective porosity of the studied subsurface storage system. For the determination of runoff components from isotopes, a simple mixing formula is used, and also the black-box model type with the mean transit time as a main hydraulic parameter of the exponential and dispersive transfer (basin response) functions (Herrmann, 1997; Maloszewski et al., 1983, 1992, 1999). Use of artificial tracers allows the discrimination of distinct flow and transport patterns within and between hydrological compartments of the study system.

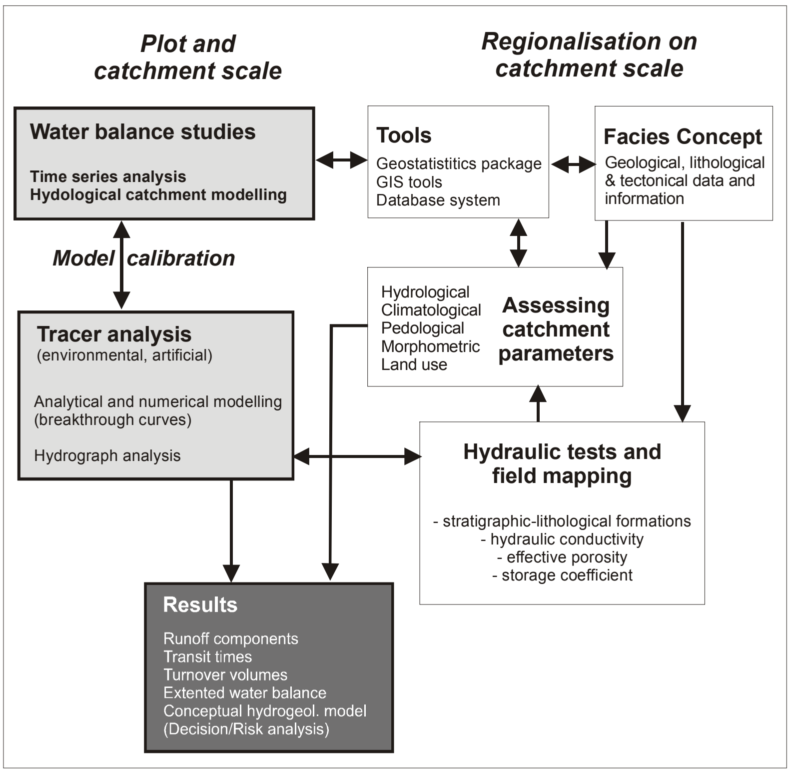

Fig. 1: ICA concept as developed in the Harz Mts study basins (cf. Table 1, from Herrmann et al., 2001a, 2001b)

Table 1: Hydrological study basins of the TUBS Department of Hydrology and Landscape Ecology

Name Location	**Area [km^2]**	**Elevation range, mean**	**Catch-ment type**	**Bedrock, soils**	**Vegetation**	**References**
Lange Bramke ***Harz Mts., Germany***	0.76	543-700	Forested, mountain	Paleozoic sand-stones and shales; podzolic cambisols	90% Norwegian spruce, 10% grassland	Herrmann et al. 2001 Holko et al. 2001 Maloszewski et al. 1999 Kim 1997 Buchtele et al. 1996 Herrmann 1994 Schwarze et al. 1994 Herrmann & Schöniger 1992 Schwarze et al. 1991 Schöniger & Herrmann 1990 Schöniger 1990 Herrmann et al. 1989 Herrmann et al. 1987 Herrmann et al. 1986 Herrmann et al. 1984
Grosse Schacht ***Harz Mts., Germany*** **Kl. Mollental** **Gr. Mollental**	9.6 2.02 1.49	341-861 430-861 435-822	Forested, mountain	Paleozoic quart-zites, shales, diabase; Cambisol-regosols	90% forest, 10% grassland	Herrmann et al. 2001 Schöniger 1998 Schöniger et al. 1997 Sommerhäuser 1994
Riefensbeek ***Harz Mts., Germany*** **Hangental**	6.0 0.7	380-641 450-612	Forested, mountain	Paleozoic schists, sand-stones, quart-zites; podsolic cambisols	90% forested 95% forested	Sommerhäuser 1994
Krummbach ***Northern Harz Foreland, Germany*** Ohebach	15 0.885	112-333 117-156	Agricult-ural, hilly	Quaternary sedi-ments (loess); clayey soils	100% arable land	Herrmann 1999 Herrmann et al. 1997 Tischer 1995 Herrmann 1994
Eisenbach ***Southern Lüneburg Heather, Germany***	4.24	62-119	Agricult-ural, hilly	Sandy moraines; Cambisols	70% arable land, irrigated, 15% fallow land	Herrmann 1999 Herrmann 1994 Schöniger 1998 Kim 1997 Herrmann & Ueberschär 1993
Lainbach ***Bavarian Alps, Germany***	18.80	670-1801	Forested, high-mountain	Triassic lime-stones,dolomite; Cretac. Sand-stones, shales; Pleistoc. glacial, lacustr. deposits lithosols, rego-sols, cambisols	80% forest and wood; alpine pastures and grassland; rock	Maloszewski et al. 1983 Stichler & Herrmann 1982 Herrmann et al. 1981 Herrmann & Stichler 1980 Herrmann et al. 1979 Stichler & Herrmann 1978 Herrmann 1978 Herrmann et al. 1973
Wimbach ***Bavarian Alps, Germany***	33.4	636-2713	Forested, high-mountain	Triassic lime-stones , dolo-mite; Pleistoc. Deposits; litho-sols, regosols, cambisols	20% forest 80% rock, fan talus, outwashed plain	Maloszewski et al. 1992

Table 1 (cont.)

Name Location	Area [km^2]	Elevation range, mean	Catch-ment type	Bedrock, soils	Vegetation	References
Cal Rodó ***Pyrenees, Spain*** Ca l'Isard **Can Vila**	4.2 1.32 0.56	960-?	Forested, agricultur-al hilly-high mountain	Paleocene rocks (limestones, clays, silts) Regosols, cambisols	10-52% agricult-ural land (arable, grassland) 17-47% forests 14-16% shrubs 1-5% badlands	Herrmann et al. 1999
Jhikhu Khola ***Middle Mts., Nepal*** **Khet River** **Bari River**	 0.1 0.125	 891-1092 878- 936	Agricult-ural, hilly	Gneiss, phyllite, quartzite; ferral-sols, fluvisols	100% arable land irrigated (*khet* land) rainfed (*bari* land)	Schumann et al. 2002 Schumann et al. 2001
High Himalaya **Nepal** **Modi Khola** **Langtang K.** **Imja Khola**	 148 340 135	 3160-8091 3800-7232 4375-8501	High-mountain	Gneisses, granites, meta-sediments; Lithosols, regosols	Rock, fan talus, outwashed plain; grassland 33% glaciated 38% glaciated 27% glaciated	Buchtele et al. 1998

2.2 Experimental basins

Most study basins in Table 1 cover <1 to 5 km². They are in no case urbanised, but predominantly either agricultural or forested and even high-alpine with pastures and rock. Central European basins are lined up along a transect from the Bavarian Alps through the Central European Highland to the hilly foreland of the Harz mountains, which is covered with loess-loam, and the Saalian sandy moraines north of it. Mediterranean mountains are represented here by the Catalonian Pyrenees, and sub-tropical ones by the Nepalese Himalayas. Since mostly short-term investigations were carried out, re-establishment of the studies is required after a while if discrimination of global change effects on runoff behaviour is intended.

3 Results

3.1 General

Major findings from holistic approaches by ICA on small basin scale refer to:

(i) Better understanding of hydrological processes and systems behaviour;
(ii) Runoff components for storm and snowmelt hydrographs;
(iii) Origin and age of subsurface components;
(iv) Groundwater table-discharge relationships;
(v) Groundwater recharge;
(vi) Detailed water balance;
(vii) Improved runoff formation concept.

Findings under (i) to (iii) were presented and discussed in more detail and in the global context in Herrmann (1997), results under (iv) and (v) in Herrmann et al. (1989), Schöniger and Herrmann (1990) and Schumann and Herrmann (2002), those under (vi) in Herrmann et al. (2001b) and under (vii) recently in Herrmann (2002). In the global change context, findings as listed under (ii) to (iv) are especially relevant because they give an answer to some of the above-mentioned questions such as runoff formation process and origin, age and pathways of water-generating single flood hydrographs.

3.2 Specific results 1: Surface-subsurface flow patterns and hydrograph formation

Much larger quantities of water can undergo an underground passage during single flood events than the traditional hydrological investigation methods allow, i.e. the proportion of actual rain or melt water leaving the basin immediately is most frequently negligible. Accordingly, direct or event-water water flow components as derived from environmental isotopes and shown in Table 2 are normally less than, for instance, synthetic hydrograph separation methods or other conventional techniques admit. Another important finding related to runoff formation is that groundwater tables correlate positively with discharge, even under steep mountainous conditions with semi-confined and confined fractured rock aquifers. The statistically significant relation is hydraulically sound and distinctly non-linear. It differs from year to year and from basin to basin.

Furthermore, groundwater table-discharge relations are distinctly hysteretic (Fig. 1). Their hydraulic interpretation has actually to be confined to the fact that rising groundwater tables during single events correspond to an increase of pressure head, thus allowing higher groundwater quantities to exfiltrate and the discharge to grow equally in flow direction. The meaning of the steeper rising limb may be that in the initial phase the river-near sections of the watershed and/or macropore/fractures systems are drained first, thus generating the flood hydrograph until a steady-state situation which is followed by the draining of more distant sections and/or micropore/fissure systems (Schöniger and Herrmann, 1990).

The mentioned hydraulic mechanism will of course not principally change with climate-induced changes in available water volumes. But growth or reduction of water fluxes caused by global warming will of course influence the actually quantitatively balanced hydrological systems.

3.3 Specific results 2: Runoff formation and partial processes

The following model concept for runoff formation as the ecohydrological target process was developed as a synthesis of these experimental findings. Accordingly, runoff formation can be split into three distinct partial processes (Herrmann, 2002) (Fig. 3):

(1) Infiltration with saturation of top soils (initial saturation)and percolation

With the effective infiltration capacity of the soil matrix achieved, infiltration water quickly drains, preferably vertically through macropore systems towards greater depths. Dye tracer experiments show that even macroscopically homogeneous soils have lots of preferential pathways once a broad infiltration front is established, which allows quick and efficient vertical transport (Schumann, 2004, Schumann et al. 2004).

Table 2: Information of hydrological relevance about small hydrological study basins of the TUBS Department of Hydrology and Landscape Ecology

Name	Hydrological research since/from..to	P [mm]	R [mm]	E [mm]	From isotopic hydro-graph separation		Mean Transit time of ground-water (yrs.)	Mathematical models used in the basin
					Old water [%]	Event type		
Lange Bramke	1949	1300	700	600	>90	Snowmelt Rainfall	2.2	DIFGA BROOK SACRAMENTO MIKE SHE FEFLOW ROCKFLOW
Grosse Schacht **Kl. Mollental** **Gr. Mollental**	1991-1993	1325	980	345	>80	Snowmelt Rainfall	2.5	FEFLOW ROCKFLOW
Alte Riefensbeek **Hangental**	1991-1993	1425	980	445				
Krummbach **Ohebach**	1987	750	225	525	>80 90	Rainfall		
Eisenbach	1993	625	535 incl. Irrig. Water	250	>80	Rainfall		BROOK SACRAMENTO FEFLOW
Lainbach	1972-1978	2160	1060	1100	1976-78: monthly 53-65: summer 72-86: winter 64-70: year events 70-90	Snowmelt Rainfall	2.1-2.2 0.6-0.8 (fast) 6.6-7.5 (delayed fraction)	SACRAMENTO
Wimbach	1988-1991	2450	1670	780	>95	Snowmelt Rainfall	4.0-4.1	
Cal Rodó	1996-1998	850	?	?			7.0-15.5 Streams: 7.0-15.0 Wells: 7.5-12.0 Springs: 10.5-15.5	TOPMODEL
Jhikhu Khola **Khet River** **Bari River**	1999-2001	1300	?	?	<10-20	Rainfall	~2	WaSiM-ETH
Modi Khola **Langtang K.** **Imja Khola**	1987-1993	2100 680 450	? ? ?	? ? ?				SACRAMENTO " "

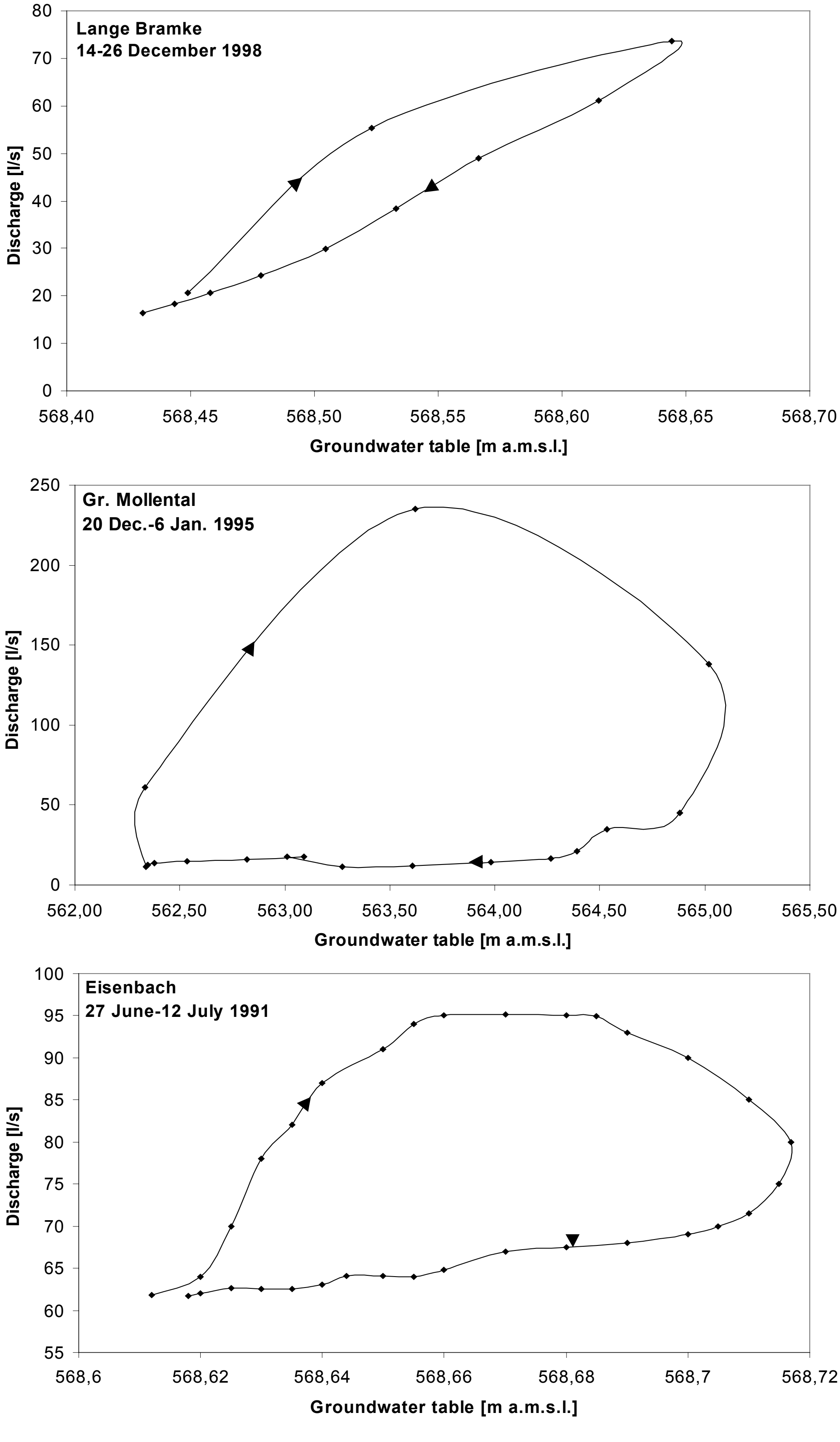

Fig. 2: Evolution of discharge vs. groundwater table in two basins of fractured bedrock in the Harz Mts. (Lange Bramke, Gr. Mollental), and in a hilly morainic basin (Eisenbach) 140 km north of Braunschweig, Germany (for description of basins see Table 1)

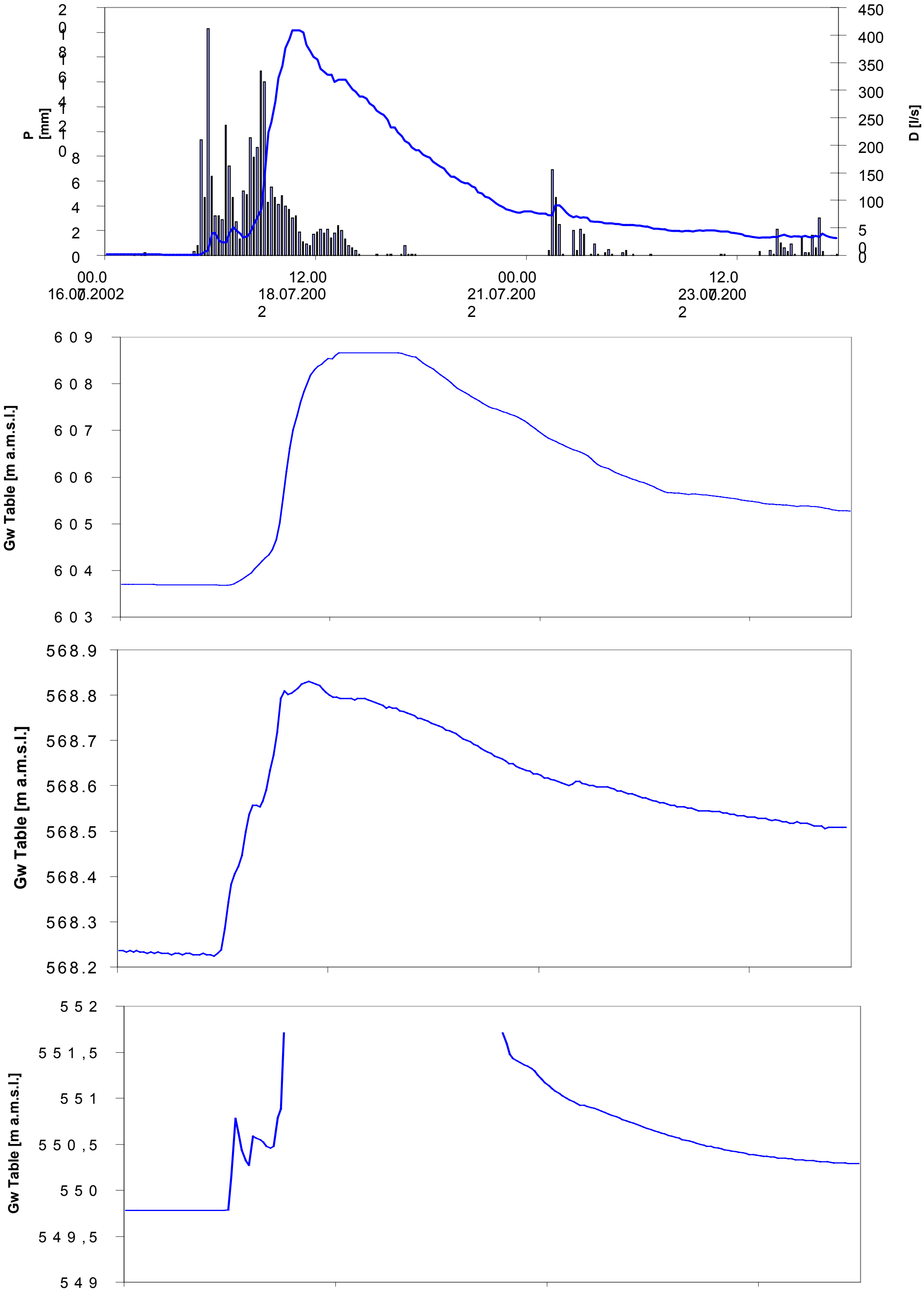

Fig. 3: Lange Bramke basin during a flood event in July 2002: Evolution of precipitation P and discharge D (top), and of groundwater tables at different wells: at medium slope of central basin (second from top), at toeslope of central basin (third from top) and at toeslope at basin outlet (bottom)

As to agricultural irrigation systems, ponding irrigation seems to cause more a rapid and quantitatively more efficient response of water fluxes travelling through preferential pathways than sprinkler irrigation does. The transportation of dissolved matter such as agro-chemicals through the unsaturated zone behaves in the same way (Schumann et al., 2004).

(2) Rise of groundwater table corresponding to increase of groundwater potential

Fluid mechanical effects due to mass transport through pulse pressure transmission and free flow through macropores in soils and fractures and fissures in the bedrock cause basin-wide compression of the capillary fringe and an increase of subsurface pressure heads. Mass displacement in the underground can be split into (i) vertical seepage in the unsaturated zone and (ii) lateral groundwater flow in the saturated zone of the watershed. As a result of pulse pressure transmission, groundwater tables are allowed to rise, thus initiating process no. (3).

(3) Groundwater exfiltration to stream channels.

Final quick and efficient exfiltration, for which the whole wetted cross-section of the river bed is acting, is a combined effect of high hydraulic potentials and pressure transmission. This finding is based on the fact that mass transfer alone can not explain the huge groundwater exfiltration rates which are necessary in order to generate a flood hydrograph in the frequent case of low hydraulic conductivity.

It should be kept in mind that the physical processes behind this runoff formation concept may be at best gradually but not principally affected by changes in a basin's water availability due to global warming. This fact is somehow encouraging with respect to the urgent need of developing a model tool for assessing runoff formation and runoff components according to the origin and age of water under changing climatic and environmental conditions.

4 Conclusions and future tasks

4.1 General conclusions with respect to ICA

- ICA concepts as proposed here seem to be most suitable for reliable hydrological systems analysis. ICA is not a recent invention, but has been developed over decades, and is best applied to mountain terrain as this has the advantage of steep hydraulic gradients, thus responding spontaneously and distinctly to an input impulse. However, ICA can be successfully applied to low-lying flatlands as well and it seems to be indispensable where hydrological systems are constituents of even more complex environmental systems.

- Environmental and artificial tracers are found to support best the assessment and confirmation of traditional water balances, and the calibration and validation of hydrological basin models.

- A primary motivation for realising ICA in environmental sciences comes from the urgent need to focus on the most relevant system processes which influence system behaviour in a changing environment. A central objective of ICA is therefore the ecohydrological runoff formation process which affects storage and transport behaviour of water and dissolved matter in small basins directly.

- ICA applications should be applied to other ecozones, too, like the sub-polar, boreal or tropical ones with a special emphasis on small mountainous basins. This would also allow better evaluation and prediction of how global warming will influence hydraulic and hydrologic behaviour of these very sensitive environments.

4.2 Specific conclusions with respect to runoff formation

- As a main result of ICA applications, traditional runoff formation concepts need to be revised or at least carefully examined for the study of water and matter fluxes in small-scale environments since they were found to be not hydraulically sound, to mostly underestimate subsurface runoff and therefore groundwater recharge rates, and to overestimate surface runoff.

- Major partial processes of runoff formation are:
  (i) Infiltration with initial saturation and following percolation;
  (ii) Rise of the groundwater table combined with increasing groundwater potential
  (iii) Increase of groundwater exfiltration

  with (ii) and (iii) mainly due to mass transport through pulse pressure transmission.

  As a side effect groundwater table-discharge relationships are hysteretic.

- Preferential flowpaths play a major role in the quick transfer of water and dissolved matter, the study of which being a priority task, since unsaturated zones with important preferential flow involve considerable contamination potential.

- Presumably, impacts of climate change subsuming land-use change on runoff formation are less efficient than on runoff regime. The reason is that the prevailing physical processes that control the hydraulic mechanisms of runoff formation will only gradually change, whereas growth or reduction of water fluxes in space and quantity and their change in source (rain or melt water) and above all their shifts in time of occurrence may alter runoff regimes in small mountainous basins considerably.

4.3 Future priority tasks

As a consequence of these findings, several priority tasks should be considered for future research in this field:

- As already proposed by Herrmann (1997) hydrologic and hydraulic results based on environmental isotopes are an essential contribution to ICA development. However, they still need to be settled on a safer and broader basis covering more (sub-polar, boreal, sub-tropical and tropical) ecozones, thus exceeding the number of approximately 100 basins which have so far been investigated world wide, the majority of which are mountainous. Furthermore, tracer studies need to be combined with geochemical investigations. The following focal activities are suggested in this context above all with respect to complex mountainous hydrological systems:

  (i) Consolidation and extension of actual process knowledge;
  (ii) Extension of the regional variety of studied environments;

(iii) Development of adequate hydraulically-founded algorithms for groundwater dynamics which will satisfy science and practice.

- The existing time series for climatic and hydrological variables in small mountainous study basins are too short to allow proper prediction of ecohydrological climate change effects. On the other hand, fund-raising for their extension is a problem if the experimental sites are not part of a regular national or international monitoring programme.

- The methodical problems associated with extrapolating measuring results or soft information to non-measured, ungauged areas, and upscaling results for medium and large basin scales should be tackled immediately in order to allow, in future, the quick transfer of research results to other areas.

- Relevant partial hydraulic and hydrologic processes should be carefully examined with respect to their sensitivity on changing boundary conditions due to global warming. This would allow more efficient experimental design focusing on the relevant system and sub-system constituents and components respectively.

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The use of hydrological models for socio-economic decisions in view of climate change

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Abstract

This study describes possible impacts of climate change on the hydrological watershed processes in the Swiss Alpine Rhine catchment and illustrates how hydrological models can be used as tools for decision-making processes for policy makers, economists and scientists. Climate change influences the hydrological catchment processes and therefore affects (i) the available water resources for hydraulic electricity production and (ii) the availability of snow for winter tourism. To investigate the impact of climate change on these factors, the distributed, grid-based hydrological Water flow and Balance Simulation Model (WaSiM-ETH) was applied in the Swiss Alpine Rhine catchment (4108 km^2) using (i) observed meteorological ground data for the control run simulation over the period 1981-2000 and (ii) 14 monthly climate change scenarios for precipitation and air temperature (IPCC, 2001) for the climate scenario runs over the period 2081-2100.

Results show a temporal shift in the runoff production, having direct consequences for the storage and release mechanisms of hydropower plants and in-stream hydraulic plants. High runoff values will increase in winter as a result of more liquid precipitation while the available water resources decrease in summer as a result of the smaller building-up of the snowpack. Results show further that the availability of snow will decrease as a result of higher temperatures. The number of days with sufficient snow covering required for skiing during the ski season decreases especially at the lower altitudes. As a consequence also the snow reliability (number of ski seasons with at least 100 days sufficient snow covering) decreases, leading to an upwards shift of snow-guaranteed areas and threatening the existence of lower situated ski-accommodations.

1 Introduction

The increasing concentration of greenhouse gases due to human activities since pre-industrial time lead to global warming and changes in precipitation pattern and other climate variables, which in turn have impacts on the hydrological cycle. Especially sensitive to changes in climate are Alpine and pre-Alpine catchments due to their heterogeneous runoff generation, and processes like the melt and accumulation of snow and glaciers. Several studies estimated an intensification of the water cycle (IPCC, 2001) and changes in the runoff regime (Bronstert et al., 2002; Chiew et al., 2002; Menzel and Bürger, 2002). These changes in hydrology are likely to affect current land and water resources design and management practices (Middelkoop et al., 2001). Hydropower generation is the energy source that is most likely to be impacted because it is sensitive to the amount, timing and geographical pattern of precipitation as well as temperature. In Switzerland, hydraulic plants produce the main part of the electricity production (56.2 % in 2002) from which more than half is generated by water releases from storage reservoirs and about 44% by in-stream hydraulic plants (SFOE, 2002). Most of the hydraulic electricity production occurs during the summer months (June to

September) when runoff volumes are highest while during the months February till April hydraulic energy production reaches its minimum. Switzerland has an electricity export surplus of 7.5 % (averaged over 1997-2002) which is mainly obtained during the summer season resulting in an annual profit of 753 million Swiss Francs (averaged over 1997-2002). More than two thirds of the total electricity production in summer originates from hydraulic plants (reservoir and in-stream) and is therefore dependent on the water supply. Also other electricity production facilities like nuclear power plants depend on sufficient stream water because they require water for cooling purposes. A changing climate might also influence, through hydrological processes like runoff production, the hydraulic electricity supply. It is therefore most important to investigate the possible consequences of a changing climate on the water supply throughout the year.

A second economic branch that might be influenced by climate change is the Swiss tourism sector whose income in winter depends considerably on the ski industry. The regularity and frequency of winters with sufficient snow are crucial factors for the long-term survival of the skiing industry, but also for operators of funiculars, chair-lifts and cableway companies in the Swiss Alps. Besides the tourist-related companies, also a lot of mountain farmers depend on winter tourism as a second source of income. A loss of that income could lead to a non-profitable situation for those farmers with subsequent consequences for mountain agriculture. It is therefore important that impact assessment studies with detailed spatially distributed hydrological models are carried out to estimate future snow volumes and distribution. Tourism representatives can use these results to develop adaptation strategies.

Spatially distributed hydrological models are one of the few tools which are capable and very valuable for evaluation of socio-economic consequences of future climate change. The main aim of this study is not to focus on the direct impacts of climate change on the hydrological catchment processes but to make an attempt to demonstrate the utility of hydrological models to assess the possible consequences for the socio-economic sector.

The Swiss Alpine Rhine catchment has been chosen because of two important reasons. This area is important for the electricity production in Switzerland. For example, 20% of the power stations with a maximum capacity of more than 100 MW are situated in this catchment. This region further locates many ski resorts, which will be affected by changes in reliability of good snow conditions. Runoff volumes and timing were evaluated to estimate the quantity of water available for electricity production and detailed analyses of changes in the frequency and regularity of days and winters with good snow conditions have been carried out in this study.

2 Methods

The hydrological Water flow and balance Simulation Model WaSiM-ETH (Schulla, 1997) has been used to simulate the possible hydrological impact of climate changes and their consequences for hydropower plants and the ski industry. WaSiM-ETH is a fully distributed catchment model using physically based algorithms for describing most of the hydrological processes. The model uses for instance a combination of an infiltration approach (Green and Amt, 1911) with estimation of saturation time according to Peschke (1987) and uses the Richards equation (Richards, 1931; Philip, 1969) for the description of the soil water fluxes in layered soils. The model further uses a temperature index method including measured global radiation (Hock, 1999) for glacier melt and a degree-day method for snowmelt (Fig. 1). Various model applications in Swiss Alpine catchments have shown that the model is capable of simulating all relevant hydrological processes in mountainous catchments (Jasper et al., 2002; Gurtz et al., 2003; Verbunt et al., 2003). An extended overview of model applications and modules can be found in Schulla and Jasper (2000).

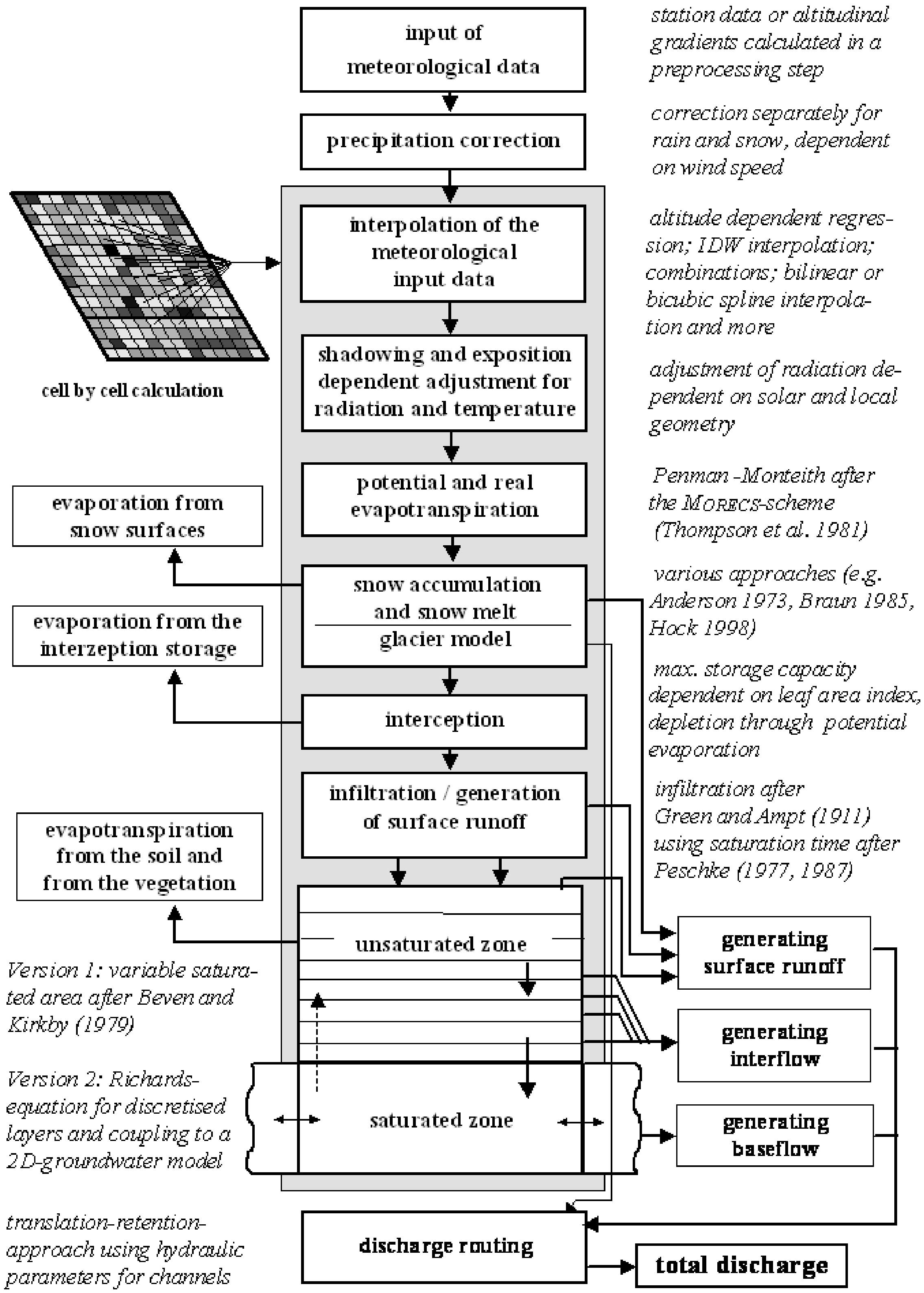

Fig. 1: Model structure of the WaSiM-ETH model (from Schulla and Jasper, 2000)

The model has been applied to the Swiss Alpine Rhine basin (Fig. 2), stretching over an area of 4108 km^2 and located in the eastern part of Switzerland, over the period 1981 to 2000 for the control run using a spatial resolution of 1000 m × 1000 m and an hourly time-step. For analyses in the Landquart catchment the spatial resolution has been reduced to 500×500 m. The altitude ranges from 571 m at the catchment outlet to 3381 m a.s.l. The catchment is mainly covered by low bushes (41%), forest (24%) rock (21%), pastures (11%) and glaciers (2%). For the control run ground observations from automatic stations (hourly data), climate stations (3 data per day) and daily rain gauges from the MeteoSwiss have been used, while for the scenario run these observed data have been altered using 14 different monthly climate change scenarios for precipitation and temperature (IPCC, 2001).

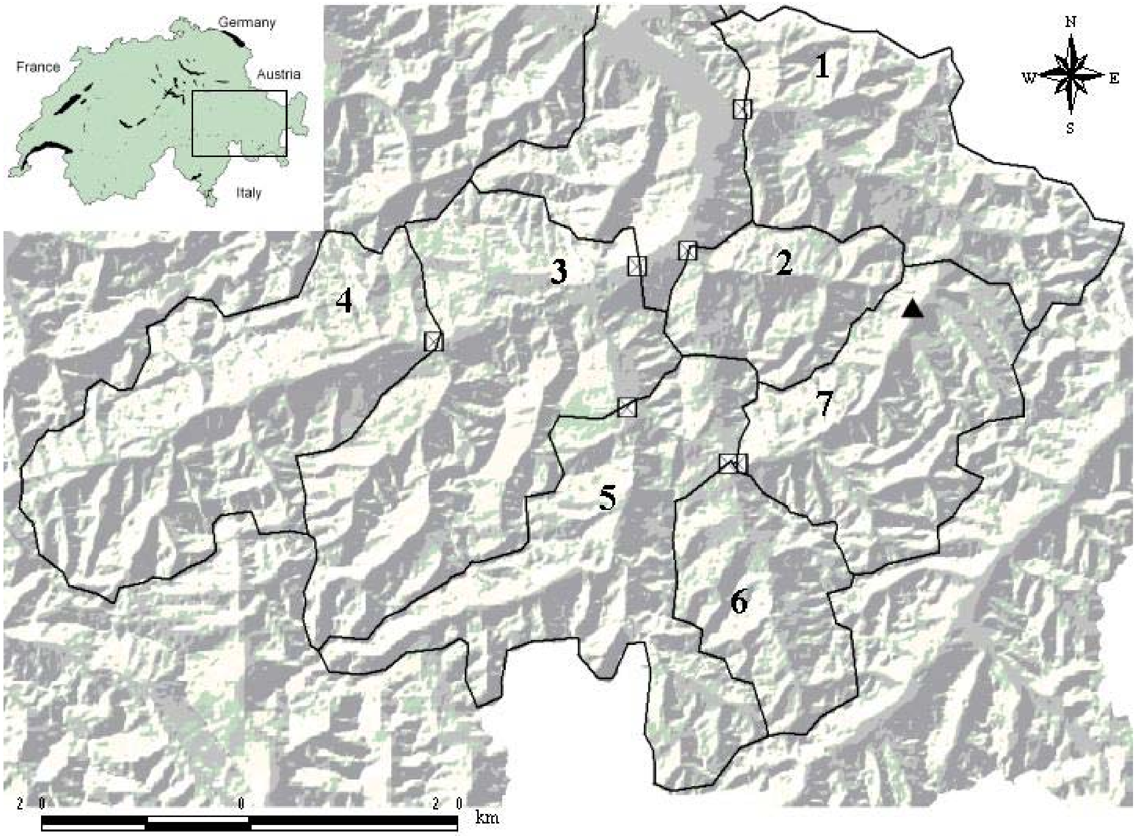

Fig. 2: Location of the Swiss Alpine Rhine basin and its sub-catchments with the snow measurement station Davos (▲) and the catchment gauges (□) 1: Landquart (616 km^2), 2: Plessur(263 km^2), 3: Rhine at Domat-Ems (3229 km^2), 4: Vorderrhein (776 km^2), 5: Hinterrhein (1575 km^2), Julia (325 km^2), 7: Albula (529 km^2)

Figure 3 shows the mean changes in precipitation and air temperature and their standard deviation as obtained from the 14 scenarios. For the hydrological parameterisation and application, the catchment has been divided into seven sub-catchments (Fig. 2). The calibration of the snow melt and accumulation parameters (Schulla and Jasper, 2000) was carried out with the use of snow water equivalent measurements at Davos at 1541 m (Fig. 2) over the period 1982-1984 (Fig. 4). Both the snow accumulation and snow melt agree with the observation in timing and volume. The calibration of the runoff parameters was done by comparing simulated runoff values with the observed ones (according to Nash and Sutcliffe, 1970) and the water balance. Table 1 shows the mean values of the water balance components of the Landquart catchment over 1981-2000 for the calibration and validation run. The mean computed and observed runoff values correspond well with each other and also the efficiencies show that the model is capable of simulating the hydrological processes in good quality.

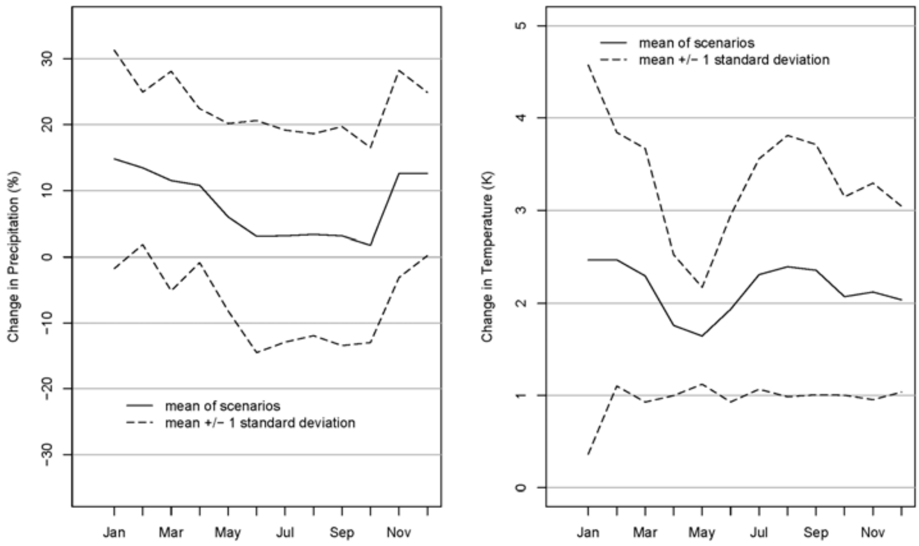

Fig. 3: The mean changes in precipitation and air temperature as projected by the 14 scenarios for the period 2081-2100 (IPCC, 2001) together with their uncertainty

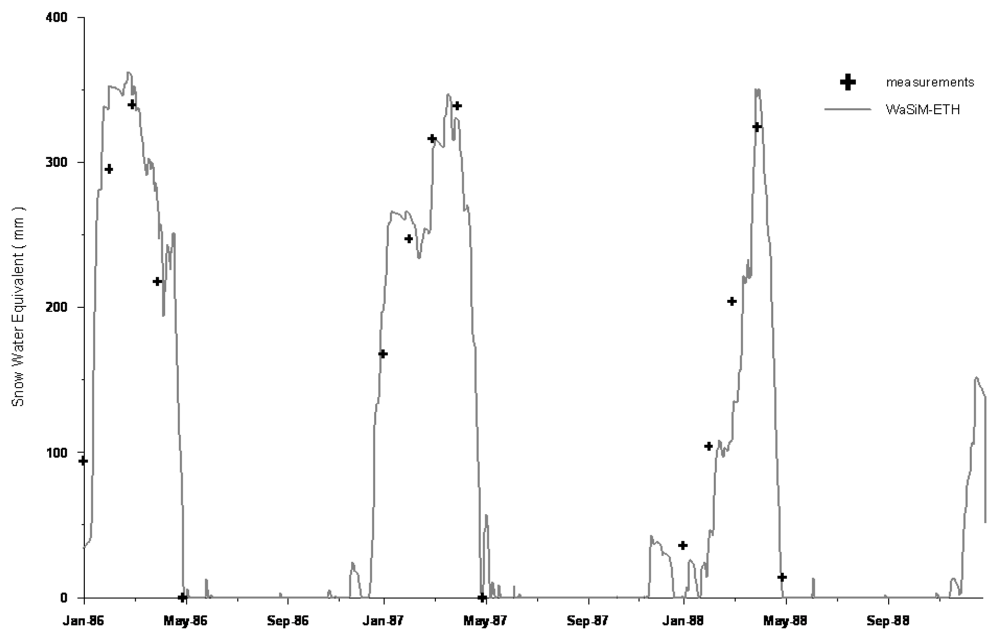

Fig. 4: Calibration of the snow parameters of the WaSiM-ETH using snow water equivalent measurements at Davos (cf. Fig. 2) for the period 1986-1988

For the investigation of the consequences of climate change on ski-resorts and cable-car companies it is assumed that the long-term survival of ski-resorts in Switzerland can be guaranteed, in terms of snow conditions, if at least 70% of the ski seasons (1st December till 15th April) have at least 100 days with good snow condition (Bürki et al., 2003). The same authors assume good ski conditions if at least 30-50 cm of snow depth is available.

Table 1: The mean water balance components in mm and the linear and logarithmic efficiencies in the Landquart catchment during the calibration period (1991-1994) and the validation period (1981-1990, 1995-2000) and the total period (1981-2000) for the control and scenario runs

	Calibration period	Validation period	Control run	Scenarios run
Precipitation	1578	1695	1668	1583
Simulated Runoff	1201	1338	1301	1091
Observed Runoff	1202	1344	1299	-
Evapotranspiration	472	454	458	633
Storage change	-95	-97	-91	-141
R^2_{lin}	0.79	0.75	0.75	-
R^2_{log}	0.81	0.83	0.83	-

3 Results

The comparison of observed and simulated runoff proves the capability of the model to simulate the hydrological processes in this alpine catchment. The underestimation of runoff in summer is caused by the inlet of water from another catchment for electricity production. The runoff distribution over the year alters as a result of climate change (Fig. 5). The hydrological processes in this alpine catchment are dominated by snow accumulation and melt and therefore react very sensitively to temperature changes. Due to higher temperatures, more precipitation falls as rain in winter and consequently runoff generation increases (Fig. 5, left) while less snow is stored (Fig. 5, right). A second reason for higher runoff values in winter is the increase of snowmelt due to more frequent occurrences of hours exceeding the threshold temperature for snow melt. Because runoff in summer and spring is mainly

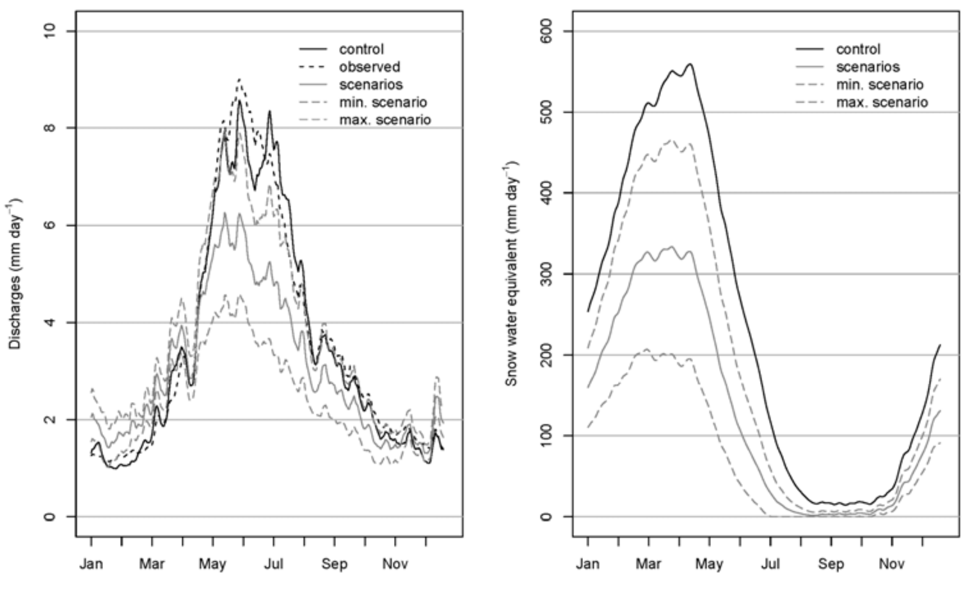

Fig. 5: The change in mean daily runoff and snow water equivalent due to climate change using the 5-day running average to smooth for the Landquart catchment over a period of 20 years

dominated by snowmelt, the above-mentioned decrease of snow accumulation, in combination with higher evapotranspiration values (Table 1), results in a considerable decrease of runoff in summer. Besides a decrease in snow water equivalent, the higher temperatures in winter and spring extend the snow-free period.

The comparison of the frequency distribution of hourly measured and simulated runoff values in Figure 6 also proves the capability of the hydrological model to simulate the runoff regime both in winter and in summer. The occurrences of high runoff values in the scenario runs decrease in summer (Fig. 6, centre) due to the aforementioned changes in snow accumulation. The occurrences of very low runoff values increase as a result of less available snow and higher evapotranspiration values. These two processes result in lower soil moisture values and therefore in an increase of the soil water storage capacity. After a precipitation event more water can then be retained in the soils which results in an increase of occurrences of very low runoff values. In winter, however, an increase of the occurrences of higher runoff values can be noticed (Fig. 6, right) as a result of more snowmelt and rain. The decrease of runoff in summer exceeds the increase in runoff in winter and therefore, especially the high, runoff values over the whole year decrease (Fig. 6, left). This study however uses monthly precipitation and temperature scenarios and therefore does not include possible changes in heavy precipitation events due to a changing climate.

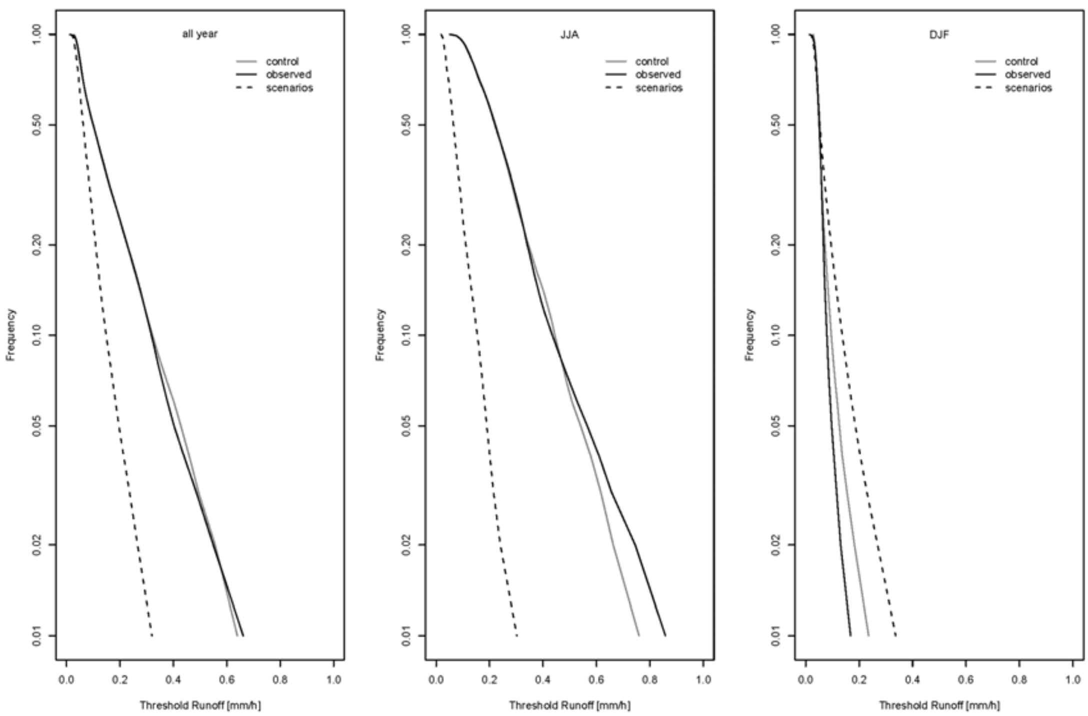

Fig. 6: Relative frequency of hourly runoff exceeding a certain threshold for the observed (black), control run (grey) and scenario run (dashed) for all year (left), June to August (centre) and December to January (right) for the Landquart catchment over a period of 20 years

Due to the climate scenarios the runoff-precipitation ratio in summer decreases especially in the middle altitude zones (Fig. 7) as a result of less available snow and due to higher evapotranspiration values. The runoff-precipitation ratio is defined as the fraction of precipitation generated as runoff in the mentioned period. A value higher than 1.0 indicates that more runoff is produced than precipitation has fallen. This is the case in spring and early summer when accumulated snow starts to melt in the Landquart catchment. As a consequence of this increased evapotranspiration, soil moisture values decrease which increases the soil moisture storage capacity and consequently decreases runoff generation. In contrast to the summer season the runoff-precipitation ratio increases in winter as a result of more snowmelt and less solid precipitation. From these figures estimates for the water quantity and timing can be made which is important information for hydropower plants. The results in changes of the precipitation-runoff ratio could contribute to the development of new release and storage mechanisms for reservoirs adapted to future climate.

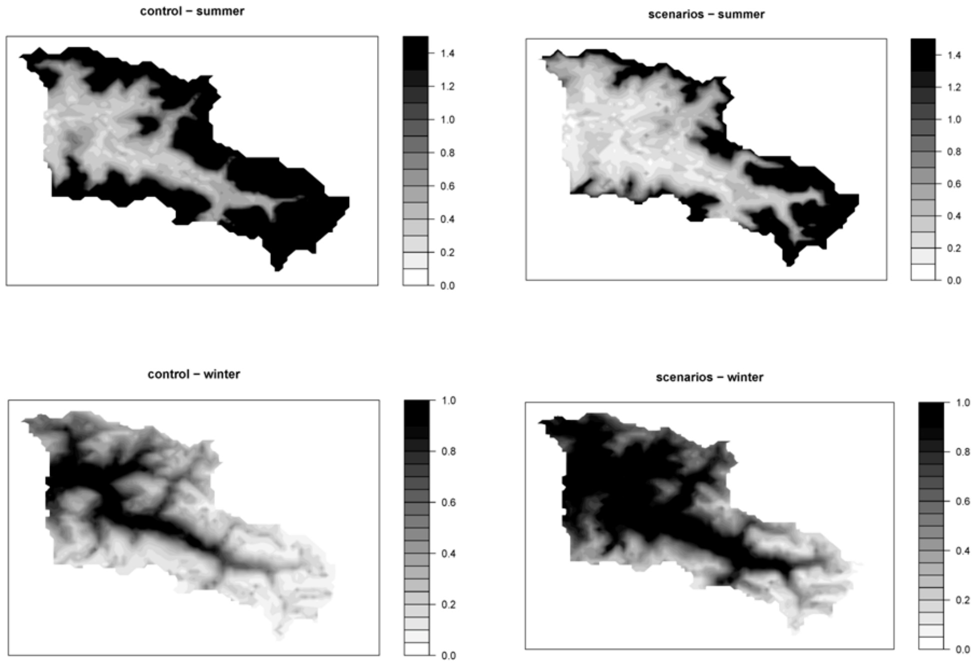

Fig. 7: The spatial distribution of the runoff-precipitation ratio in the Landquart catchment over a period of 20 years. Control run (left), scenario run (right), summer (upper) and winter (bottom)

The storage change (precipitation minus evapotranspiration minus runoff) in summer (June-August) is, especially in the middle and higher elevation zones, strongly negative in the control run (Fig. 8, upper left). Snow which has been stored during winter melts in spring and summer. In the lower areas, where the runoff generation is based on precipitation events because snow has already melted away before the beginning of summer, the storage change is only slightly negative. The storage change in the scenario runs shows a less negative storage change in summer (Fig. 8, upper right), despite an increase in evapotranspiration, indicating that, apart from the upper elevation zones, most snow has already melted away before the beginning of June. These results clearly illustrate the decrease in water volume available for hydraulic electricity production in summer. During the winter months (December-February) water is accumulated in most parts of the catchment in the control run (Fig. 8, bottom left). Evapotranspiration values are very low because of an extended snow cover and low air temperatures. Negative air temperatures further cause solid precipitation and therefore no immediate runoff generation. Only in the lowest altitudes where temperatures exceed the threshold temperature for snowmelt and liquid precipitation, is the storage change negative. The results of the climate scenarios show that the storage change is in larger part negative as a result of more liquid precipitation and snowmelt and secondary by a small increase in evapotranspiration. This increase in evapotranspiration is caused by (i) higher air temperatures and (ii) by an earlier snow-free surface which increases the energy for evapotranspiration because of lower albedo values. The figures clearly demonstrate the increase in water supply for hydraulic electricity production in winter. The results can be used to develop new release and storage mechanisms adapted to the shift in water supply over the year.

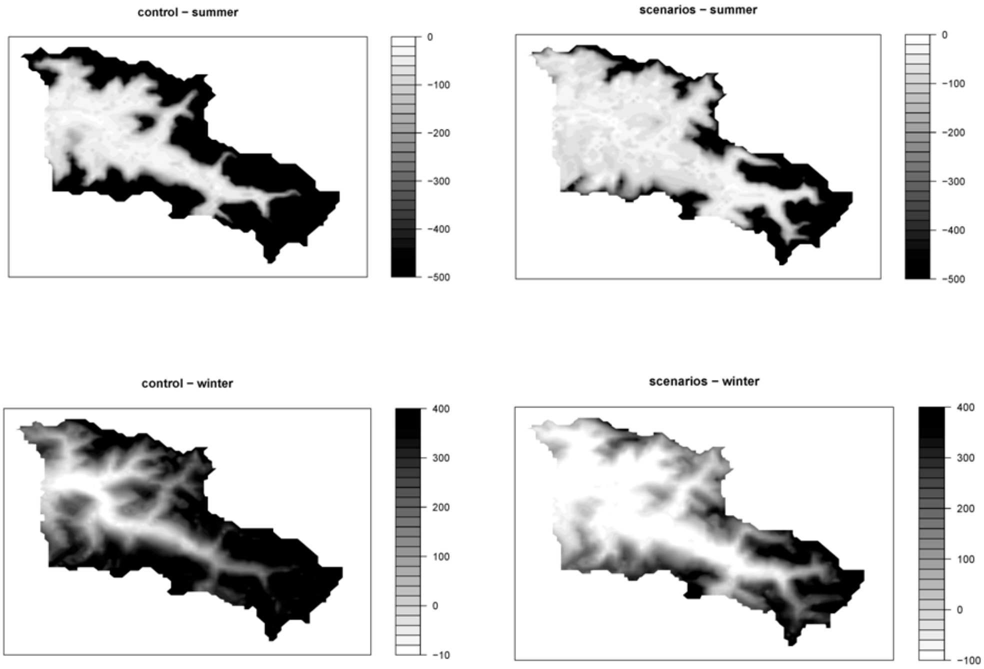

Fig. 8: The spatial distribution of the mean storage change (precipitation minus runoff minus evapotranspiration) in the Landquart catchment over a period of 20 years. Control run (left), scenario run (right), summer (upper) and winter (bottom)

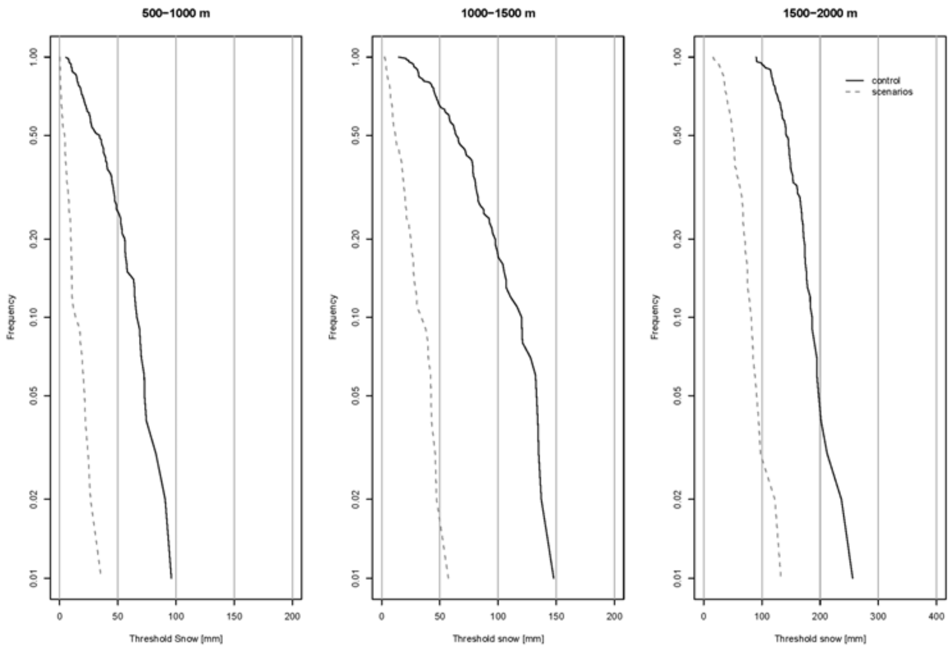

Fig. 9: The relative frequency of the mean snow water equivalent in February in the Swiss Alpine Rhine catchment exceeding a certain threshold over a period of 20 years. Control run (1981-2000; solid line) and scenario run (2081-2100; dashed line)

The relative frequency of snow water equivalent exceeding a certain threshold for the Domat-Ems catchment in February clearly decreases as a result of higher temperatures. For the 500-1000 m zone, for example, the frequency of a negligible monthly amount of snow (< 5 mm) in February increases from almost zero to about 50% (Fig. 9, left). This means that the snow guarantee strongly decreases in the areas below 1000 m as a result of climate change. The same behaviour can be seen in the altitude zone from 1000 to 1500 m asl. Above 1500 m the decrease (in mm) is about the same for all frequencies indicating that the possibility of a mean snow water equivalent which equals zero is negligible even with the use of climate change scenarios. However, in this zone the decrease in the minimum mean monthly amount is largest, thus threatening the snow guarantee in some parts of this altitude zone.

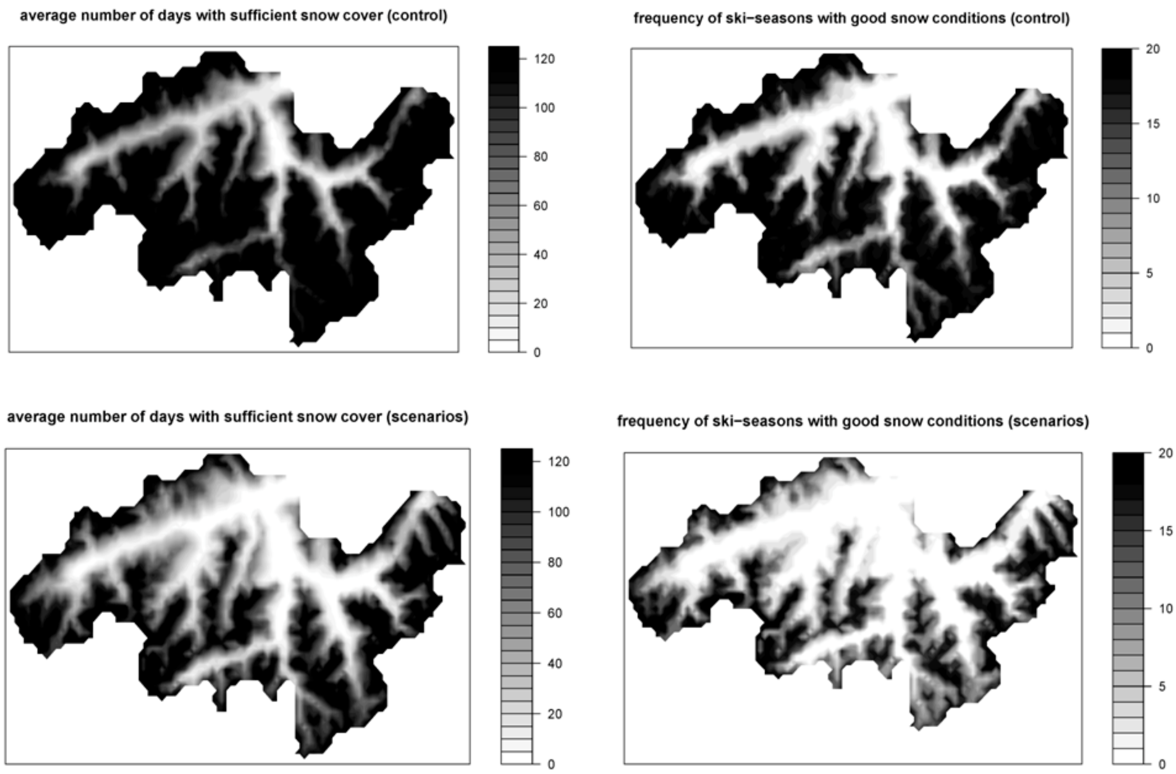

Fig. 10: The change in the spatial distribution of the number of days with sufficient snow cover (more than 50 cm) during the ski season (1 December till 15 April) (left), the spatially distributed change in frequency of ski seasons with sufficient days (more than 100) with sufficient snow (right) in the Swiss Alpine Rhine catchment for the control run (1981-2000) (top) and the scenario run (2081-2100) (bottom)

Figure 10 shows the spatial distribution of days with sufficient snow for skiing and the number of seasons with at least 100 days with good snow conditions in the Swiss Alpine Rhine catchment (Fig. 2). Good snow conditions for skiing are assumed when the snow cover is at least 50 cm and the long-term survival of ski resorts in Switzerland can be guaranteed if at least 70% of the ski seasons have at least 100 days with the above-mentioned good snow conditions (Bürki et al., 2003). Higher temperatures cause the number of days with sufficient snow for skiing to decrease considerably. The frequency of ski seasons with more than 100 days with good snow conditions declines, especially in the mid-altitudes, even more. From these figures the information for each altitude has been derived (Fig. 11), demonstrating that currently on average on 100 days there are snow conditions (30 cm and 50 cm) at altitudes of approximately 1625 m and 1750 m respectively, while with the use of climate change scenarios these altitudes increase to 2150 m and 2300 m respectively. This demonstrates an upward shift of about 500 altitude meters. Also the altitude where 70% of the seasons (14) have at least 100 days with good snow conditions (30 cm and 50 cm) increases from 1700 m and 1850 m respectively to 2200 m and 2400 m asl respectively. This represents an upward shift of approximately 500 meters for the long-term survival of ski resorts (according to snow conditions). From these model results it can be concluded that it will be necessary for the lower situated ski resorts especially to develop adaptation strategies for possible consequences of future climate change.

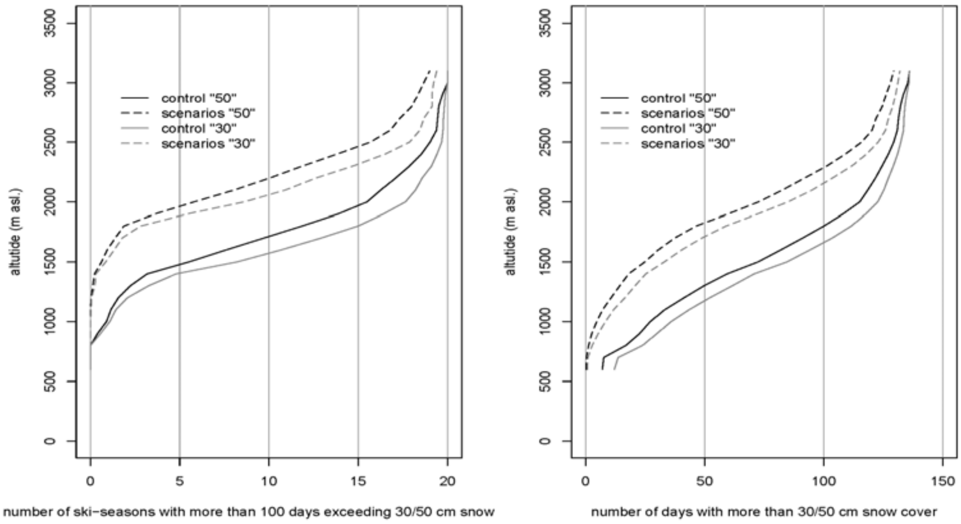

Fig. 11: The altitudinal distribution of the number of ski seasons with more than 100 days exceeding 30 cm (grey) and 50 cm (black) snow (left) and the average number of days in a ski season with at least 30 cm and 50 cm for the control run (1981-2000, solid) and the scenario run (2081-2100, dashed)

4 Discussion

This study investigated the possible consequences of climate change with the use of a spatially distributed hydrological model and demonstrated how these results can be used for socio-economic decisions and adaptation strategies. From the results it can be stated that:

- The annual hydrological water balance will undergo considerable changes. Precipitation slightly decreases because of a decrease in maximum precipitation during the summer months. Evapotranspiration shows a large increase assuming no change in the stomata resistance. This can be explained by the extended snow-free period and higher air temperatures, which positively affect the evapotranspiration rate. As a result of less precipitation and higher evapotranspiration values, annual runoff decreases. Furthermore, the amount of solid precipitation decreases and consequently less precipitation is stored as snow. This, in combination with higher evapotranspiration values, accelerates the water cycle in this Alpine catchment.
- The change in the water cycle also affects the hydraulic electricity production in this Alpine region. In winter more rain instead of snow consequently results in an increase in runoff production. Storage reservoirs can fill up more rapidly or release more water in winter compared to the current hydrologic regime and in-stream hydraulic plants can also

profit from more runoff during the winter months. Currently, runoff generation and hydraulic electricity production are highest in summer, mainly as a result of snow melt. The summer electricity production in Switzerland exceeds the domestic electricity demand which results in a net electricity export to the surrounding countries. This, however, could change in future as a result of a temporal shift in water supply. Model results show a drastic decrease of runoff in summer as a consequence of less building-up of the snowpack during the winter months and higher evapotranspiration values. This will lead to a decrease in summer electricity production of in-stream hydraulic plants. This shift in runoff supply will also force the release and storage mechanisms of reservoirs to be adapted to the new situation. In addition, higher air temperatures in summer will cause an increase in energy and water demand. The first is, for example, caused by more air-conditioning systems in offices and houses. More domestic energy consumption in combination with a decrease of electricity production will have consequences for the aforementioned electricity export in summer. A possible consequence could be an increase in the use of other electricity generating facilities like nuclear and conventional thermal power plants. These facilities, however, require water for cooling purposes and less river water in combination with higher water temperatures could limit their production.

- Besides consequences for the energy sector, climate change could substantially impact winter tourism in Alpine areas. Model results show not only a decrease in days with good snow condition for skiing purposes but also a decrease in the frequency of snow-reliable ski seasons. The altitude which guarantees, in the view of snow conditions, the long-term survival of ski resorts shifts upwards by approximately 500 meters. This will force ski resorts, cable-car companies and also tourist offices in general to be aware of these possible consequences and to develop adaptation strategies. The results of hydrological models are of great use for this and should therefore be incorporated when making these adaptation strategies.
- The relatively high uncertainty of the climate change scenarios is no reason to neglect possible consequences. Continuous improvements are made in the physics of the Global Circulation Models (GCMs) and Regional Climate Models (RCMs) which generate the climate change scenarios. It is, however, important that the societies and decision-makers are aware of these model uncertainties. Therefore, it is important that a range of scenarios is used for the hydrological assessment study in order to cover all possible outcomes.
- Not only hydrologic factors like water supply and snow availability will influence the tourism and energy sector in Switzerland. When making strategies or when taking long-term decisions it is, however, recommended to consider these changes in hydrology. For this purpose it is important to have spatially distributed hydrological models which have proved their capabilities in the area to be investigated. The development of the hydrological models should be adjusted with the needs of the decision-makers and the industries concerned. If necessary, local assessment studies can be carried out with a more detailed grid resolution to evaluate the socio-economic consequences of a changing climate.

5 Conclusion

From the results of this study it can be concluded that climate change will impact the hydrological processes in the Swiss Alpine Rhine catchment. Snow accumulation and melt and consequently the runoff generation react very sensitively to changes in temperatures and therefore a small increase in air temperature can result in large changes. The impact of climate change may not be neglected in this sensitive area and impact studies need to be carried out. This study further showed that spatially distributed hydrological models are very useful tools for climate impact assessment studies also for those with a socio-economic background. Water supply for hydraulic electricity production will change and winter tourism could be jeopardised due to less snow reliability. In the process of adaptation strategies it is therefore recommended that the results of hydrological models be considered. To adjust hydrological models to the needs of the industries and authorities concerned, a good and open communication between scientists and industry and authorities is desirable.

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Mountain hydrology research in Slovakia

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Abstract

This paper gives an overview of research projects devoted in the last years to mountain hydrology in Slovakia. Experimental mountain hydrology research, i.e. research based on field data collected in specifically equipped catchments or plots is performed only by a few research units. Most projects are devoted to theoretical research, i.e. the research based mostly on the data from the standard observation networks. The projects are typically covered by governmental funding through grant agencies or the end users (ministries, operationally oriented institutes).

The main research issues in mountain hydrology in Slovakia in recent years have been assessment of the impact of climate change on hydrological processes and water resources management, rainfall-runoff relationship including process studies and flood protection, regionalisation and water quality. Climate-change impact studies were focused on the analysis of data time series, preparation of climate change scenarios, estimation of impacts in hydrology and water management, and proposal of basic adaptation strategies. Research of rainfall-runoff relationship covered runoff formation, occurrence and analysis of the climatic and hydrological situation during floods, assessment of new rainfall design values, role of forest and groundwater storage during floods, and hydraulic research of the rivers.

Regionalisation concentrated on methods of determination of homogenous regions and calculation of hydrological characteristics for individual regions. Water quality research comprised a wide range of studies devoted to stream water quality and balance of nutrients in the hydrological cycle. It is expected that hydrological extremes including flood protection, assessment of climate change impacts and regionalisation will remain the most important issues of mountain hydrological research in Slovakia also in the future. However, the role of evapotranspiration, soils and seasonal snow cover in the hydrological cycle of mountain environment should also be targeted. The role of continuing monitoring, possibly in the updated observation networks, should also not be forgotten.

1 Introduction

Slovakia is a mountainous country. Lowlands (with elevations of up to 300 m a.s.l.) cover just 22% of the country. From this point of view, almost all the hydrological research in Slovakia is performed in the mountainous environment (Fig. 1).

Experimental hydrological research, i.e. the research using the data from the specifically equipped mountain catchment is performed only at the Institute of Hydrology SAS. Extended monitoring of mountain environment in the High Tatras, i.e. the highest part of the Carpathians, which covers also climatic monitoring, is carried out by the High Tatras National Park Research Station. Other few experimental sites providing data on hydrological processes related to forest hydrology are maintained by the Faculty of Forestry of the Technical University Zvolen.

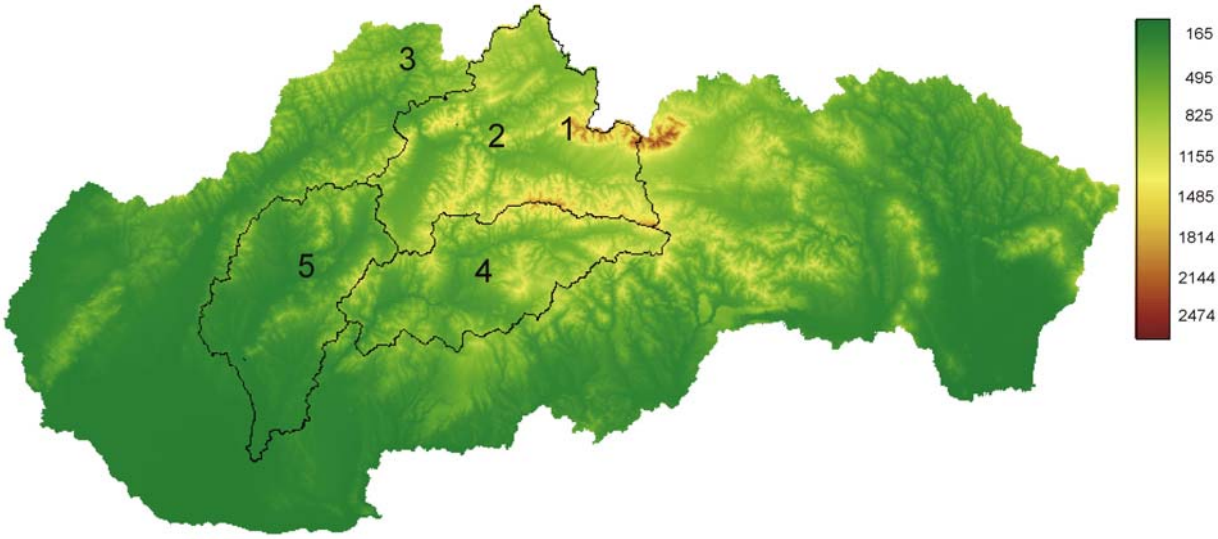


Fig. 1: DEM of Slovakia and the parts of river basins where most mountain hydrology research took place: 1-the Jalovecky creek catchment, 2-Vah; 3-Kysuca, 4-Hron, 5-Nitra

Theoretical research using standard data, i.e. the data collected in the standard networks of the hydrometeorological service, maps etc., sometimes extended by field campaigns, is performed at the Academy of Sciences (Institute of Hydrology, partially also Geographical Institute), universities (Slovak Technical University and Comenius University in Bratislava, Agricultural University in Nitra, Technical University in Zvolen) and other institutes (Slovak Hydrometeorological Institute, Water Management Institute).

An important fact that affected hydrological research in Slovakia was the transition from the former state-planned research to today's grant system that has led to a more competitive environment with higher responsibility for smaller research teams or even individuals. On the other hand, it has caused the atomisation of research.

Most of the recent projects in the field of mountain hydrology in Slovakia have been devoted to the assessment of climate change impacts on hydrology and water management, rainfall-runoff relationships including floods and regionalisation. Other research projects have dealt with snow hydrology, evapotranspiration, water quality, river morphology and sediment transport including hydrobiological issues. The projects were typically supported by governmental funding, either by grant agencies or by the end users represented by ministries or operationally oriented institutes like the Slovak Hydrometeorological Institute and the Water Management Institute. These research projects are listed at http://www.vega.sav.sk and http://www.apvt.gov.sk. Relatively few research projects have been carried out as part of international projects.

The aim of this paper is to give an overview of recent research projects devoted to mountain hydrology in Slovakia. The paper is based on the national report to IAHS (Szolgay, 2003) and the state-of-the-art report on surface hydrology in Slovakia (Miklánek, 2003). Instead of providing a detailed description of all the projects and their results, we have concentrated on the main issues.

2 Main research issues in mountain hydrology in Slovakia

2.1 Impact of climate change on hydrological processes and water resources management

The expected impact of climate change in general, vulnerability assessment and adaptation measures for Slovakia were summarised in the Third National Communication on Climate Change (2001). An overview of impacts on climate-related sectors was given by Lapin *et al.* (2002); hydrological impacts were reviewed by Majerčáková (1999, 2000).

Generally, the research projects addressed the following issues:

- Analysis of time series of precipitation, runoff, groundwater regime (groundwater runoff, spring yields) and evapotranspiration data with the aim of detecting climate change signals;
- Preparation of several analogous, incremental and GCM (General Circulation Model) based climate change scenarios for the 2010, 2030 and 2075 time horizons (monthly and annual time series of air temperature, precipitation and air humidity); preparation of scenarios of extreme monthly and daily precipitation totals for selected time horizons (2010, 2030, 2075);
- Estimation of climate change impacts on the mean annual flow, mean monthly flow, yields of the main water reservoirs and changes in the hydrological regime including snow cover in mountains;
- Proposal of basic strategies for the adaptation processes in water resources management to deal with climate change impacts.

Times series analyses revealed decreasing trends in groundwater runoff and spring yields (e.g. Fendeková, 2000) and time shift in the occurrence of runoff extremes (Pekárová and Pekár, 2000). The analysis of historical floods (Halmová, 2001) indicated an increased extremality of the flood regime in some regions (Pekárová and Miklánek, 2001). Climate scenarios (e.g. Lapin et al., 2000) expect significant increases of annual air temperature (2-4˚C), small changes in the long-term precipitation totals and significant increases of short-term precipitation extremes by 20-50%. According to modelling exercises such a climate would lead to the increase of winter flows and decrease of spring and summer flows (e.g. Hlavčová et al., 2000). The increase of winter flows and decrease of spring flows are connected with changes of seasonal snowpack. Seasonal snowpack would be one of the most seriously affected components of the hydrological cycle (Kostka and Holko, 2000). The duration of the snowpack in the mountains could be as much as one month shorter. Maximum snow-water equivalent during winter seasons could reach only one half of its present values. Even in the highest mountains the more pronounced seasonal snowpack as measured by the value of the snow-water equivalent would last for longer periods only in the high elevations (Fig. 2). Generally, it is expected that the climate change would affect the northern part of Slovakia less than its southern part. Nevertheless, the whole country could become more vulnerable to drought in the summer and autumn. Water available in reservoirs could cover just 65-90% of present maximum withdrawal. Simulated effects of the land-use change in natural mountain catchments caused solely by the change of climate should not be so pronounced as the anticipated effects the climate change itself (Kostka and Holko, 2001).

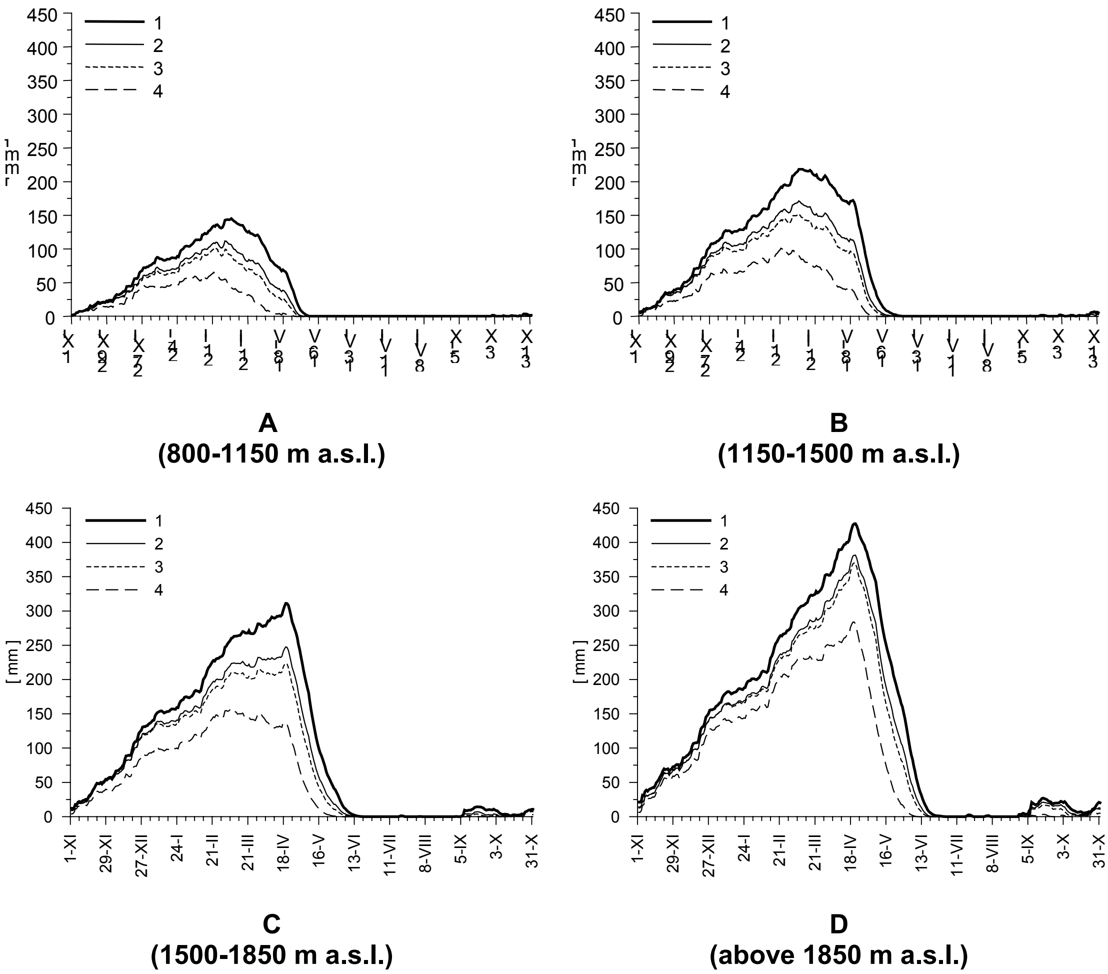


Fig. 2: Mean daily values of snow-water equivalent [mm] simulated for the small mountain catchment of the Jalovecky creek and elevation zones 800-1150 m (A), 1150-1500 m (B), 1500-1850 m (C) and above 1850 m (D). Simulation according to present climatic conditions (1) and climate scenarios CCCM 2010 (2), CCCM 2030 (3) and CCCM 2075 (4) (from Kostka and Holko 2000)

The main objective of the climate change related research is the application of knowledge in the formulation of adaptation strategies. The basic adaptation strategies proposed in Slovakia include the transformation of natural hydrologic resources into managed resources, interannual and seasonal redistribution of water, revitalisation of watersheds, afforestation and forest protection (e.g. Szolgay and Hlavčová, 2000; Szolgay et al., 2002). The following tools should be used:

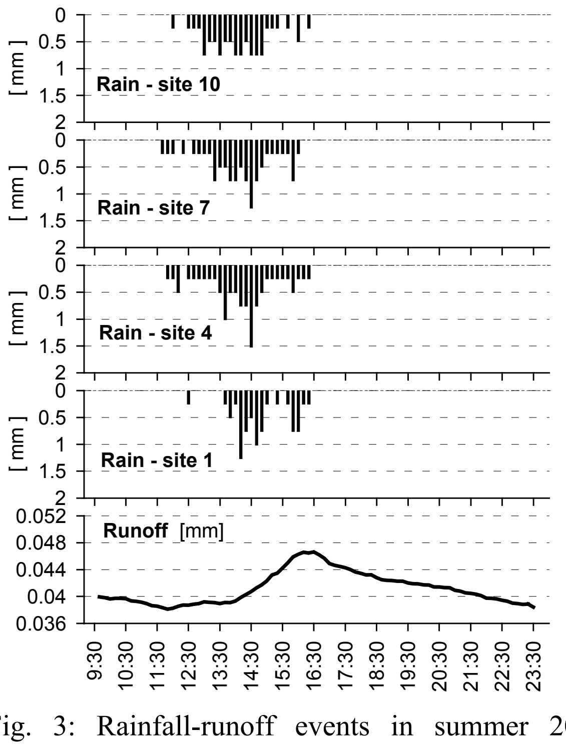
- Direct measures to control water consumption, e.g. reduction of specific consumption of drinking water by means of technical measures, decrease of water losses, utilisation of non-drinking water for specific purposes, etc.;
- Indirect measures influencing the behaviour of water consumers: subventions, taxes and charges in water management, better information of the population about possible climate change impacts, improved attitude of population to water sources;
- Institutional change leading to a more effective water use: full implementation of the new environmental legislation in the area of water management, implementation of the results of climate change research in strategic concepts of water management, municipal and land use planning, etc.;

- Improvement of operation of existing water management systems: optimisation of water management and water supply systems as a whole, inventory of operation of existing water reservoirs and thorough professional discussion about construction of the new reservoirs, strengthening of hydrological processes monitoring in smaller catchments, realisation of measures that have areal effects on the rainfall-runoff relationship in the country.

2.2 Rainfall-runoff relationship

The rainfall-runoff relationship is the central topic of hydrological research in Slovakia. It can be studied from various points of view like the estimation of areal precipitation in catchments, runoff formation, occurrence and causes of extreme events like floods. The practical aspect like flood protection, which originally initiated the research in this field, is still an important target.

The long-term experimental research of mountain hydrology is performed only by the Institute of Hydrology SAS. The research is carried out in the mountain catchment of the Jalovecky creek in the Western Tatra Mountains, with an area of 22.2 km^2, mean elevation of 1500 m a.s.l. and mean slope 30º. Hydrological research in the catchment that started at the end of 1980s was devoted to the areal distribution of precipitation, transpiration and evapotranspiration measurement and modelling, soil moisture distribution, snow hydrology and runoff formation. The reaction of catchment runoff to rainfall is very fast (Fig. 3). However, runoff separations showed that the pre-event component was often the dominant component of runoff measured at the catchment outlet. The overland flow was not found to be very frequent in this mountain catchment.



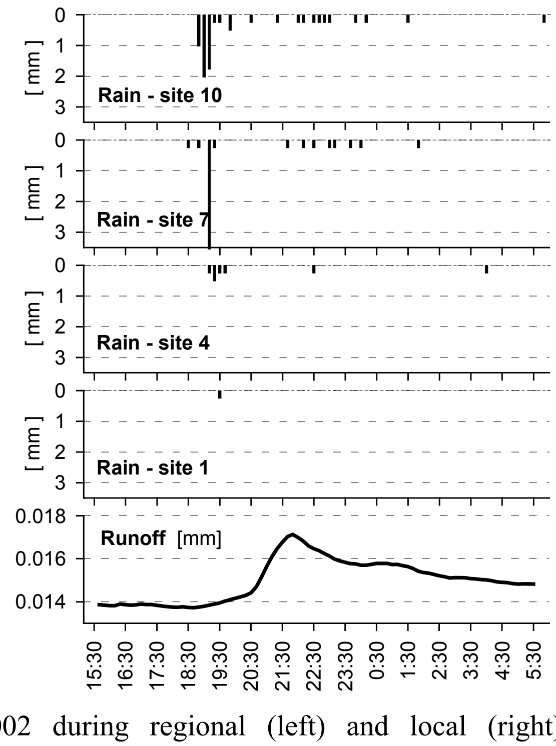


Fig. 3: Rainfall-runoff events in summer 2002 during regional (left) and local (right) precipitation. Time step of measurement: 10 minutes; locations of rainfall observation sites: 1 - catchment outlet, 4 and 7; catchment mean elevation (1500 m a.s.l.) in the south-western and north-western parts and 10-1900 m a.s.l. in the northern part (Kostka and Holko, 2003)

Rainfall amount seems to be the primary factor influencing the reaction of the Jalovecky creek catchment runoff during the warm period of the year. This factor was superior to other factors taken into account like the soil moisture before the event. Rainfall-runoff data indicate that the increase of discharge often did not occur unless certain value of "effective" rainfall was exceeded (Kostka and Holko, 2003).

Majerčáková (2000) noted that the last years indicated partially increased extremality of runoff conditions in Slovakia. Mean values for the large river basins did not differ from the long-term values. However, quite a number of regional and flash floods occurred. On the other hand, long-term droughts were observed. Flash floods caused by extremely intensive rainfall that have occurred recently in Slovakia were investigated individually. The formation of floods in ungauged basins was reconstructed using data from the on-site hydrological survey, data available from the standard hydrological and meteorological networks and radar and satellite data (Majerčáková and Škoda, 1998; Šťastný and Majerčáková, 2003). The occurrence of flash floods in Slovakia in 1997-2002 along with the analysis of catchment characteristics was studied by Grešková (2003).

A number of studies with the data taken from standard networks or field campaigns were performed in mountain parts of the rivers Hron, Kysuca, Nitra and Vah. Lapin et al. (2001) and Šťastný et al. (2001) analysed weather conditions accompanying floods in the upper Hron catchment. Analysis of annual and seasonal maxima of one to five-day rainfall depths in the same catchment lead to the new design rainfall (e.g. Stehlová et al., 2001; Jurčová et al., 2002). Although the number of statistically acceptable distribution functions was found to be rather high, the resulting design rainfall values estimated from the distribution functions did not exhibit significant differences. Part of the above work was done within the project "Investigation of the anthropogenic factors effect on water systems" coordinated by the Water Research Institute in Bratislava. The project was initiated by the Ministry of Agriculture after the floods which occurred in Central Europe in 1997. One of the objectives of the project was flood protection research in selected catchments. The research was focused on a number of issues: inventory of current flood protection measures, dynamics of floods in small streams and rivers, rainfall-runoff relationship and possible influence of climate change on the design values, influence of vegetation on runoff regime (runoff coefficient, temporal characteristics of the flood), management of mountain streams and its influence on catchment runoff characteristics, increase of retention capacity of groundwater storage, analysis of economical and ecological values of the inundation area and its protection against floods, design of protection measures based on computations of water levels during big floods, simulation of dynamics of floods on the tributaries of the main rivers, assessment of effects of water reservoirs and old river channels during floods, design discharge values for selected profiles (Holubec, 2003). The Hron river and the Kysuca river catchments were selected as study areas. An overview of final results and proposals for future research are available at http://www.vuvh.sk/projekty/27-34/27-34.html. The project brought many interesting results. Čaboun (2003) presented the results on the influence of forest on runoff and proposed suitable management practices. Valtýni and Závacká (2003) reported on the role of small structures on mountain streams in flood protection. They documented that low dams (0.3 m high) on mountain streams could decrease culmination discharge by 10-15%. Numerical simulation of river hydraulics for the purpose of flood protection of selected cities and villages, and research of the role of old river channels in flood transformation was carried out by a number of authors (e.g. Mišík and Lukáč, 2003; Matok, 2003). Kovalčík (2003) analysed potential conflicts between technical measures and environmental interests in selected catchments. Petrovič (2003, 2003a) reported on the possibilities of utilisation of radar data and evaluated the application of LIDAR data in the flood risk assessment. Žilavý (2003) analysed the role of polders in flood protection of morphologically different environments.

The relationship between surface water and groundwater has been a research objective in recent years. Fendeková and Fendek (2002) used stochastic modelling for the estimation of the relationship between surface waters and groundwater in the weathered zone of granitic rocks in the High Tatra Mountains, where very quick runoff and an immediate reaction of groundwater on external inputs were observed. Baranovičová (2003, 2003a) studied the possibility of increase of retention capacity of groundwater storage in the Hron and Kysuca river basins and the relationship between surface water and groundwater during the flood.

In other projects, various risks associated with flooding were characterised by simple relations based on informative numerical values deduced from the actual conditions of the Slovak Republic. Reduction of the flood risks achievable by geotechnical measures covering stability increases in embankments, transport communications and buildings was suggested by Hulla (2002).

2.3 Regionalisation

One of the tasks of operational hydrology is to provide end users with various hydrological characteristics. Because the characteristics are often needed for ungauged basins, regionalisation remains an important research issue with clear practical outputs. An overview of hydrological and hydrogeographical typification and regionalisation in Slovakia was given by Kohnová and Solín (2002). Hanušin (2003) presented regional classification of runoff regime. A recent compilation of an extensive database of the physiographic characteristics of small basins in Slovakia (Solín et al., 2000) enabled the new hydrogeographical regional classification of Slovakia. Six regional types of minimum and mean annual runoff regimes were identified using the mean annual precipitation and mean altitude of the basins as differentiating factors (Solín and Grešková, 2000; Solín and Cebecauer, 2001). Other studies applied statistical methods (Hosking and Wallis, regional frequency analysis, cluster analysis) in the analysis of runoff and precipitation data (e.g. Kohnová and Szolgay, 2001; Solín, 2002). Various physiographic properties of basins, rainfall and flood runoff characteristics were used as factors for the differentiation of homogeneous regions and regional types (pooling groups). Several methods for the definition of homogeneous regions and regional types were tested. Aspects under which the concept of regional homogeneity can be used in regional frequency analysis of floods and extreme rainfall under the rather heterogeneous runoff generating conditions in Slovakia were studied and discussed (Kohnová et al., 2000). The results of the last works showed that different combinations of independent variables can provide statistically comparable results. The authors suggested that the idea of geographical regions may be abandoned.

3 Water quality

The studies were focused on the impact of land use on stream water quality, balance of nitrates in the water cycle, variability of suspended sediment loads, modelling of pollutants loads, influence of water from urbanised areas on the quality of river water, identification of the main sources of diffuse pollution and management of water quality in the Vah, Hron and Nitra river catchments.

The results of the water quality research in the experimental basins of the Institute of Hydrology of the Slovak Academy of Sciences were summarised in a monograph by Pekárová et al. (1999). Empirical exponential relationships were derived for the estimation of monthly nitrate concentrations and nitrate loads in small basins. The nitrate balance, defined as the difference between input by atmospheric water (precipitation) and output of the basin (runoff), showed typically positive values in the agricultural basin, while negative values were found in a forested basin. These results indicate that the forested basins may have purifying effects on surface water (Koníček and Stančík, 1999). The data on insoluble matter concentrations during diverse runoff events were used to derive empirical relationships between insoluble matter concentrations and specific yields (Bača, 2002).

Dian (2003) presented the methodology of the assessment of point source pollution of river water and the results of nutrients balance for several profiles on the river Hron. He also proposed the strategy of nutrients management in the catchment. Földešová and Výboch (2003) analysed sources of pollution in the upper Nitra river catchment. Hiller (2003) studied the transport of contaminants in the soil-water system. Kútnik and Baranovičová (2003) used simple runoff separation to determine the influence of diffuse pollution sources on river water quality. Their results showed that 60-80% of river water pollution came from diffuse sources. Luther (2003) analysed the effect of water treatment plants on the improvement of river water quality. He noted that municipal sewerage played a key role in the nutrients pollution of the river Hron. Sokáč (2003) described a mathematical model of river water quality. Weigeltová (2003) analysed eutrophication of the rivers Hron and Nitra. Lichner et al. (2002) reported on the system for the monitoring and early warning of water pollution that is being developed within the framework of the EC's 5th Framework Programme Project.

Long-term research of the water quality of mountain lakes in the Tatra mountains is being carried out by Czech scientists (e.g. Kopáček et al., 2000, 2001). The ecosystem of Central Europe experienced a large "experiment" connected with the drastic reduction of emissions during the 1990s in parts of Germany, Poland, Czech Republic and Slovakia (e.g. 80% and 30% reductions of S and N emissions, respectively). Parallel decreases in deposition rates of SO_4, nitrate (NO_3) and ammonium (NH_4) have resulted in a relatively rapid improvement of water quality in acidified mountain lakes.

4 Future development

It is not easy to predict the development of society and its activities including research. However, it can be expected that the following issues will be the most important targets of hydrological research in Slovakia in the near future:

- Hydrological extremes - understanding the generation of floods and droughts, statistical treatment of existing data series, modelling and predictions;
- Impacts of climate and land-use changes - scenarios of hydrological behaviour, simulation of probable impacts;
- Regionalisation - application of advanced methods (e.g. rainfall-runoff modelling in small catchments) to estimate hydrological characteristics for operational hydrology.

In January 2000, the Slovak government approved the programme of flood protection of Slovakia until 2010 (project POVAPSYS). Although most funds were allocated to concrete technical measures, a number of research projects should be supported to provide the knowledge necessary to mitigate the negative effects of floods. Nine partial research sub-projects, which will be co-ordinated by various institutes, were approved:

- Hydrological and climatic aspects of floods
- Rainfall-runoff process and design values
- Spatial structure of catchments, intensification of risk areas and factors
- Interaction of surface, soil and groundwater during floods
- Flood vulnerability in agriculture, forestry, water management and settlement
- Flood situation in the rivers and technical measures
- Role of reservoirs and dams in flood protection
- Co-ordination of research projects

Extreme events, impacts of climate change and regionalisation are already "classical" topics of mountain hydrology research. Results of research performed in these areas are often directly applicable in practice. However, there are other topics like evapotranspiration and the role of soils or the weathered zone transforming rainfall into runoff where vegetation effects should not be omitted, and these are still studied very little in mountain environments. Without their better understanding, the hydrological cycle in mountains cannot be fully understood. Snow hydrology research will be another topic of research in Slovakia in the near future.

Research needs data. The need for data is the "never-ending story" of hydrology. This is true especially in mountains where data acquisition is not easy. However, without reliable data even the simplest calculations like the basic hydrological balance are ambiguous (Holko et al., 2001). Some data can be obtained during field campaigns, but long-term monitoring is essential. Several recent studies devoted to various tasks (hydrological balance, design values, flood protection, regionalisation) have indicated, for example, that a better network of precipitation stations in the mountains would be needed. Although new ways of data acquisition and processing are under development, preservation and improvement (not inevitably extension) of current standard observation networks should not be forgotten. Otherwise, even the best models and statistical methods may be of little use.

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Czech highlands and peneplains and their hydrological role, with special regard to the Bohemo-Moravian Highland

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Abstract

Typical Czech highlands or peneplains have broad flat hilltops on which arable agriculture is practised, with altitudes between 300 and 800 m a.s.l. This paper discusses the hydrological role in terms of water balance, runoff variability and structure, and water quality of highlands and peneplains. The Bohemo-Moravian Highland (BMH) and many other Czech highlands are formed of acid crystalline rocks. The other two major types are underlain by Precambrian and Palaeozoic metamorphic rocks and by the Carpathian Flysh formations. The small catchments in isolated highlands typically have runoff coefficients of about 0.3 and an average annual runoff about 100 to 400 mm. The crystalline rocks give rise to a rapid turnover and a short residence time of groundwater.

In the absence of environmental tracer studies, the information has been derived from seasonal trends of nitrate concentrations. Similar trends were also observed in the Precambrain (Palaeozoic) region, while measurements in the other geological environments are scarce. The Carpathian Flysh highland regions appear to have a lower baseflow to total flow proportion and a faster groundwater turnover than the other regions. The rapid turnover of water in BMH and other crystalline rock regions does not allow enough denitrification. The concentrations of nitrate in the streams of BMH and similar regions are high and reveal a distinct seasonal trend. The decomposition of runoff into three main components (direct flow, interflow and baseflow), in conjunction with a simple mixing model, suggest that the interflow and, to a lesser extent, the baseflow, are the main carriers of nitrate. The subdrainage (tile drainage) water typically contains higher concentrations of nitrate than the stream water. The diffuse nitrate pollution problem can be tackled in two different ways: either by imposing limitations on agronomic practices or by a forced conversion of selected arable lands into grasslands or forests. The drainage runoff from some subdrained sites has to be retarded in order to increase the groundwater residence time.

1 Introduction

Central Europe in the broader sense comprises high mountains of the Alpine and the Carpathian systems as well as mountainous ranges of medium elevation (between about 800 and 2000 m a.s.l.), e.g. those belonging to the Bohemian massif, still predominantly of mountainous character. Both types of mountains act as ”water towers”. Their high elevation brings about high precipitation and low evapotranspiration, and the resulting surplus of water balance feeds the large European rivers and other important water sources. Beside the mountains, large areas of Central Europe are made up of highlands or peneplains of lower altitude, in which the surplus of annual water balance is less noticeable, as well as of lowlands with a passive water balance. Typical highlands, in contrast to mountains, have broad flat hilltops on which arable agriculture is possible and, frequently, essential for the regions' economy. Figure 1 shows the regions of the Czech Republic lying between 500 and 800 m a.s.l. The actual extent of highlands and peneplains is slightly larger than that indicated in Figure 1 because the same character of landscape can be found in many places even at lower elevations, with hill tops as low as about 300 m a.s.l. and valley bottoms as low as about 200 m a.s.l. This paper discusses the hydrological role of highlands and peneplains in the Czech Republic, paying special regard to the Bohemo-Moravian Highland (Českomoravská vrchovina, denoted below as BMH), in which and near to which several small experimental catchments of the authors' institute (RISWC) are located. The basic description is illustrated by some original results of RISWC research teams.

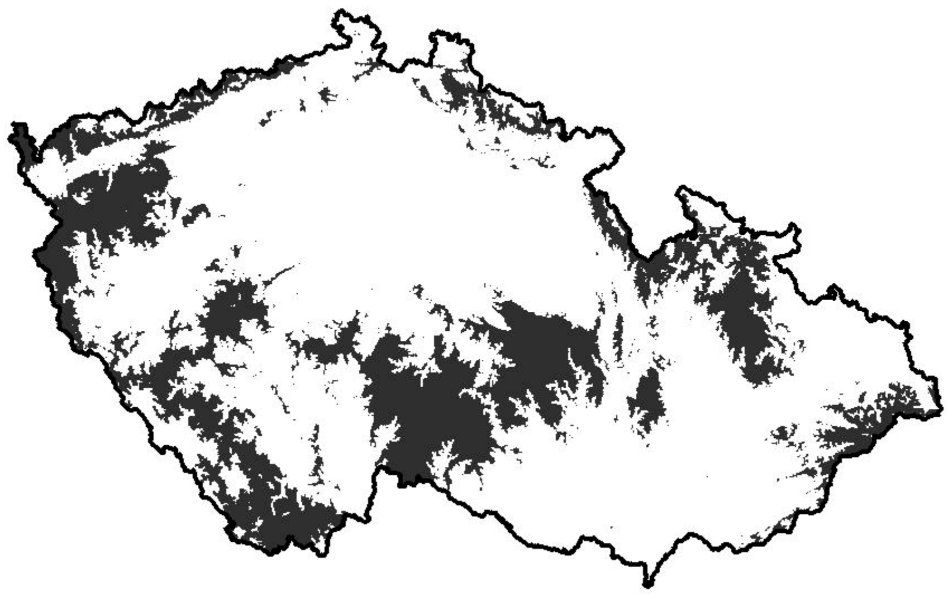

Fig. 1: Altitudes between 500 and 800 m a.s.l. (Fuksa et al. 2003) in Czech Republic. Mountains (above 800 m) and midlands and lowlands (below 500m) are denoted as white.

2 Highlands of the Czech Republic

Because of the limited extent of the paper, the picture described in this section is necessarily simplified and reflects only the most relevant features of the main regions. The majority of Czech highlands are similar to BMH in their geology, hydrogeology, orography and hydrology. They are predominantly formed of acid crystalline (deep igneous or metamorphic) rocks of uncertain age, such as granite, granodiorite, granulite, orthogneiss, paragneiss and mica schist. This group of highlands comprises, in particular, the Central Bohemian Highland and the foothill zones of many mountain ranges in the western part of the country, such as Šumava (Bohemian Forest), Krušné hory (Ore Mountains), Krkonoše (Giants' Mountains), Jizerské hory, Orlické hory and Hrubý Jeseník (Fig. 2).

Fig. 2: Crystalline rock regions in Czech Republic (Fuksa et al. 2003)

The remaining Czech highlands are of a different nature. The Precambrian and Palaeozoic regions (such as Brdy and their foothill zones and the surroundings of the Plzeň basin in West Bohemia) are mainly formed of metamorphic sedimentary rocks (such as shales and phyllite). Roughly similar to them are also the Palaeozoic formations in the North and Central Moravia (Nízký Jeseník, Oderské vrchy and Drahanská vrchovina). Figure 3 shows the location of these two groups of formations. The southern and eastern regions of Moravia are occupied by the Carpathian Flysh tertiary rocks (mainly sandstone and shales). The highlands in the Flysh regions are either foothill zones of the mountainous ranges of Bílé Karpaty and Beskydy or separate highlands (e.g. Chřiby) (Fig. 4). Quite specific is the hydrologic behaviour of catchments in the remaining three minor groups of the Czech highlands, namely the north-east Bohemian cretaceous sandstone regions (in fact, rarely reaching the altitudes required to qualify them as highlands), the Palaeozoic karstic regions near Beroun and Blansko towns (highlighted in Figure 3) and the small volcanic, mainly basaltic formations of north and west Bohemia. The cretaceous sandstone regions comprise deep and important aquifers, while the karstic regions are characterised by a very rapid runoff through large underground conduits and, on the other hand, dry plateaus on hilltops and slopes. The rocks, of which the volcanic regions are composed, have, as a rule, low permeability. These volcanic regions are small and do not resemble typical highlands because their hilltops are usually steep and narrow and of little significance for arable agriculture. If the hard rocks of any category are overlain by fluvial terraces or aeolic (mainly loessial) quaternary deposits, a separate groundwater turnover may develop in these deposits, thus modifying the hydrological functioning of the landscape. This, however, rarely occurs in typical highlands. Neither the three above-mentioned minor geology types nor the cases of surface sedimentary deposits on hill tops are treated in detail in this paper.

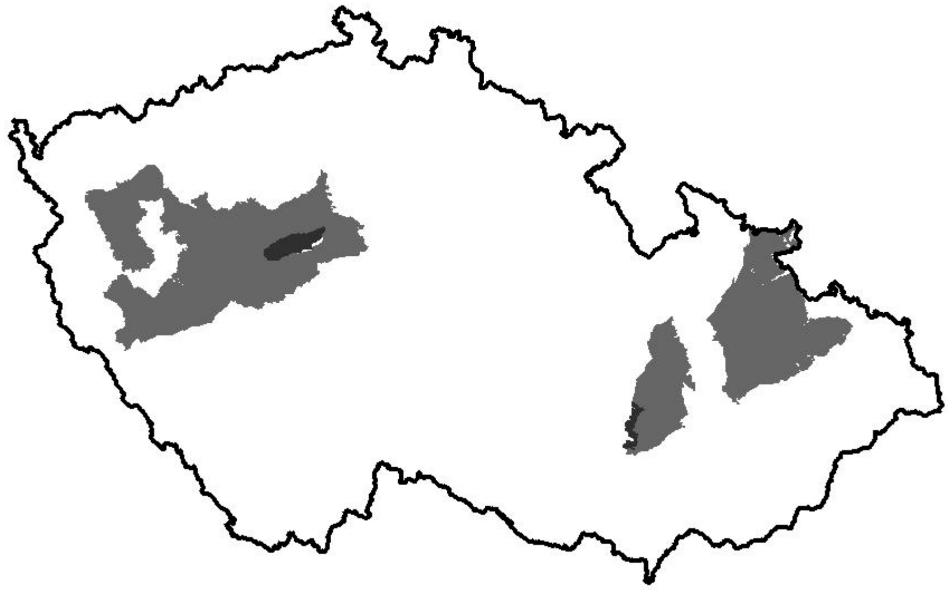

Fig. 3: Precambrian and Palaeozoic formations in Czech Republic (Fuksa et al., 2003). Dark black spots denote karstic regions.

Fig. 4: Carpathian Flysh formations in Czech Republic (Fuksa et al., 2003)

3 Methods and materials

The highland regions of the Czech Republic are characterised below by their water balance pattern, runoff variability, runoff structure, i.e. the proportion between runoff components, and water quality. The information summarised below is based on standard published data (Horský, 1970). The maps in Figure 1-4 were taken from Fuksa et al. (2003). The standard data are supplemented by results obtained in experimental catchments of the RISWC, which are mainly located in or near the Bohemo-Moravian Highland (Table 1). Basic properties of these catchments were described by Doležal et al. (2002a, 2002b) and Kulhavý et al. (2002).

Table 1: Basic characteristics of the main RISWC experimental catchments

Catchment name:	Cerhovický potok	Černičí	Dolský potok	Kopaninský tok	Kotelský potok	Žejbro *)
Av. latitude:	49° 51' E	49° 37' N	49° 47' N	49° 28' N	49° 47' N	49° 48' N
Av. longitude:	13° 50' E	15° 04' E	15° 59' E	15° 17' E	15° 59' E	15° 59' E
Altitude (m): min – max (av.)	390 – 572 (481)	448 - 543 (496)	456 - 676 (566)	467 - 578 (523)	438 - 663 (551)	355-676 (516)
Area (km^2)	7.36	1.42	4.78	6.69	3.21	48.3
% crop lands:	18 %	73 %	68 %	52 %	76 %	63 %
% grasslands:	22 %	7 %	7 %	14 %	10 %	15 %
% forests:	60 %	17 %	1 %	30 %	3 %	16 %
% drained lands:	16 %	17 %	22 %	10 %	38 %	23 %
Precipitation (mm/year):	617	722	764	665	764	764
Av. temperature (°C):	7.5	7.5	6.3	7.0	6.3	6.3
Main parent rock:	mica schist	paragneiss	phyllite	paragneiss	phyllite	phyllite, deep igneous, Cretaceous sediments
Geologic formation:	Pre-cambrian/ Palaeozoic	crystalline rocks	mixed **)	crystalline rocks	mixed **)	mixed **)

*) Regular gauging site of the Czech Hydrometeorological Institute

**) Dolský potok and Kotelský potok are twin catchments, sub-catchments of Žejbro, underlain by deep igneous and Precambrian/Palaeozoic (mainly phyllite) rocks in their upper parts and by Cretaceous sedimentary rocks in their downstream parts.

Selected stream flow data from the experimental catchments (see Table 2) were analysed as to the probability of exceedance of average daily flow and the structure of runoff. The empirical probability of exceedance was estimated using the Hazen plotting position equation (Cunnane, 1989). The methods of runoff component separation used for this purpose were described by Doležal et al. (2003). As a matter of fact, two methods, neither of them employing any data other than the hydrographs, were applied, namely, the digital filter suggested by Chapman and Maxwell (1996), referred to as Method 1 in Grayson et al. (1996) and an original method referred to as GROUND (Kulhavý et al., 2001), based on a simple conceptual model. The digital filter was calibrated using two other runoff separation methods by Kille (1970) and Kliner and Kněžek (1974). The GROUND method has not yet been calibrated but is at least qualitatively validated by a successful comparison with the results of a semi-distributed model (Jain, 1997). GROUND was used for separating the direct flow component, and the digital filter for separating the baseflow component. The remainder of the flow was regarded as the interflow.

The regions not covered by experimental catchments can at the moment be described in broad terms only by using published data (Horský, 1970). These data refer to the period 1931-1960 and may not therefore be fully adequate for the present situation. Nevertheless, they are useful for comparisons between different regions and rivers, the more so that they are not affected by the recently built dams and reservoirs and, therefore, reflect more fully the natural conditions. Two sorts of data were taken from Horský (1970). Firstly, the long-term average annual runoff coefficients (runoff/precipitation) for gradually expanding partial catchments of selected rivers, starting from their headwaters, were plotted against the areas of the partial catchments. Secondly, we tried to characterise the long-term average proportion of baseflow to the total flow by the ratio of the 180-day flow (i.e. the flow which is exceeded on 180 days in an average year) to the average annual flow. The feasibility of this approach was tested on the data from experimental catchments (see Table 2 and Fig. 5). The 180-day to average annual flow ratio is certainly not equivalent to the average baseflow to total flow ratio but the former is correlated to the latter and can therefore be used as a qualitative measure of the importance of baseflow in a particular catchment or region.

Table 2: Runoff separation results, average flows and 180-day flows in the experimental catchments

Stream, profile	Period(s) selected	Average proportion of			Average flow (l/s)	180-day flow (% average)
		Direct runoff %	Interflow %	Baseflow %		
Černičí, P1	06/01/98 - 22/07/01	29.8	47.5	22.7	5.42	27.04
Kopaninský t., T7	25/06/91 - 31/10/00	23.0	39.0	38.0	27.19	76.40
Cerhovický p., A1	23/10/96 - 29/11/00	32.0	34.6	33.4	21.88	46.93
Dolský p.	01/04/82 - 31/10/93 01/11/96 - 31/03/00	35.6	43.0	21.4	20.67	31.05
Kotelský p.	01/04/82 - 31/10/93 01/11/96 - 31/03/00	44.8	37.8	17.4	24.42	22.28
Žejbro	01/11/77 - 31/12/97	30.2	41.3	28.5	273.83	48.94

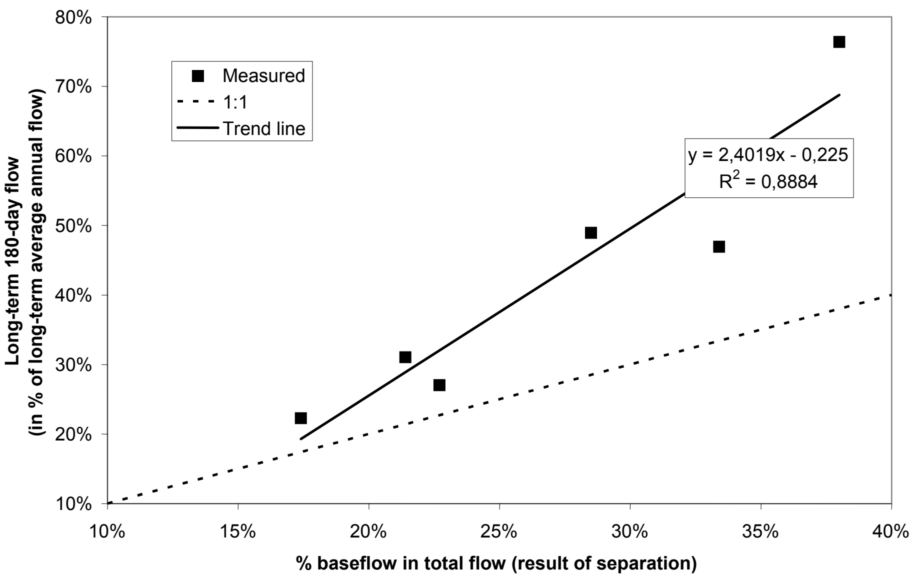

Fig 5: Relation between proportion of 180-flow to average total flow and proportion of baseflow to total flow for the experimental catchments. The graph corresponds to data in Table 2.

The application of the runoff separation methods allowed us to obtain separate daily flow hydrographs for each of the three runoff components (direct flow, interflow and baseflow). In the case of the Kopaninský tok catchment, these daily component flows were correlated to the nitrate concentration in stream water. In addition, an oversimplified but still useful model was adopted in order to investigate which of the three runoff components is the main carrier of nitrate. It was assumed that the water supplied to the stream by a particular flow component has its characteristic constant concentration of nitrate. Then the average concentration of nitrate in the stream water would be a result of mixing, according to the mass balance equations:

$$Q_{total} = \sum_i Q_i \; ; \quad Y_{total} = \sum_i Y_i = Q_{total}\, c \; ; \quad Y_i = Q_i\, c_i \tag{1}$$

where Q_{total} is the total stream discharge (e.g., in $l.s^{-1}$), Q_i is the stream discharge due to the i-th runoff component (in the same units), Y_{total} is the total nitrate yield (e.g., in mg $NO_3.s^{-1}$), Y_i is the nitrate yield due to the i-th runoff component (in the same units), c is the average nitrate concentration in stream water (e.g., in mg $NO_3.l^{-1}$) and c_i is the hypothetical constant concentration of water brought in by the i-th runoff component (in the same units), wherein i stands for direct runoff, interflow and baseflow, respectively.

From (1), the total nitrate yield Y_{total} and the average nitrate concentration c can be estimated as:

$$\hat{Y}_{total} = \sum_i Q_i\, c_i \; ; \quad \hat{c} = \frac{\sum_i Q_i\, c_i}{Q_{total}} \tag{2}$$

where the hat sign denotes an estimate of the true value. The unknown values of component concentrations c_i were estimated by nonlinear optimisation, using the sum of squared differences $(Y_{total} - \hat{Y}_{total})^2$ as an objective function to be minimised.

4 Results and discussion

4.1 Water balance

The water balance of a catchment can be characterised by the long-term average runoff coefficient. The water balance patterns of Czech highlands and peneplains vary from location to location, mainly depending on the regional climate, which in turn is essentially determined by the elevation of the catchment. The term "highlands" will be used below to denote both types of landscape. Furthermore, there is a big difference between the highland-like foothill regions of higher mountains and the isolated highlands not adjacent to higher mountains. The headwaters of streams and rivers in the former regions are often found in relatively high mountains and, because of the mountainous climate, show high runoff coefficients of up to 0.8. Because of the abundant water supply, these streams usually preserve higher runoff coefficients even in their downstream reaches. On the other hand, streams that originate in the highland regions themselves are characterised by moderate values of runoff coefficients of about 0.3 in their headwaters as well as in their downstream reaches. Figure 5 depicts the average long-term runoff coefficients for several typical Czech rivers. The Labe river originates in the highest Czech Giants' Mountains which allows relatively high runoff coefficients in the middle and downstream reaches to be preserved. Similarly, the Bečva originates in the Beskydy Mountains.

The Svratka originates in the highest part of BMH where the elevation is over 800 m a.s.l., hence the relatively high runoff coefficients of its upstream reaches. As we proceed downstream, the Svratka runoff coefficients decrease, approaching 0.3, a typical value for Czech highlands. The Želivka is the most typical BMH river, with the runoff coefficient about 0.3 over its entire length. The Úslava originates in and flows through the south-west Bohemian Precambrian peneplains. The remaining two rivers do not belong to the highland/peneplain landscape type and their data are presented in Figure 6 for comparison. The Mrlina originates in and flows through the north-east Bohemian Cretaceous sedimentary plateau and lowland, and the Jevišovka originates in the south-east periphery of BMH and flows eastwards through the Dyje-Svratka lowland, one of driest parts of the country.

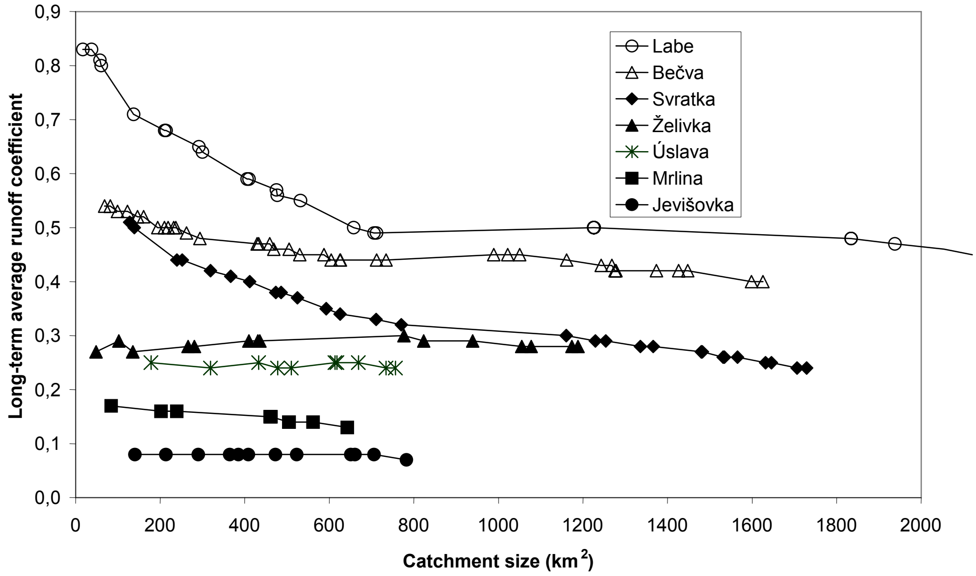

Fig. 6: Average long-term runoff coefficients of some typical Czech rivers, plotted as functions of the catchment size starting from headwaters

The overall average water balance of small catchments in the Czech highlands is positive, resulting in an average annual runoff of about 100 to 400 mm. This makes it possible to feed minor rivers. For example, the rivers Chrudimka, Sázava, Želivka, Jihlava, Svratka and Svitava, and many other smaller ones, originate in BMH. From the point of view of the average annual water balance, there are also differences between individual catchments within one and the same geologic formation. This fact is illustrated in Figs. 7 and 8 in which the dependence of the long-term average runoff coefficient and of the long-term average annual precipition on the catchment area is plotted for typical rivers of the three main highland rock types, namely the rivers Svratka and Želivka of the crystalline rock region, the rivers Úslava and Litavka of the Precambrian/Palaeozoic region and the river Dřevnice of the Flysh region. The relatively large runoff coefficients produced by the Svratka catchments from relatively low annual precipitation sums contrast with opposite trends of Želivka catchments. Similarly, the Litavka catchment produces roughly the same runoff coefficients as the other Precambrian/Palaeozoic catchment (Úslava), even though the precipitation in the former is signicantly lower than in the latter. These effects result from a complex interplay of many factors of which the two most important are probably lower evapotranspiration (mainly due to higher elevation) and lower average rock permeability in the Svratka and the Litavka catchments. One way to investigate these factors more deeply would be to distinguish between wet and dry years as it was done by Soukup (1988) for the Cidlina catchment.

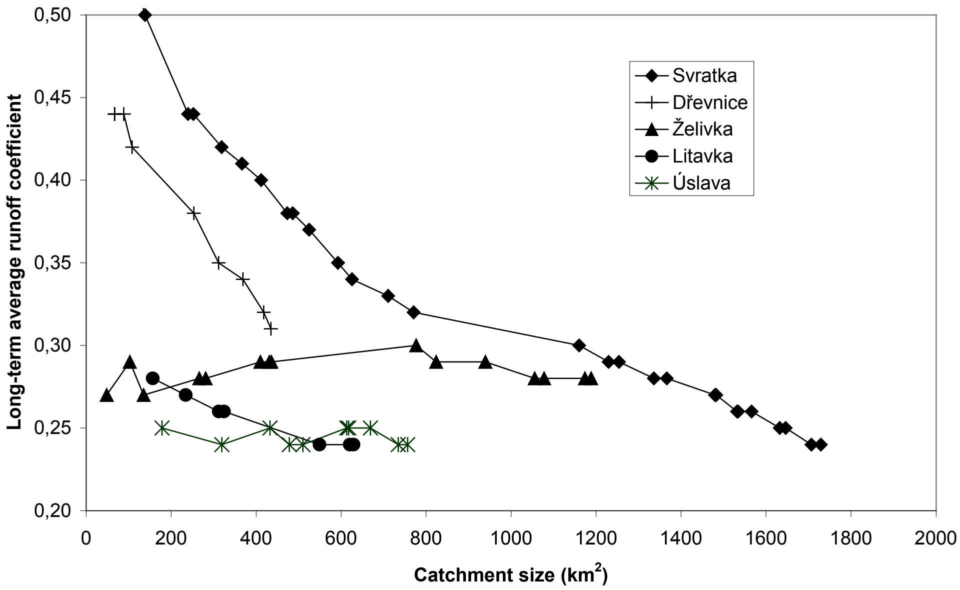

Fig. 7: Average long-term runoff coefficients for typical highland-fed Czech rivers (Svratka and Želivka - crystalline rock regions; Úslava and Litavka – Precambrian/Palaeozoic region; Dřevnice – Flysh region), plotted as functions of the catchment size starting from headwaters

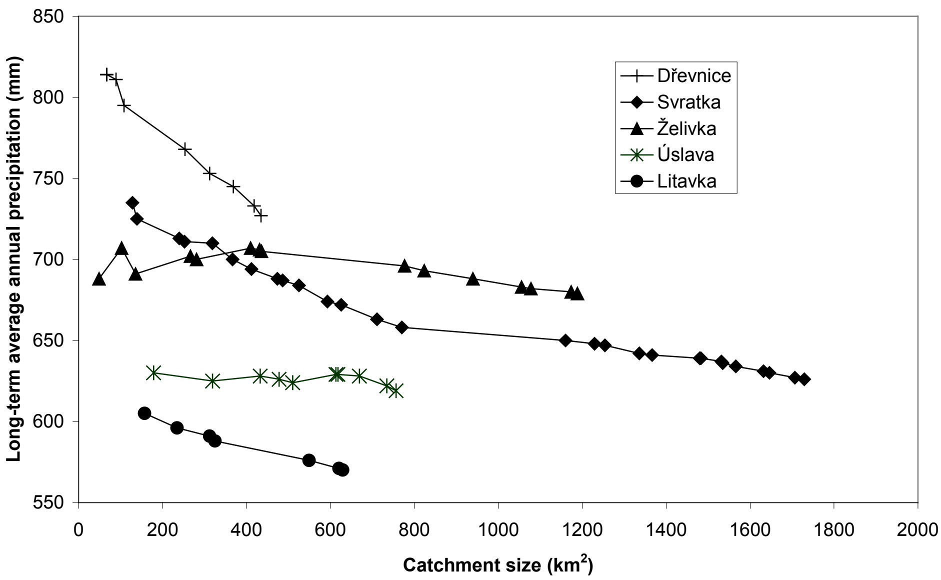

Fig. 8: Average long-term annual precipitation sums for typical highland-fed Czech rivers (Svratka and Želivka - crystalline rock regions; Úslava and Litavka – Precambrian/Palaeozoic region; Dřevnice – Flysh region), plotted as functions of the catchment size starting from headwaters

4.2 Runoff generation

Runoff variability and runoff structure, i.e. the average proportion between individual runoff components, as well as the turnover of groundwater, i.e. its depth of circulation and residence time, depend considerably on the geology of the region. The igneous and metamorphic rocks of uncertain age, usually referred to as “crystalline”, of which the bulk of BMH is composed, are virtually impervious, except for faults and weathered zones. They therefore give rise to a rapid turnover of groundwater in the shallow regolith and to a dense network of temporary springs and minute perennial streams and fishponds. The portion of interflow in the total runoff is high (typically about 40 %), as demonstrated by Doležal et al. (2003) (see Table 2).

The residence time of groundwater in the crystalline rock catchments is small. Environmental isotope tracer studies (e.g., FRIEND, 1997) suggest that the groundwater residence times in similar catchments in other countries are of the order of one year or more. Unfortunately, no tracer studies have yet been made in the experimental catchments listed in Table 1. Nevertheless, some information can be derived from the water quality monitoring as shown below. The seasonal trend of nitrate concentrations in the small stream water of the crystalline rock region (Fig. 10) reveals a well defined maximum in the late winter and early spring months (January to April). Similar seasonal patterns have been observed in the other crystalline rock, Precambrian/Palaeozoic and mixed geology experimental catchments with arable agriculture (Cerhovický potok, Černičí, Dolský potok and Kotelský potok). The leaching of nitrate from arable lands mainly occurs in the autumn, winter and spring months when the arable lands are either bare or the crops growing on them are not developed enough, while the amount of mineral nitrogen in the soil, mainly produced by the mineralisation of organic matter in late summer and early autumn, is large (Armstrong and Burt, 1993). The interval between the usual time of maximum nitrate input into groundwater (September to December) and the time of its usual maximum concentration in the stream (January to April) does not exceed a few months. Hence, the nitrate acts as a *sui generis* environmental, even if non-conservative, tracer. Herrmann (2003) suggests that the transport of nitrate involves only the most superficial layers of groundwater and, therefore, the average residence time of groundwater, taking into account its deeper layers as well, must be longer than that derived from the “nitrate pulse” travel time. Nevertheless, the nitrate tracing results may be used as a relative measure in comparisons of different environments as to their groundwater residence times. Some data for the forest subcatchments of the Cerhovický potok and the Kopaninský tok suggest that the release of nitrate from a forest ecosystem into groundwater occurs mainly in spring months when the increased temperatures favour the mineralisation of freshly created forest litter. This leads to nitrate concentration maxima in forest stream and forest spring water in late summer and early autumn (Fig.11), without challenging the hypothesis of short nitrate pulse travel times.

Measurements in the other geological environments are scarce. The standard data (Horský, 1970) can be exploited to give a rough picture. In the absence of more accurate data such as those obtained from environmental tracers studies, one can take the ratio of the 180-day flow to the long-term average flow as an indicator of the relative baseflow magnitude, as illustrated above in Table 2 and Figure 5. Figure 9 shows these ratios as functions of the catchment size for typical rivers in main Czech highlands.

From these data it can be concluded that the groundwater turnover in most Precambrian and Palaeozoic formations is approximately equally fast as that in the crystalline rock regions. The discernibly lower baseflow proportions in the river Svratka (in comparison with the rivers Želivka, Úslava and Litavka, as well with the river Labe which in its upper 2000 km^2 of the catchment area drains crystalline, Palaeozoic and Cretaceous formations), correspond to the above findings concerning the high runoff coefficients in the Svratka catchment. The rivers of the Carpathian Flysh region (Bečva and Dřevnice) have apparently much lower baseflow to total flow proportions. This is mainly due to low permeability of the underlying rocks and to steep slopes of the hills. Both these factors contribute to fast runoff and low water retention in the catchments. It is reasonable to assume, on the basis of these observations, that the

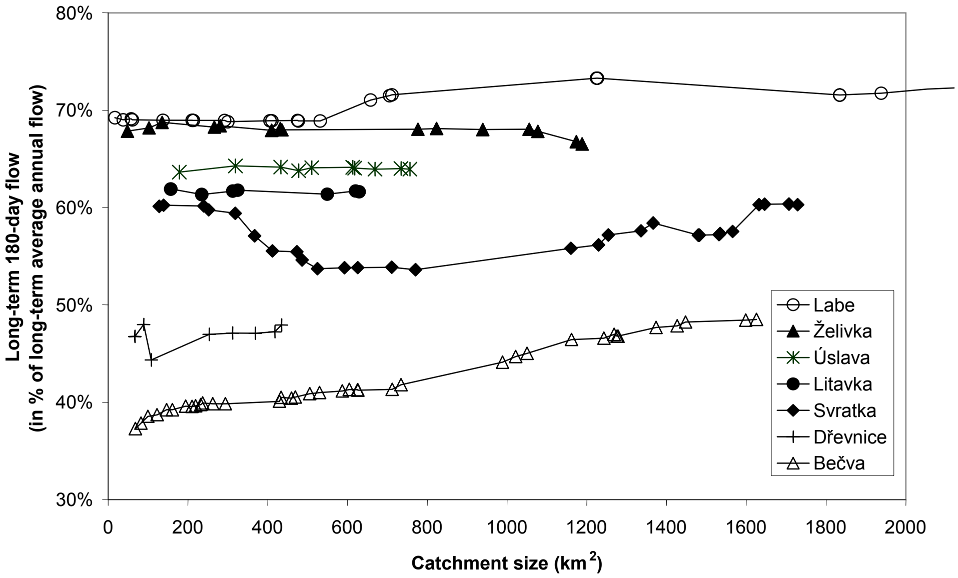

Fig. 9: Ratio between 180-day flow and average long-term average total flow as a function of the catchment size starting from headwaters for typical Czech highlands rivers. Respective data of Labe and Bečva mountainous rivers are shown for comparison.

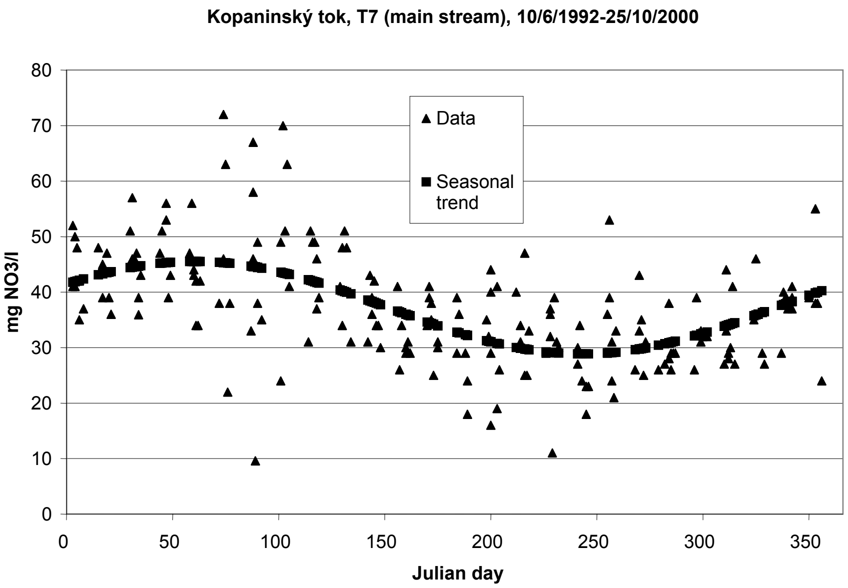

Fig. 10: Seasonal trend of nitrate concentrations in stream water of the Kopaninský tok catchment (profile T7, 10/6/92-25/10/00)

groundwater turnover in the Flysh region highlands is even faster and shallower than that in the crystalline or the Precambrian/Palaeozoic regions. Of course, this assumption has to be verified by more detailed measurements.

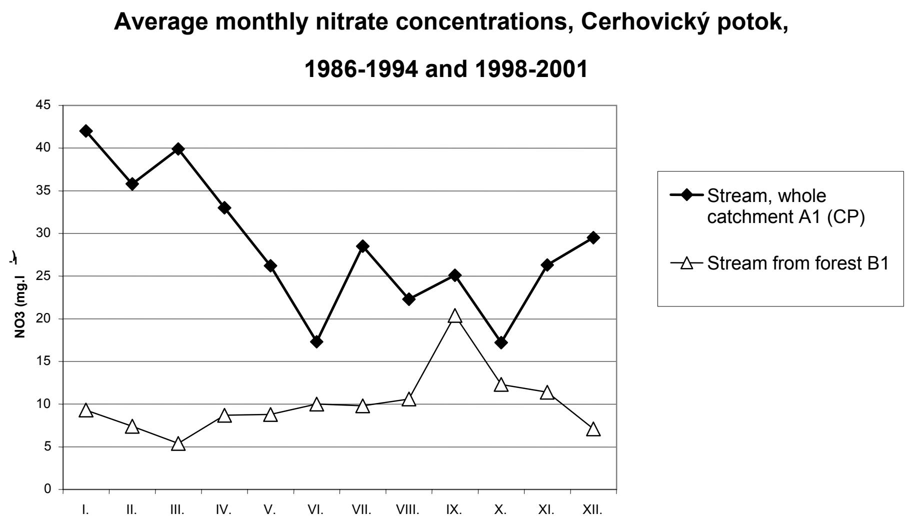

Fig. 11: Seasonal trends of nitrate concentrations in the stream water of the Cerhovický potok catchment in 1986-1994 and 1998-2001 in the closing profiles of the whole catchment (A1) and a forested subcatchment (B1; 3.15 km^2 in size)

4.3 Water quality generation

In terms of water quality, the rapid turnover of water in BMH and other crystalline rock regions does not allow enough denitrification. The residence time of groundwater is further reduced due to the effect of artificial subdrainage (tile drainage) systems on agricultural lands. Most sites in the crystalline rock regions are therefore highly vulnerable to the nitrate pollution. They were labelled as such in the process of vulnerable zones delineation for the purpose of application of the EU nitrate directive (Anonymous, 2003). The catchments which are underlain by Precambrian and Palaeozoic metamorphic rocks in south-west Bohemia behave in a similar way.

On average, the concentrations of nitrate in the streams of BMH and similar regions are high, and sometimes higher than the drinking water limit concentration of 50 mg NO_3/l. They reveal a distinct seasonal trend (Kvítek et al., 2002b, see Figs. 10 and 11 as examples), as discussed above under runoff generation. The streams and springs that are recharged by forested lands have considerably lower concentrations of nitrate than those collecting water from arable lands (see Fig. 11, Soukup et al., 2001; Soukup and Pilná, 2003; Kvítek and Doležal, 2003; Doležal and Kvítek, 2004).

The runoff components into which the total stream flow can be decomposed differ among themselves as to the reaction time on the precipitation events, to the depth of the soil/parent rock zone involved and to the distance (from the recipient) of the site where the runoff is generated. Therefore, it can be expected that different runoff components also play different roles in the leaching, transportation, transformation and discharge of nitrogen. Such investigation was done for the Kopaninský potok catchment in BMH (Kvítek and Doležal, 2003, Doležal and Kvítek, 2004). The simple model, described by equations (1) and (2), provided rough estimates of average nitrate concentrations in the water of individual runoff components: 37 mg NO_3/l for the baseflow, 55 mg NO_3/l for the interflow and 24 mg NO_3/l for the direct runoff. The results indicate that the interflow and, to a lesser extent, the baseflow are the main carriers of nitrate towards the stream in agricultural catchments of the crystalline rock region. This conclusion is, of course, only qualitative. No comparable studies have been made up to now for the other highland regions in the Czech Republic.

Furthermore, the studies made in the experimental catchments confirm that the subdrainage (tile drainage) water contains higher concentrations of nitrate. Figure 12 compares nitrate concentrations, plotted against their probabilities of exceedance which were estimated from the Hazen plotting position equation, for subdrainage water and for stream water in the Dolský potok and Kotelský potok catchments. Similar results have been obtained in the other experimental catchments listed in Table 1. As stated above, the drainage systems provide a short-cut for runoff and, thereby, reduce the opportunity for denitrification. The drainage systems may therefore have a negative impact on the stream water quality, beside their obvious positive effects on the ease and economy of agricultural production.

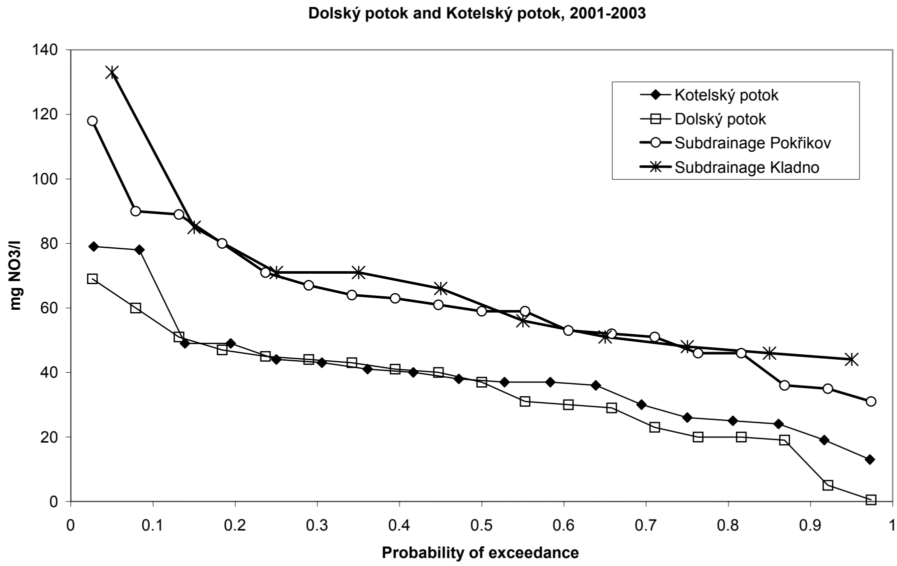

Fig. 12: Empirical probability of exceedance curves of nitrate concentrations for the stream water in the Dolský potok and Kotelský potok catchments and in the runoff from two tile drainage systems in the Dolský potok catchment, 2001-2003

4.4 Practical implications

The Czech Republic is now in the process of implementation of the EU Nitrate Directive (Anonymous, 1991). The problem is being tackled in two different ways. One way is to allow arable agriculture on virtually all existing arable lands, but to impose limitations on the use of fertilisers, on growing some crops (such as legumes, potatoes and silage maize) and on performing some other farming operations (such as the incorporation of legumes and green manure). The limitations must be compulsorily observed in selected vulnerable regions (Anonymous, 2003). The other way would be a forced conversion of selected arable lands (such as the drained lands in the transitional zones and the most permeable and shallow soils in the recharge zones) into non-intensive grasslands or forests, thus not imposing any serious restrictions on the remaining arable lands (Kvítek et al., 2002a). The problem is still open and the actual outcome will probably be a compromise between the two approaches described above.

The waterlogged slopes and narrow valleys in the crystalline rock highland region were traditionally used, if at all, as forests or meadows. Since the 1960s, many former meadows have been drained by subsurface tile drainage systems and turned into arable lands. The redox status of formerly waterlogged sites has thus been shifted towards the oxidation side due to drainage and tillage, rendering the removal of nitrogen from shallow groundwater by denitrification less efficient. The combination of the diffuse pollution by nitrate in the recharge zones with the lack of opportunity for denitrification in the transitional and discharge zones makes the stream water excessively polluted. The actual pattern of runoff and water quality generation in small agricultural catchments is still being studied in order to identify the actual causes of the pollution and to propose the measures for improvement. In fact, some drained arable lands on slopes, too difficult to cultivate, have already been spontaneously abandoned. In addition, the subdrainage runoff from these lands has to be retarded (Soukup et al., 1998, 2002) in order to increase the groundwater residence time and the opportunity for the nitrate in groundwater to be removed by denitrification.

5 Conclusions

The water balance pattern of the Czech highlands, expressed by the long-term average runoff coefficient, is less positive in terms of water surplus available for runoff than the “water tower”-like balance of mountains but more positive than that of lowlands where evapotranspiration rates often exceeds precipitation amounts. The water balance of the Czech highlands results in an average annual runoff about 100-400 mm. The actual water balance pattern mainly depends on the elevation and local climate but also, to some extent, on the geology of the region. The runoff structure and runoff variability are perceptibly influenced by the geology. In general, however, the groundwater turnover in most Czech highlands is shallow and rapid and the residence time of water in catchments is small. The nitrate pulse travel time is only few months. The groundwater turnover in the Precambrian/Palaeozoic regions is roughly equally fast as that in the crystalline rock regions, while it is reasonable to assume that this is faster in the Carpathian Flysh regions. It appears that the highland regions other than those underlain by crystalline rocks have not yet been studied enough as to their runoff and water quality generation processes. This pertains in particular to the Carpathian Flysh regions.

Arable agriculture in Czech highlands is socially and economically important and cannot be fully replaced by any other economic activity. However, it must be regulated, either by imposing limitations on agronomy on the existing arable lands or by reducing the area of arable lands. The actual ways of regulation may differ from region to region, bearing in mind different geology, geomorphology and traditions of different regions. It seems inevitable to retard the tile drainage runoff from the recharge zones and the transitional zones of the crystalline rock highland regions.

Acknowledgement

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Influence of vegetative cover changes on the soil water regime in headwater regions in the Czech Republic

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Abstract

The influence of vegetative cover on the soil water regime in the Modry potok catchment in the Giant Mts. (Krkonose) is studied in this paper. Several monitored plots located in this catchment in different positions (valley, slope) are covered by different kinds of vegetation (dwarf pine forest, spruce forest, meadows). The maximum retention capacity of the catchment (about 70 mm) and the retention capacity of the soil surface (20 mm) are evaluated in two contrast periods: the catastrophic flood in August 2002 and the long-term drought in August 2003. Based on soil moisture measurements in monitored plots fully covered by plants, it is shown that: (1) in wet conditions, when the plants can fully transpire, the vegetative cover composition does not influence the soil water regime; (2) in the course of droughts, the soil water regime is highly influenced by the plant cover composition. Based on the monitoring of the water and heat regime in the growing season the homeostatic role of the plant transpiration was proved. Consequently, the water regime of a catchment during wet conditions (rainfall-runoff relationship) is independent of the species composition of the plant cover if the area of the transpiring vegetation remains unchanged. The monitoring network which covers the main massifs of the Bohemian border is discussed here.

1 Introduction

Long-term attention is paid to the study of the relationship between the vegetation cover, and the heat and water circulation in the landscape. The question of how the water regime of a catchment is influenced by forest has been studied in the Czech Republic since the beginning of the 20th century. The first research basins – Kychova and Zdechovka in the Beskydy Mts. – were established by Valek in 1928 (Valek, 1937). Precipitation and runoff measurement in these basins has continued up to the present time. Another experiment was started in 1954 in the Raztoka catchment (Beskydy Mts., drainage area 2.067 km^2, elevation from 602 to 1084 m a.s.l., mean annual precipitation 1269 mm, runoff 833 mm, bedrock formed of sandstone). Based on this experiment, it was found that the rainfall-runoff transformation is not significantly influenced when the spruce forest is replaced by beech forest. This conclusion was derived using the double mass curve of precipitation and runoff (Chlebek and Jarabac, 1988).

Now research activities are aimed at the mountainous regions covered by damaged forests. This interest has been invoked by a series of climatic and hydrological disasters like floods in 1997, 1998 and 2002 or droughts in 2000 and 2003. A calamitous deforestation of the Bohemian and partly Silesian border has caused such significant ecological damage that it is impossible to rely on the remedial potential of the nature, and it is necessary to step up the active renewal of the vegetation cover. The antecedent research was predominantly motivated by the effort to better recognise the hydric functions of the forest (Chlebek and Jarabac, 1988). The majority of the affected mountains is situated in landscape-protected areas or national parks. Therefore the use of the well-tried techniques for clear cutting of the damaged forest with subsequent afforestation of the clearings is questionable.

In addition, the research effort is complicated by the changing climatic of the last 50 years that became a marked global warming during the course of the last decade. The annual average of the air temperature in the open landscape of the Czech Republic increased by about 1.4 ^{o}C during the last 50 years (Bodri and Cermak, 1997). Taking into account a lapse rate of –0.66 K per 100 m, which is estimated for the Czech Republic, the warming represents an illusory decrease of the whole country of about 210 m, and thus, the shift of the mountains to the climatic zone corresponding rather to highlands. This fact complicates the application of older results of hydrological research. These results were obtained in different climatic conditions compared to the present ones.

In this article typical results of the monitoring of the influence of various vegetation covers on soil water regime and water retention will be shown. The contribution is based on the monitoring of the hydrological and meteorological data in the four experimental plots in the Modry potok catchments in the Giant Mts. These plots differ in the type of vegetation (dwarf pine, spruce forest, meadows in the valley and meadows above the forest margin) and in position (valley bottom and different slope positions). In two contrast periods, during the catastrophic flood in August 2002 and during the long-term drought in August 2003, the retention capacities are estimated. The vegetation-cover influence on the soil water regime is documented with the help of soil moisture measurements.

2 Methodology

In order to study the water regime of mountainous forested catchments, three experimental watersheds were established: (1) the Liz basin (Sumava Mts. – southern Bohemia, brown podzolic soil, moldanubic crystallinicum, paragneiss, prevailing type of tree: spruce aged up to 120 years); (2) the Uhlirska basin (the Jizerske hory Mts. – northern Bohemia; brown podzolic soil, podzol, peat, Variscan igneous rocks of granite massif of the Krkonose-Jizerske hory crystalline complex, biotitic gneiss, prevailing type of tree: spruce aged up to 80 years for 15 % and 15 years for 85 % of the area); (3) the Modry potok basin (the Giant Mts. – north-eastern Bohemia; ferrous humic podsole, brown podzolic soil, rocks of metamorphic aureole of Variscan granite pluton, mica schist, spruce and dwarf pine covering 62 % and meadow 38 % of the area).

These experimental catchments are placed in the main massifs of the Bohemian border mountains. They differ especially in the level of the anthropogenic impacts on vegetation cover. The Liz catchment represents a relatively healthy productive forest in a clear landscape. The Uhlirska basin is situated in a formerly heavily polluted region of the so-called “Black Triangle”. At the beginning of the nineties the top parts of the Jizerske hory Mts. were nearly completely deforested. At present the prevailing part of this catchment is covered by regenerated forest. The Modry potok basin in the Giant Mts. represents the original spruce forest in the lower part of the basin and the artic-alpine tundra with dwarf pine covers the upper part above the timberline. Brief characteristics of the catchments are presented in Tables 1, 2 and 3 and positions of the catchments are shown in Figure 1.

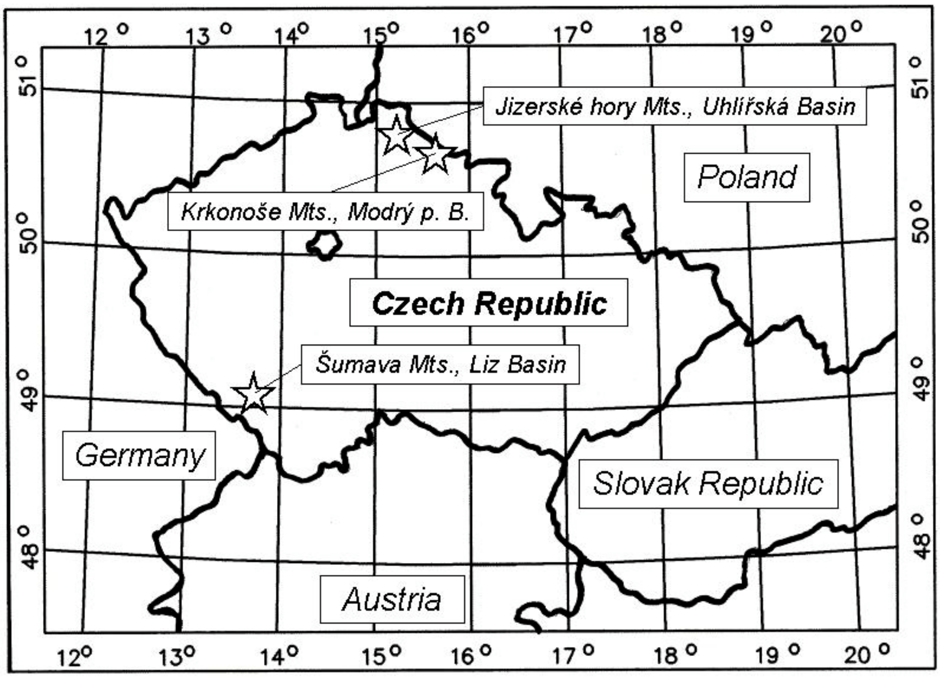

Fig. 1: Location of the experimental plots in the Czech Republic

The basic parameters (precipitation amount and intensity, air and soil temperatures, global radiation, suction pressures and soil moistures, discharge in the closure profile) are recorded in all experimental catchments. Based on the measured data the actual transpiration and outflow of water below the soil profile to the sloped subsoil horizont transporting water to the small brook are evaluated. Furthermore, the total retention capacity of the basin, retention of water on the soil surface, in the soil profile and in the subsoil layer are assessed. The methodology of the measurement, data processing and evaluation have been published (Tesar and Sir, 1998; Tesar et al., 2001, 2003). The monitoring network is formed by twenty fully automatic stations. The network is operated jointly by the Institute of Hydrodynamics of the Academy of Sciences of the Czech Republic in Prague, Faculty of Civil Engineering of the Czech Technical University in Prague, Czech Hydrometeorological Institute in Prague and Hradec Kralove and Krkonose National Park Administration in Vrchlabi.

3 Experimental catchments and areas

3.1 The Sumava Mts.

The Liz catchment, Zabrod arable land and Zabrod meadow experimental areas are situated in the mountainous and submontane region of the Sumava Mts. These localities lie in the Vimperk Highlands that extend in its south-eastern part to the Landscape Protected Area and National Park of the Sumava Mts. and are part of the Moldanubicum metamorphic complex. It is formed mainly by the metamorphosed rocks, paragneiss with smaller injected localities in the northern part of the region. In valley bottoms all bedrock is covered by noncalcic (acid) sediments, in depressions and the middle parts of slopes also by quaternary sediments.

The clayey-sandy and sandy-clayey soils of middle depth represent the prevailing soil type. The forest soil type is mainly Eutric Cambisol (Stagno-slightly-gleyic Cambisol, Stagnogleyic Cambisol, Albic Luvisol). Relatively frequently the soil type is Ferro-humic Podzol. In the valleys close to the water courses Eutric Fluvisol, Gleyic Fluvisol and Eutric Histosol occur. On the highest hilltops Lithosol can be found. Eutric Cambisol, Gleyic Fluvisol and partly also Eutric Fluvisol are agriculturally exploited. The increased amount of precipitation together with lower temperatures has resulted in increased leaching intensity that jointly with an acid reaction causes significant accumulations of acid organic matter on the soil surface. The fleeter granularity composition of the bedrocks of the acid Eutric Cambisol and Ferro-humic Podzol eliminates the influence of the higher amount of precipitation so that the gleyzation does not appear. Only on the bottom part of the slopes and on the platforms with stratified deposited geest rock-forming material is a relatively lower permeable deluvium formed with various stage of gleyzation. Gleyic Fluvisol is significantly influenced by the relief feature and hydrological conditions.

The Liz catchment is located in the south-western part of the Vimperk Highland in the basin of the Zdikov brook that flows through the wider meadow depression. In its upper part this brook is formed on the northerly oriented forest slopes, with the Liz catchment here being at a distance of about 4 km from the village of Zdikov in the district of the town of Prachatice. The experimental areas of Zabrod arable land and Zabrod meadow are situated below the forested slopes. The Liz catchment is fully forested. Forest cover belongs to the acid spruce beech type. The soil type is the oligotrophic forest Eutric Cambisol. The coordinates are 13º40'01" – 13º41'00"E and 49º03'23" – 49º04'09"N. Maximum elevation is 1074 m a.s.l., minimum elevation 828 m a.s.l., mean elevation 941.5 m a.s.l., average land slope 16.55 %, catchment length 1.45 km, length of streams 2.28 km. Table 1 gives the characteristics of the Liz catchment and Figure 2 describes its physical geographic situation. The Zabrod meadow experimental area is exploited as a permanent meadow. In 1976 the locality was drained by pipe drainage. The soil type is the acid slightly gleyic Eutric Cambisol. The coordinates are

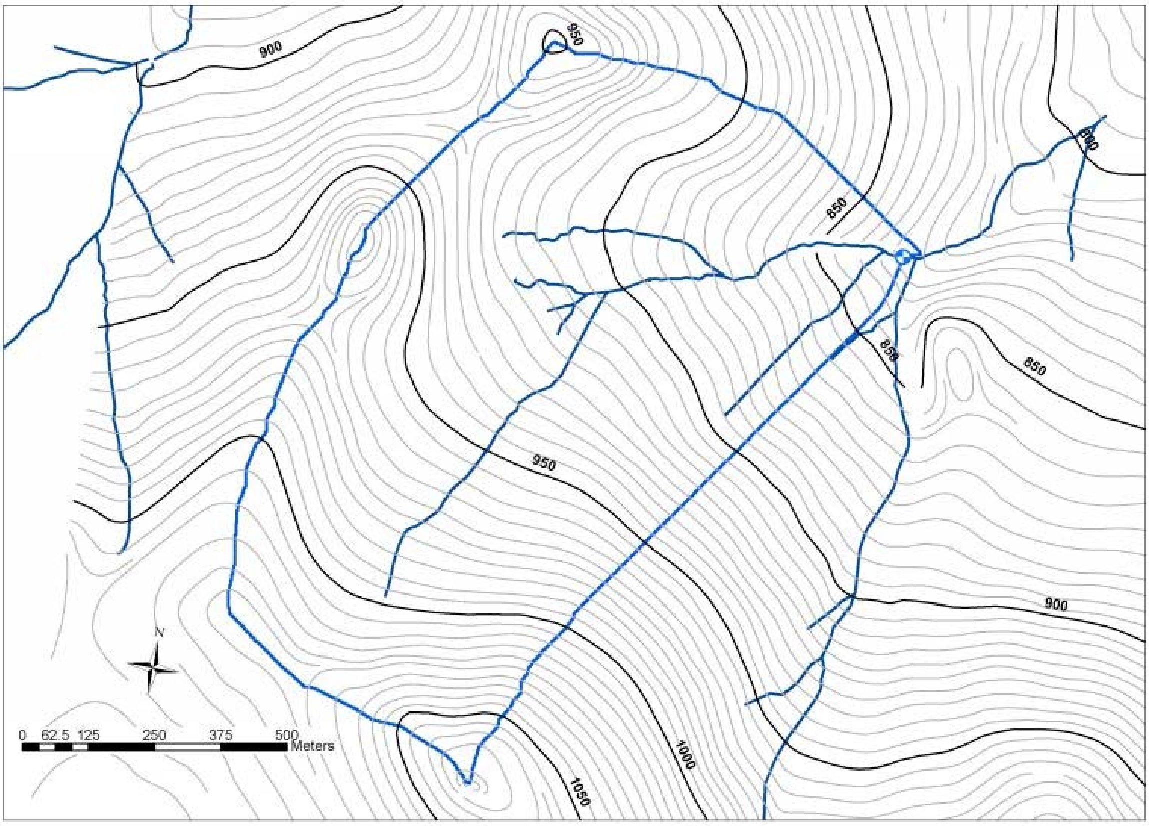

Fig. 2: Physical geographic situation of the Liz experimental catchment

13º41'45"E and 49º04'15"N, elevation is 788 m a.s.l. The Zabrod arable land experimental area was exploited as arable land; now it is covered by permanent grass. In 1976 the locality was drained by pipe drainage. The soil type is the acid podzolic Eutric Cambisol. The coordinates are 13º41'45"E and 49º04'13"N, and elevation is 789.5 m a.s.l.

Table 1: Characteristics of the Liz experimental catchment in the Sumava Mts.

District	Prachatice
Land register of the village/town	Zdikov
Geographic position – E longitude of closing profile	13º40'58"
Geographic position – N latitude of closing profile	49º3'59"
Maximum elevation	1074.0 m a.s.l.
Minimum elevation	828.0 m a.s.l.
Drainage area	0.989 km^2
Physical-geographic location	Bohemian Highlands – mountainous country
Geomorphological unit	The Sumava Mts. (Bohemian Forest)
Hydrological order of the observed water body	1-08-02-013
Sequence of streams to main river	Zdikovsky potok brook – Stassky potok brook – Spulka river – Volynka river – Otava river – Vltava river (Moldau)
Vegetation cover and land-use	Mixed forest (spruce 87%, beech 6%, other 7%), age up to 120 years old
Geological unit	Moldanubic Crystalline Massif: gneiss, paragneiss
Soil type	Podzolic Eutric Cambisol
Mean annual air temperature	6.3 ºC
Mean air temperature in January	–3.4 ºC
Mean air temperature in July	13.6 ºC
Mean annual precipitation	825 mm
Mean number of days with snow cover	92

The above-mentioned experimental stands are equipped with automatic monitoring stations for the continuous measurements of air and soil temperatures, suction pressures in the soil (water tensiometers), soil moisture (HFP soil moisture meters) and precipitation amount and intensity (rain gauge with a catchment area of 500 cm^2). The HFP soil moisture meter is a microcomputer-controlled device where the soil moisture is estimated using the high-frequency permittivity measurement. Measurement accuracy in field conditions is about 1% (vol.). In the closing profile of the Liz catchment the discharge is recorded. Next to this closing profile an automatic monitoring system for the gradient measurement of the heat and water transfer in the surface layer of the atmosphere and soil is installed. The Liz catchment has been included in the GEOMON monitoring network (**Geo**chemical **Mo**nitoring **N**etwork). GEOMON represents a network of small forested catchments in the territory of the Czech Republic (Fottova, 2003). The monitoring has been coordinated by the Czech Geological Survey since 1994. The deposition fluxes of the fifteen major ionic species based on bulk precipitation and throughfall analyses have been calculated for the 1994–2002 period.

3.2 The Giant Mts. (Krkonose)

The experimental locality Labska louka lies in the western part of the Giant Mts. close to the headspring of the Elbe river. The Modry potok catchment is situated in the eastern part of the Giant Mts. with the highest point being Studnicni hora Mt. This region is formed by the Krkonose-Jizerske hory crystalline complex. The crystalline complex is found on the northern margin of the Bohemian Massif. Due to their type and age, the rocks forming the crystalline complex are similar to the rocks of the Moldanubic Crystalline Massif in south Bohemia. The bedrock differs in Labska louka and Modry potok. In the Labska louka the bedrock is formed by biotitic granite becoming coarse-grained granite on the southern margin of the given locality (Variscan granite pluton). In the Modry potok the bedrock is formed by rocks of the crystalline complex. These rocks form here the contact of the older rocks (pre-Cambrian) with granite rocks of the Paleozoic at the beginning of the Upper Carbon (metamorphic aureole). Rock types are presented by the mica-schist, phyllite, gneiss, amphibolites and sometimes quartzite and erlane.

The Labska louka lies in the western part of the arctic-alpine tundra of the Giant Mts. on its northern margin close to the border with Poland, above the timberline. The climatic conditions correspond to the characteristics of the cold climatic zone (the average air temperature in January of about –6 ^{o}C, in July between 10 ^{o}C and 12 ^{o}C). The total mean annual precipitation ranges from 1300 to 1400 mm. The Labska louka is situated on the flush surface (peneplain) of the granite massif that is affected by the chemical weathering from the warm period of the end of the Mesozoic era and Tertiary. This disintegrated surface was tabulated to the form of a peneplain. The content of the clayey minerals presents a testament of the weathered surface of the granite pluton. The depth of the weathered zone ranges up to tens of meters. The structure of the soil profile reflects relatively homogeneous geological bedrock with the occurrence of stony fields, detritus and stony streams with the occurrence of solifluction. The prevailing soil type is the mountainous humic and ferro-humic podsole with an admixture of peat (Dystric Histosol). Peat-bogs have developed in some places (e.g. Pancava peat-bog).

In the Labska louka, there are several experimental sites differing in vegetation cover (grass and dwarf pine stand). Each of the experimental sites is equipped with an automatic monitoring station for continuous measurement of air and soil temperatures, suction pressures in the soil, soil moisture, and precipitation amount and intensity.

The Modry potok catchment (upper part of the Modry dul) is located in the eastern part of the Giant Mts. It lies at a distance of about 5 km from the village of Pec pod Snezkou in the district of Trutnov town. The drainage area of this catchment is 2.62 km^2. The highest point is the Studnicni hora Mt. (1554 m a.s.l.); minimum elevation of the closing profile is 1010 m a.s.l. This catchment lies in the centre of crystalline rocks. The coordinates of the closing profile are 15º42'49"E and 50º42'48"N. In the upper part of the catchment, on the southern slope of the valley below the Modre saddle, there is an avalanche slope. On this south-faced slope with a nivation depression an extensive snow accumulation appears every year and creates a big transverse snowpatch. The same situation is found in the upper closure of the valley with long-lasting snowpatches. During the spring melt the big water storage accumulated in the snow is released. Table 2 lists the characteristics of the Modry potok catchment, and Figure 3 describes its physical geographic situation.

On the southern slope of the Studnicni hora Mt. there are extended stony fields and detritus formed mainly by the greyish white mica schist with quartzite and erlane, also gneiss. Along the Modry potok brook stream and sporadically along its tributaries fluvial or fluviodeluvial sediments are deposited and in some places peat-bogs have developed to a smaller extent. The soil types are mountainous humic and ferro-humic podsole and Lithosol with a very thin humic layer; the deeper soil of about 60 cm can be found in the bottom part of the valley close to the Modry potok brook. The climatic conditions correspond to the characteristics of the cold humid climatic zone. Mean annual precipitation ranges from 1200 to 1300 mm.

Table 2: Characteristics of the Modry potok experimental catchment in the Giant Mts.

District	Trutnov
Land register of the village/town	Pec pod Snezkou
Geographic position – E longitude Gr. of closing profile	15º42'49"
Geographic position – N latitude of closing profile	50º42'48"
Maximum elevation	1554.0 m a.s.l.
Minimum elevation	1010.0 m a.s.l.
Drainage area	2.620 km^2
Physical-geographic location	Bohemian Highlands – mountainous country
Geomorphological unit	The Giant Mts. (Krkonose)
Hydrological order of the observed water body	1-01-02-001
Sequence of streams to main river	Modry potok brook – Upa river – Labe river (Elbe)
Vegetation cover and land-use	Forest (spruce and dwarf pine) 62% and mountainous meadows 38%
Geological unit	Krkonose-Jizerske hory Crystalline Complex; mica-schist, phyllite, gneiss, amphibolites, quartzite, erlane
Soil type	Mountainous Humic and Ferro-humic Podzol, Lithosols
Mean annual of air temperature	2.9 ºC
Mean air temperature in January	–5.9 ºC
Mean air temperature in July	12.1 ºC
Mean annual precipitation	1261 mm
Mean number of days with snow cover	196

Automatic monitoring stations are installed at several localities differing in the type of vegetation cover – in the grassland above the forest margin (in the figures denoted as upper meadow), in the growth of dwarf pine, in the growth of mature spruce forest and in the grassland below the spruce forest close to the bottom of the valley (in the figures denoted as valley meadow). The discharge at the closing profile is continuously recorded. An automatic meteorological station on the Studnicni hora Mt. represents the highest position of the catchment. The Modry potok catchment has been included in the GEOMON monitoring network. The mass balance has been measured since 1994: chemistry of the surface runoff, throughfall and bulk precipitation.

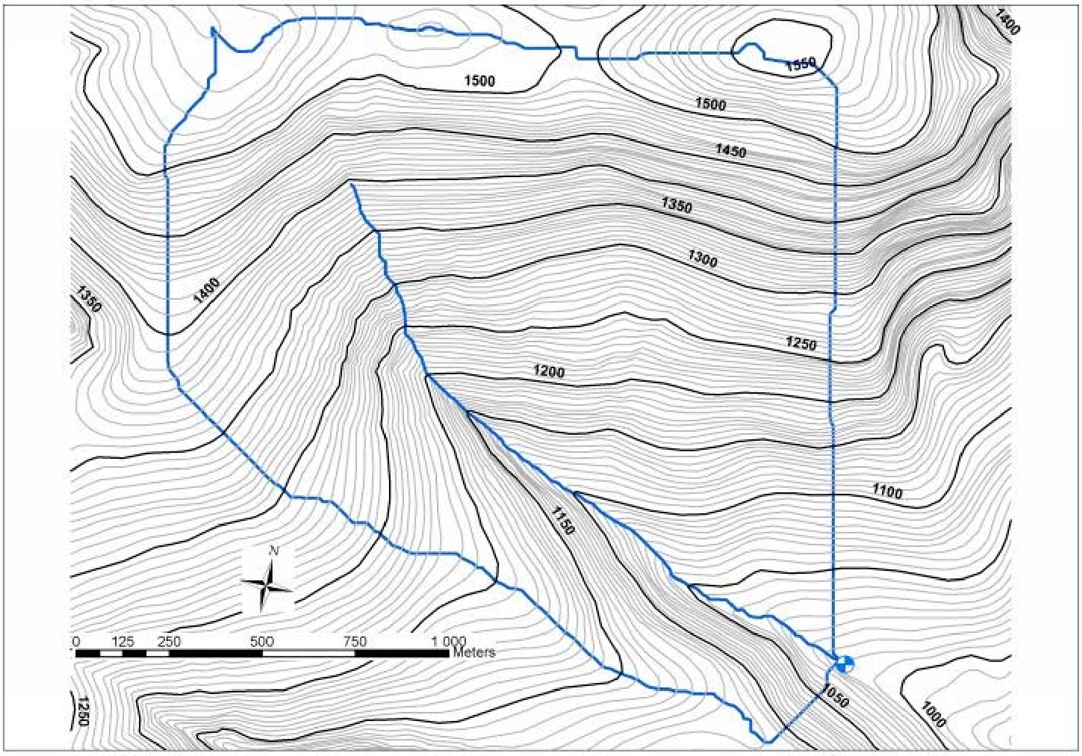

Fig. 3: Physical geographic sitution of the Modry potok experimental catchment

3.3 Jizerske hory Mts.

The Uhlirska catchment is located in the western part of the Jizerske hory Mts. at a distance of about 7 km from the village of Bedrichov in the district of Jablonec nad Nisou town. It lies in the Cerna Nisa basin. The region of the Jizerske hory Mts. is composed of granite and monzogranite rocks of the Variscan granite pluton Massif. The basic rock type is porphyry medium granular biotite granite. In the crystalline complex cover the metamorphic rocks of the Under-Proterozoic and Under-Paleozoic age occur. The quaternary cover sediments are shallow. They are predominantly formed by the slope detritus with weathered substratum, peat sediments and fluviodeluvial sandy loam often with an admixture of rock fragments.

In the Uhlirska catchment soil profiles can be split into two basic groups. The first is formed by the soil profiles in the upper part of the catchment which originates from the weathered granite substratum belonging to the Cambisols registered as acid Eutric Cambisol with Distric Gleyic Cambisol soil sub-type. These are clayey-sandy and sandy-clayey soils with an admixture of rock fragments partly very coarse without any marked structure. The soil profile is regularly formed by 5 cm of a vegetation cover, 15–20 cm of the peat humic black coloured layer, 10 cm of the transitional gleyic greyish black clayey-loamy layer, 30 cm of the brown or ochre clayey-sandy layer and 30 cm of the eluvial yellow brownish layer which changes smoothly to weathered granite. Through the whole soil profile the emphatic disturbances occur in the form of connected vertical in-leaks of iron oxide. The second group is formed by the soil profile at the valley bottom with alluvial deposit that is covered by peat layers of different depths. The soil profile is regularly formed by 5 cm of vegetation cover, 0.5–2.0 cm of peat, 0.5–1.0 m of clayey-gravelly, very compacted soil without any structure with a depth of a few meters. These peat regions cover 10% of the drainage area of the catchment. The remaining area is formed by the soil profile of the Eutric Cambisol that changes peat in the waterlogged spots.

The drainage area of the Uhlirska basin is 1.87 km^2. The coordinates of the closing profile are 15º08'54"E and 50º49'31"N. Maximum elevation of the catchment is 872 m a.s.l., minimum elevation 774 m a.s.l. and mean elevation 822 m a.s.l., average slope of the thalweg 2.3 %, catchment length 2.1 km, average width of the catchment 0.89 km. The mean length of the slopes is about 450 m. The Uhlirska catchment area was nearly completely deforested at the beginning of the eighties. New forests are up to 20 years old. Table 3 summarises the characteristics of the Uhlirska catchment and Figure 4 describes its physical geographic situation.

Table 3: Characteristics of the Uhlirska experimental catchment in the Jizerske hory Mts.

District	Jablonec nad Nisou
Land register of the village/town	Bedrichov
Geographic position – E longitude Gr. of closing profile	15º08'54"
Geographic position – N latitude of closing profile	50º49'31"
Maximum elevation	870.0 m a.s.l.
Minimum elevation	774.0 m a.s.l.
Drainage area	1.870 km^2
Physical-geographic location	Bohemian Highlands – mountainous country
Geomorphological unit	The Jizerske hory Mts.
Hydrological order of the observed water body	2-04-07-016
Sequence of streams to main river	Cerna Nisa river – Luzicka Nisa river – Odra river
Vegetation cover and land-use	Forest (prevailing type is spruce 15%), naked surface or spruce forest up to 15 years old 85%
Geological unit	Krkonose-Jizerske hory Crystalline Complex; porphyry medium granular biotite granite
Soil type	Podzolic Eutric Cambisol, Ferro-humic Podzol, Eutric Histosol, Distric Histosol
Mean annual of the air temperature	6.5 ºC
Mean air temperature in January	–4.8 ºC
Mean air temperature in July	13.8 ºC
Mean annual precipitation total	1400 mm
Mean number of days with snow cover	172

The Uhlirska catchment lies in the area with the highest precipitation in the Czech Republic, amounting to more than 1300 mm per annum; the average air temperature is 6.5 ^{o} C. This area represents the mountainous type region with an average elevation of 780 m a.s.l. The results of precipitation measurements for the time period 1901–1950 are: the total precipitation for the growth season (April – September) 781 mm and for the winter season (October–March) 598 mm. The hydrological data for the Cerna Nisa basin, the Uhlirska catchment (time period 1931–1960) are: annual precipitation 1400 mm, runoff depth 1018 mm, runoff loss 382 mm. Annual mean discharge is 63 l/s and specific discharge 33.7 l/s km^2.

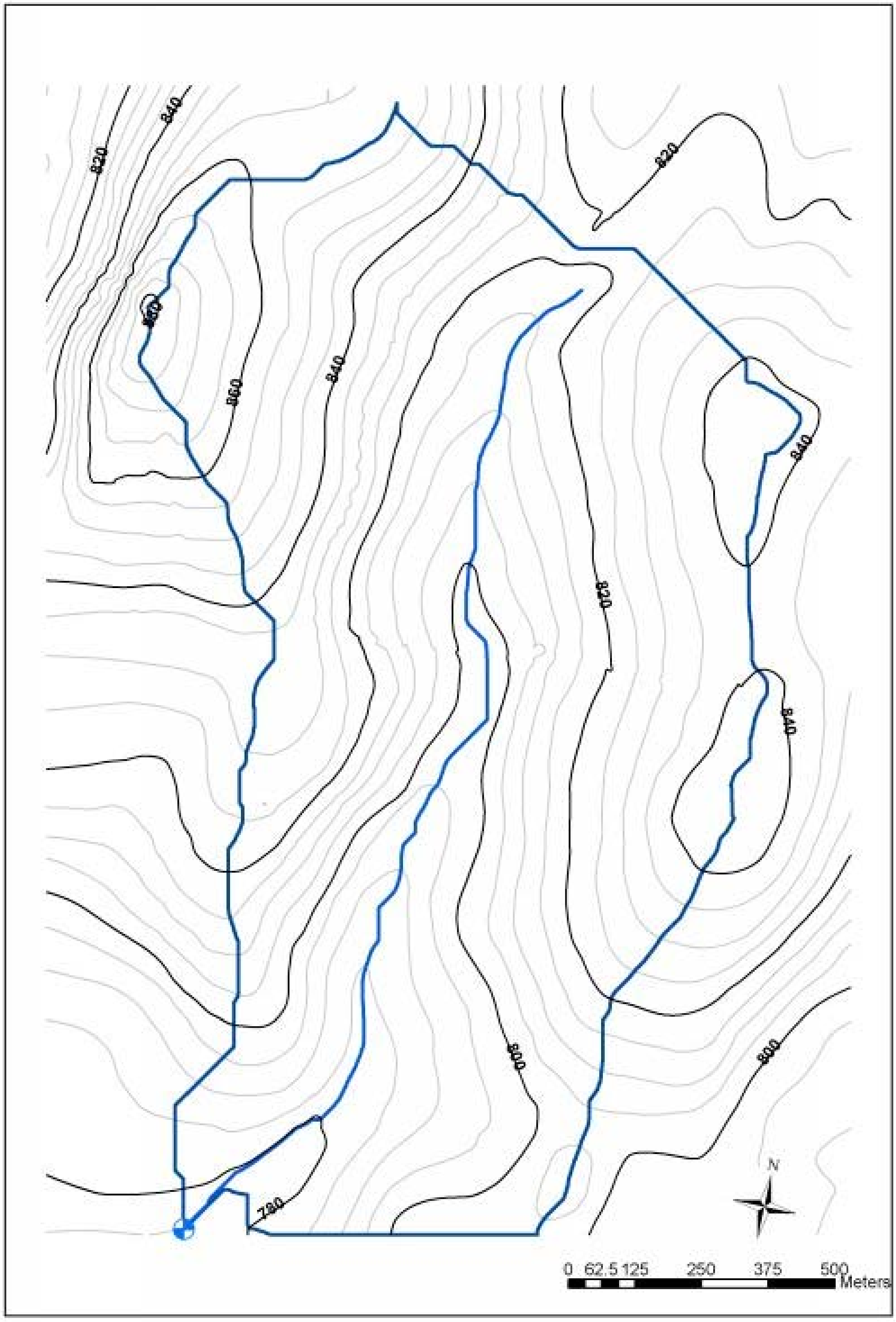

Fig. 4: Physical geographic situation of the Uhlirska experimental catchment

In the Uhlirska catchment the slope transect was chosen and instrumentally equipped. The slope soil profile developed on the granite is very shallow, it reaches a depth of about 1 m on average and it is formed by the Eutric Cambisol with an important percentage of rock fragments. Conversion from the soil profile to the weathered zone of the granite is very gentle. At the valley bottom there is a surface layer of moist peat with a depth of 0.5–1.0 m with clayey, ochre-coloured gravel below. On the monitored slope and on the forest stand the sets of the water tensiometers are installed.

An automatic meteorological station is located in the upper part of the catchment. In the forest there are wo catching areas for the measurements of the throughfall. In the second third of this catchment a snow-monitoring station has been placed for the continuous monitoring of the snow cover depth and water equivalent, snow temperatures at various levels, and air temperature and humidity at 2 m height. Five automatic rain gauges, two cloud and fog water collectors have been placed here as well. In the closing profile an automatic station with discharge, pH and conductivity records of the surface runoff is located. On the right bank and close to the climatic station 32 plastic pipes for the measuring of soil moisture have been installed. The Uhlirska catchment is part of the GEOMON monitoring network. The mass balance has been measured in this basin since 1994: chemistry of the surface runoff, throughfall and bulk precipitation.

4 Results and discussion

Soil moisture at a depth of 15 cm during August 2002 and 2003 at the measuring plots in the Modry potok catchment are shown in Figures 5a, 5b and Figures 7a, 7b. Soil moistures above 50 % (vol.) are biased due to non-linearity of the soil moisture sensors. The results presented clearly illustrate how the soil moisture of the surface layer reacts to precipitation. The corresponding precipitation is depicted in Figure 6 and Figure 8. The highest soil moisture was found below the dwarf pine cover due to the high content of peat in the soil. The lowest soil moisture was found in both grassland locations: above the forest margin (denoted as upper meadow in the figures) and below the spruce forest close to the bottom of the valley (denoted as valley meadow). This is caused by the low retention capacity of the mainly mineral and simply structured soil. The peat soil below a dwarf pine cover largely accumulates water so that even a small precipitation input causes a marked soil moisture increase (Fig. 5).

August 2003 was extraordinarily warm. Figures 7a and 7b show the continuous withdrawal of the soil moisture till the precipitation events on 18-19 August. The decrease of the soil moisture at 15 cm is roughly the same as in each of the monitored plots. It proves that different vegetation cover transpires identically. The same phenomenon was observed after the infiltration of precipitation from 21 August to the end of the month.

The total catchment retention was derived as a difference of the cumulative precipitation and cumulative runoff (Czelis and Spitz, 2003). The maximum total catchment retention during the precipitation event of 18-19 August is evaluated in Figure 8. During this precipitation event the maximum total retention was about 50 mm whereas precipitation amounted to 60 mm at the moment of maximum retention. Surface runoff did not occur. A surplus of 10 mm probably passed through the soil profile to the subsoil. Accordingly, the retention capacity of the surface layer was not reached by rain water.

During the extremely rainy month of August 2002 (Fig. 5) the maximum rainfall amount was recorded from 10-14 August. The maximum total catchment retention during this precipitation period can be estimated at 70 mm (Fig. 5). The precipitation reached 130 mm at the moment of maximum retention. During the rainfall event surface runoff occurred because the retention capacity of the surface layer of 20 mm was strongly exceeded. This capacity can be estimated as a difference between a maximum total retention of 70 mm during an extreme precipitation event and of 50 mm during maximum precipitation which does not cause any surface runoff.

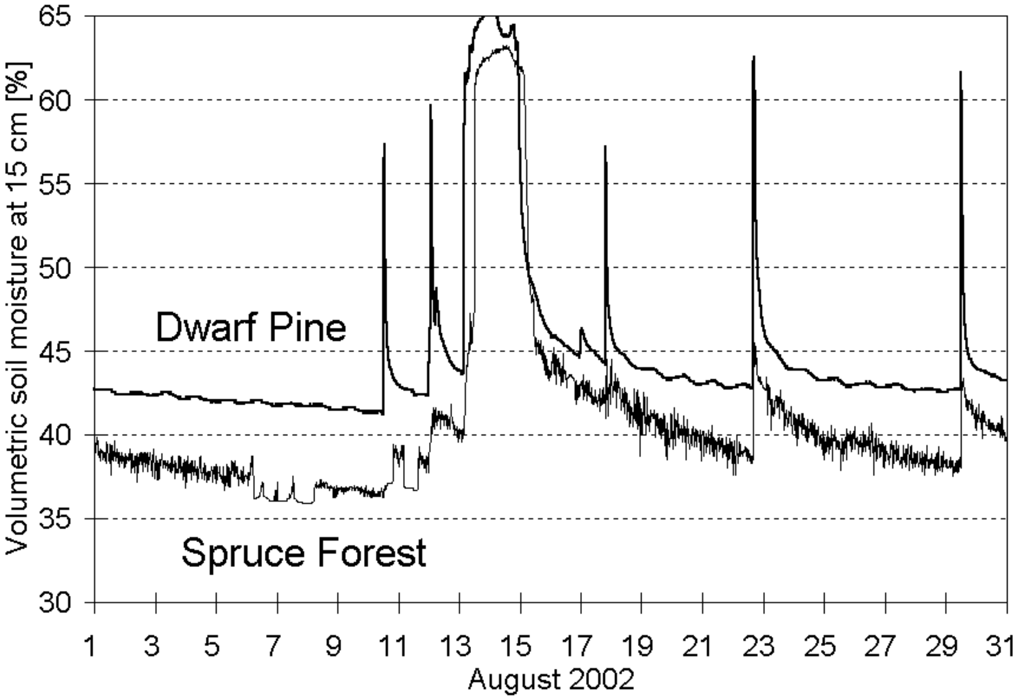

Fig. 5a: Soil moisture at a depth of 15 cm at two localities in the Modry potok catchment (dwarf pine and spruce forest) during August 2002

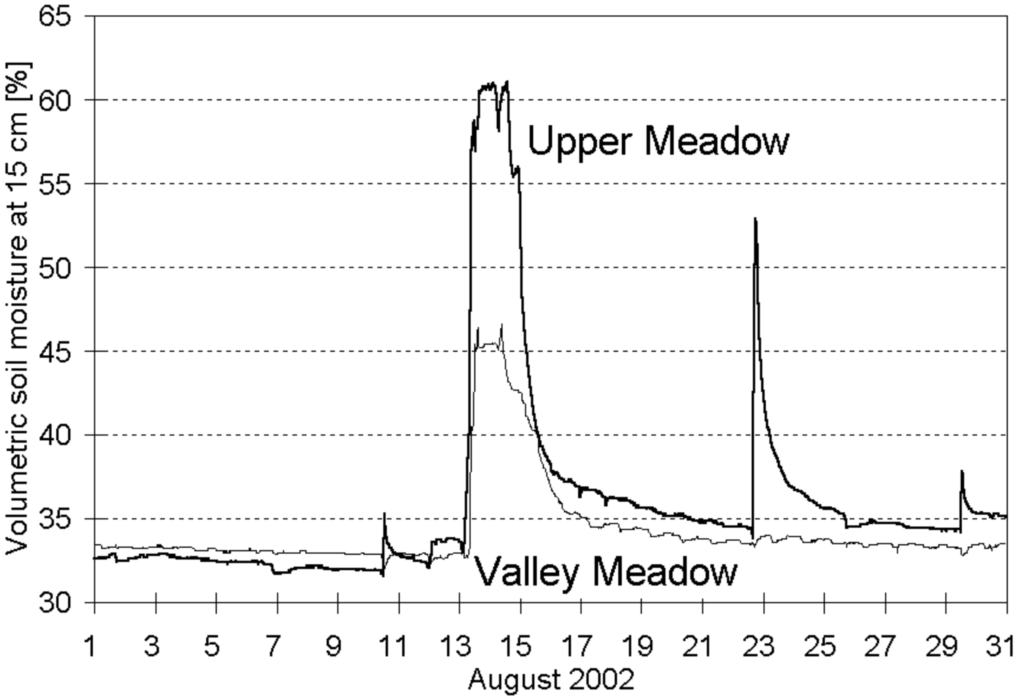

Fig. 5b: Soil moisture at a depth of 15 cm at two localities in the Modry potok catchment (upper meadow and valley meadow) during August 2002

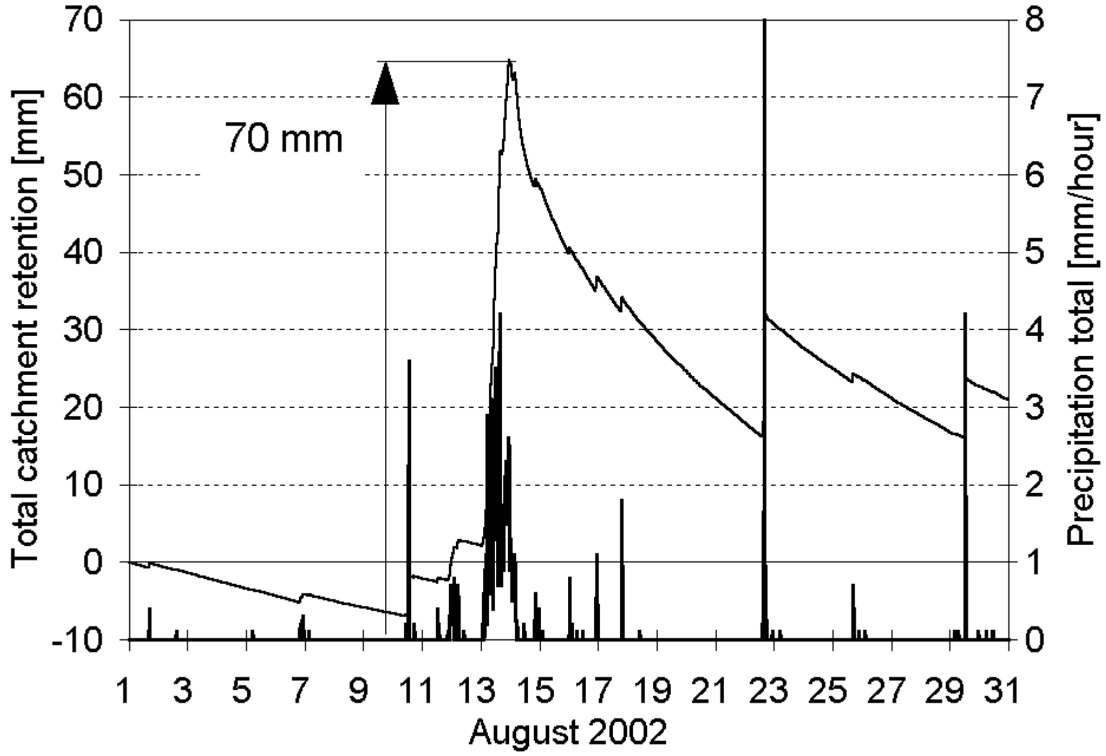

Fig. 6: Precipitation and water retention in the Modry potok catchment during August 2002

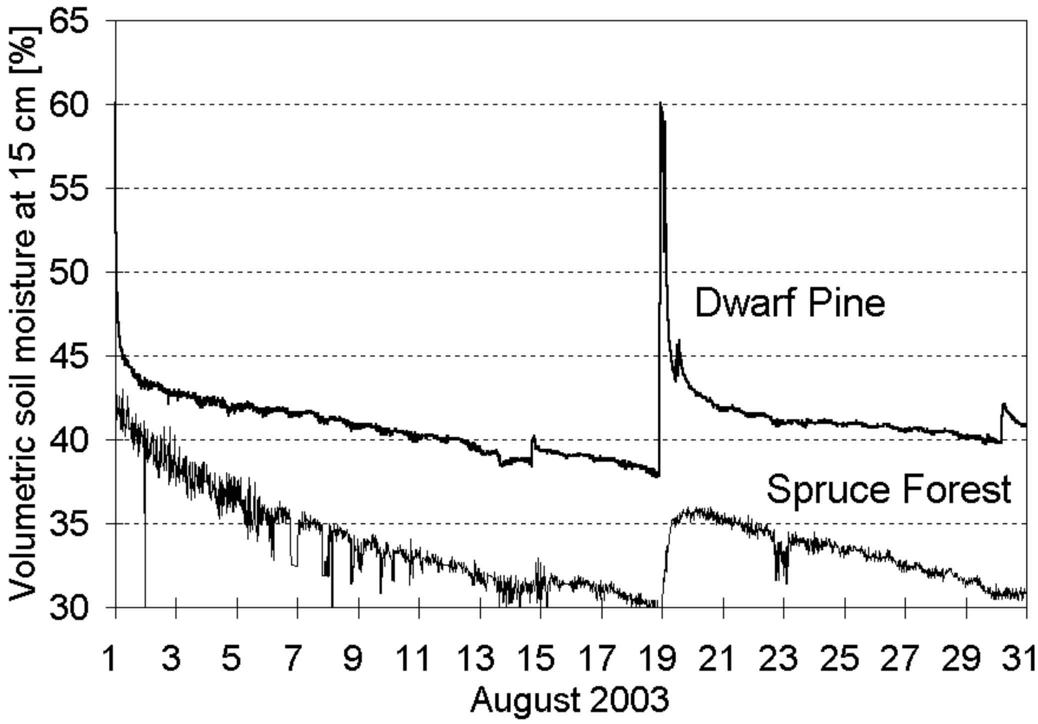

Fig. 7a: Soil moisture at a depth of 15 cm at two localities in the Modry potok catchment (dwarf pine and spruce forest) during August 2003

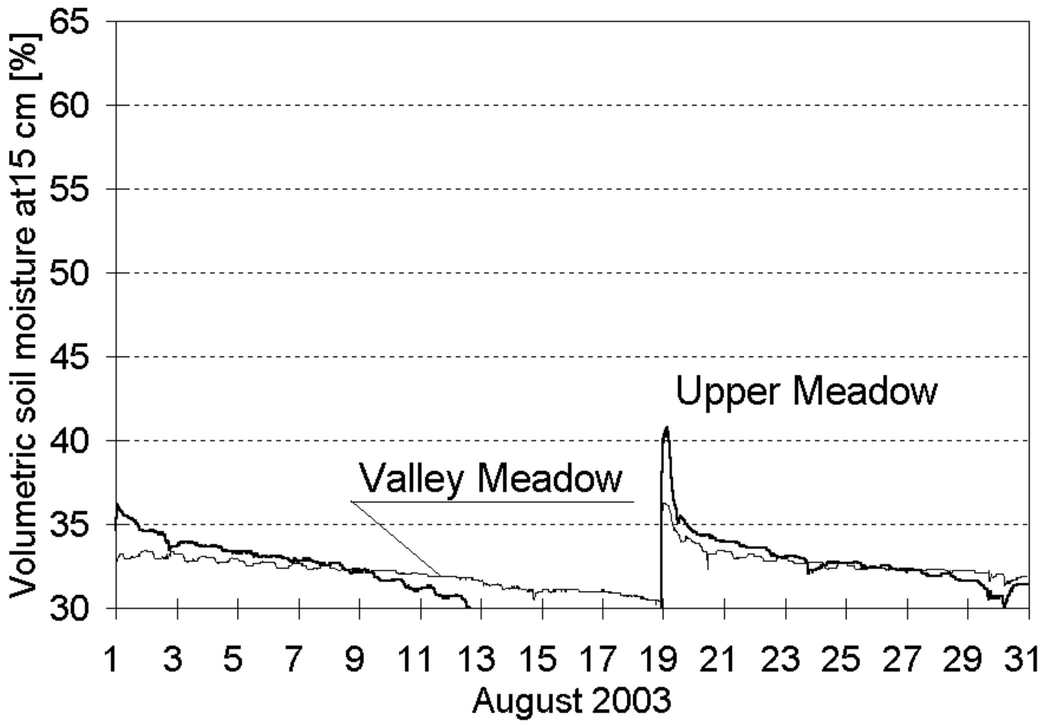

Fig. 7b: Soil moisture at a depth of 15 cm at two localities in the Modry potok catchment (upper meadow and valley meadow) during August 2003

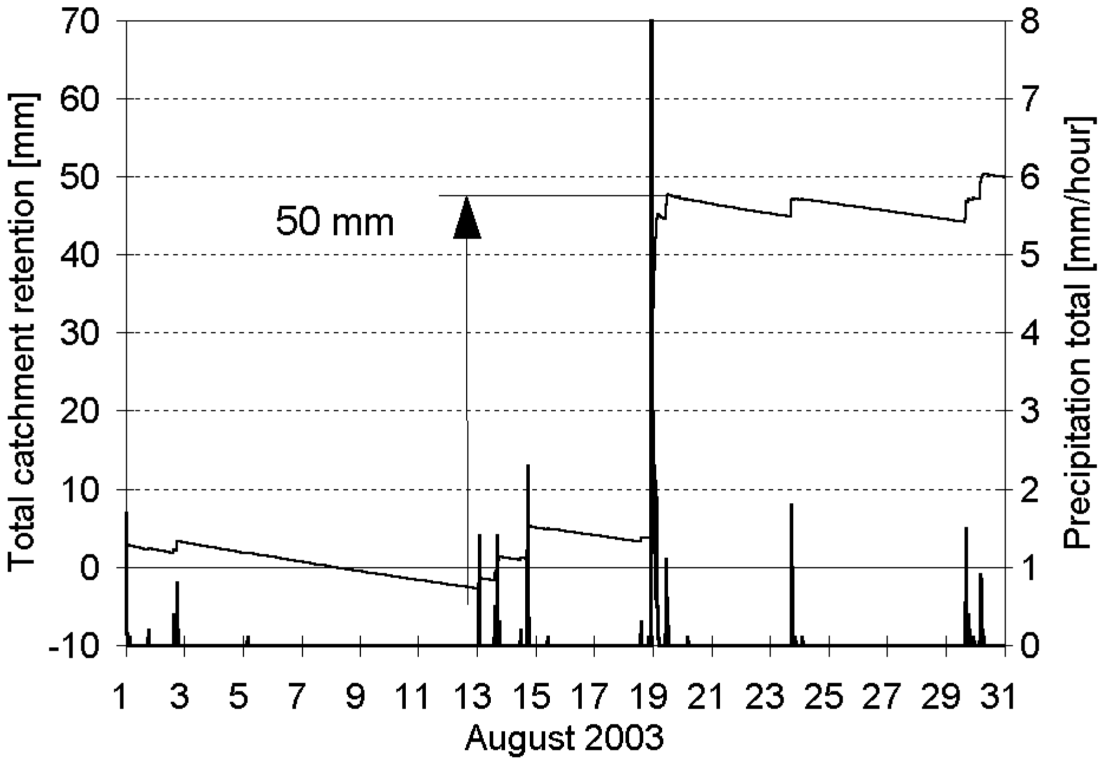

Fig. 8: Precipitation and water retention in the Modry potok catchment during August 2003

5 Conclusions

To conclude, the actual knowledge about the influence of the vegetation cover and its changes on the regime of the soil and head water regimes of catchments, not only in the Giant Mts. but also in the Sumava and Jizerske hory Mts., confirms the validity of the conclusions drawn from the long-term experimental research in the Beskydy Mts. According to the publication (Chlebek and Jarabac, 1988): "The research of the rainfall-runoff relationships in the experimental catchments of the Beskydy Mts. provided a finding that the successive renewal intervention, affected less than 50% of a drainage area, did not influence the annual runoff depth. Only after this percentage has been exceeded is it possible to observe a tendency to a reasonable increase of the runoff depth, but the reasons for these changes cannot be exactly identified. The probable explanation means that the restriction of the evapotranspiration for the benefit of the runoff arises when the whole ecosystem is suddenly affected. Under conditions of successive renewal of the vegetation cover, a natural compensatory tendency supporting the stability of the water component of the forest environment can be applied long-term. It will be possible to apply the practical effects of this finding to the strategies of both the forestry and water management after verification by further research".

It is necessary to emphasise that a conclusion on the independency of the soil water regime from the vegetation cover diversity is not valid during droughts that are extreme from a plant-growing point of view. Under these conditions the diversity of the water-handling of the plants is expressed markedly between the individual vegetation cover as e.g. shown in the studies of the water regime under the subtropical conditions when the lack of water represents a limiting factor of the plant growth (Scott and Lesch, 1997).

Under extreme precipitation such as 60 mm daily, the retention of water on the soil surface strongly depends on the species composition of the vegetation cover and on its evolutionary stage (Kurik, 2000). Approximately 20 mm of the maximum total retention of 70 mm can be influenced by the vegetation type in the Modry potok catchment.

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Hydrological investigations of experimental watershed basins

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1 Introduction

The beginning of hydrological investigations in Bulgaria dates back to the early years of the 20th century when the first specialised investigations were conducted in connection with the planned construction of energy and melioration facilities along rivers in Central Bulgaria – the rivers Rossitsa, Topolnitsa and Tundja. Large dams and water power plants were constructed later on each of them. This motivated the establishment (after 1920) of a modern hydrological network of experimental watershed basins (EWBs) for the collection of information required for the identification of the energy potential of the water resources and the possibilities for their utilisation for irrigation and water supply, as well as for the resolution of problems related to their management and protection. Consequently, the need to create experimental hydrological basins for performing scientific investigations, complex measurements and student training was recognised (Fig. 1). Multi-annual, continuous and regular measurements were launched at some of these sites, which had served as the basis for regional or specialised studies, scientific publications and discussions on the water cycle, soil erosion, forest management issues, productivity of forests and agriculture, optimum efficiency of protection activities and a range of other research and practical issues.

This paper contains a brief description of the major operating experimental basins and sites in Bulgaria and their subordination to different research institutes. Several hydrological investigations are presented in brief with the aim of identifying the opportunities, which they offer.

2 Experimental watershed basins (EWBs)

A multitude of temporary EWB were set up in past decades in response to the needs of empirical information by different research institutes and universities. Some of them have won a lasting place in the programmes of their creators and have become part of the non-material stock for conducting profound research in the field of hydrology, forestry, environmental pollution, biomonitoring, protection of bio-diversity, etc. Even more numerous are the experimental sites in the field of agriculture, investigation of the soil resources, etc. As a result of the financial constraints imposed during the recent 10-15 years, their number has significantly diminished and currently only the representative hydrological basins shown in Figure 1 are still operating.

2.1 Yundola-based EWB of the Forestry University, Sofia

The EWB is situated in the Yundola location in the Rila Mountains in Central South Bulgaria on an area of 321 hectares at an altitude of 1500 m (Fig. 2). It includes 10 plots with different

Fig. 1: Representative hydrological basins in Bulgaria

orientations, terrain gradients and densities of tree vegetation. The plots are equipped with controlled metering systems. The region is covered by mixed coniferous forests. The river network is dense and includes small permanent and numerous temporary streams running at high velocity down steep gradients.

The EWB comprises ten water catchments (Fig. 3), eight partial and two general ones (Upper Water catchment and Bottom Water catchment), which embrace the former ones. Their major hydrographic characteristics are shown in Table 1. A limnigraphic gauge is set up at the estuary of each water catchment as well as a network of six pluviographic gauges, three gauges located along the watershed divide and another three within the boundaries of the investigated hydrographic network. The observations of the precipitation rate and the resulting water runoff are carried out on a daily basis from the period of spring thawing (the beginning of May) till the autumn freeze (the beginning of November).

In terms of geological-petrographic structure southern Bulgarian granites (granite-gneises) predominate in the area. The soils in the experimental plots are represented by one zonal type: brown forest soils. According to the climatic division in the regions, the area of the EWB falls entirely under the medium-mountainous part of the mountain climatic region of the transition continental subregion of the European continental climatic region. In terms of vegetation cover the experimental plot belongs to the medium or mountainous belt consisting of mixed forests - Norway spruce, silver fir and beech.

Fig. 2: View of the Yundola locality in the Rhodopes Mountains

Table 1: Range of fluctuation of the hydrographic characteristics of the partial Water catchments (according to Biolchev et al., 1970)

Water catchment	Area, km^2	Coefficient of extension of the watershed	Average width of the watershed, km	Symmetry of the water catchment area	Length of hydrograph. network, km	Density of hydrographic network	Average gradient, %	Mean altitude above sea level, m
1	0.144	1.12	0.232	0.210	0.600	5.26	25.6	1.548
2	0.222	1.43	0.500	0.198	1.100	4.97	14.1	1.561
3	0.097	1.32	0.173	0.031	0.550	5.67	32.2	1.551
4	0.324	1.13	0.330	0.429	1.200	3.45	20.0	1.542
5	0.082	1.23	0.137	0.219	0.500	6.09	33.4	1.538
6	0.245	1.15	0.288	0.429	0.850	3.49	23.9	1.472

Because of the high water-bearing capacity of this part of the Rila and Rhodopes Mountains big hydro-engineering facilities have been constructed here – large dams, surface and underground water power plants, high-pressure pipelines and high-altitude mountain-water collection channels, etc. Further construction works are underway at present as well.

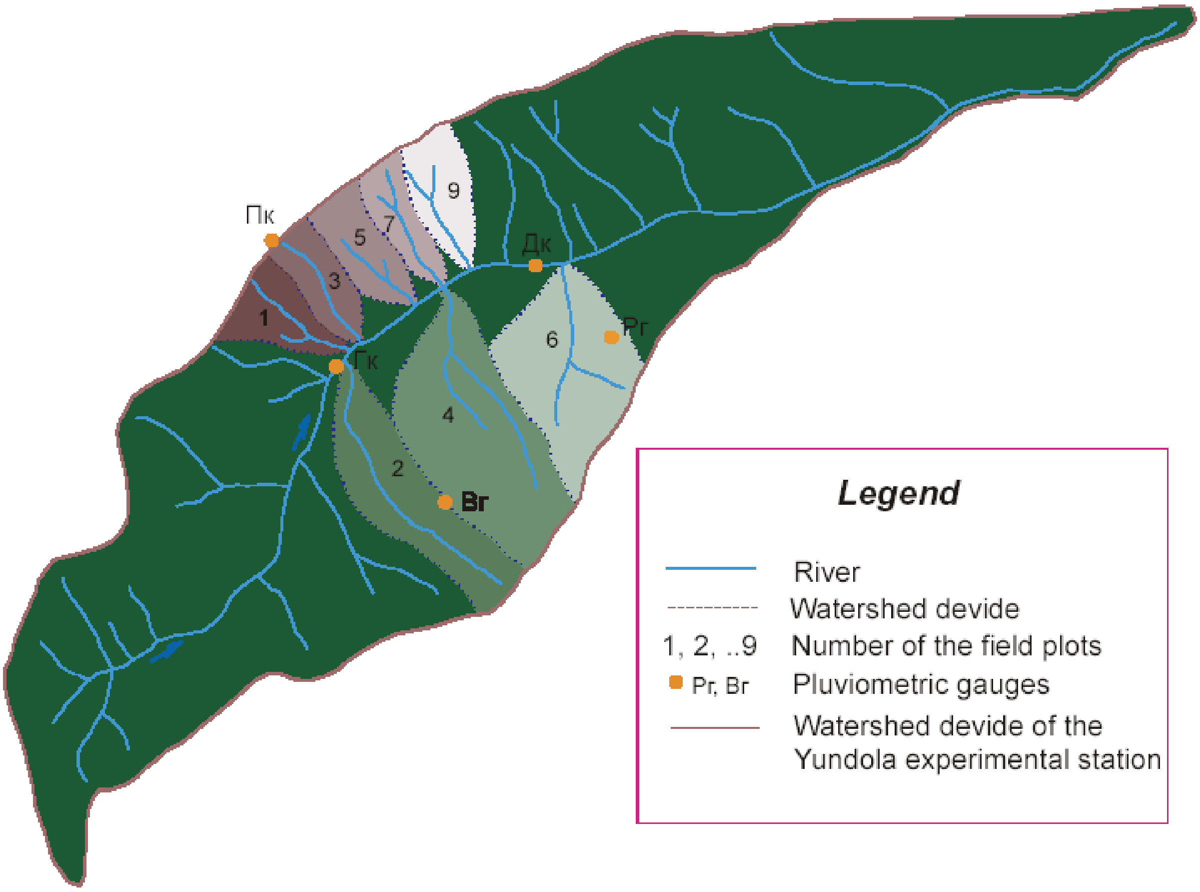

Fig. 3: Schematic plan of the location of the experimental hydrological basins

The EWB was founded in 1961. Regular observations, however, started in 1965. It is part of the EWB of the Training Experimental Forestry Enterprise. The main purpose of the EWB is the systematic study of the processes of liquid and solid runoff formation with special emphasis on the role of forest ecosystems and the factors of coniferous forest management. In this connection studies have been made of the characteristics of soil and litter forest cover, the forest stand and regeneration, runoff chemistry and leaf mass biochemistry. Experiments have been conducted with different modalities of fertilising. The influence of logging technology on the water-bearing and soil protection functions of forests and precipitation chemistry in the case of air pollution have been studied. The information provides the opportunity of making "background" assessments of the effects of selection, shelter-wood and clear cuttings. Another major aim of the studies is to reveal the main factors, relationships and forms of manifestation of water-provoked erosion.

Many other studies and experiments, related to almost all the components of the forest ecosystems, have been conducted here since the EWB was established in the early 1960s. The main users of the results of the scientific studies are expected to be the following:

- Forestry business entities which will be able to get recent information about the advance of soil erosion, the appropriate erosion-preventive activities, the conditions for and risks of formation and spread of high drainage water quantities;
- Water and energy supply business entities for which the amount of available water resources and the risk of rapid clogging of water reservoirs are of utmost significance.

2.2 EWB at Petrohan of the Forestry University, Sofia

The EWB is situated in the West Stara Planina (the Balkan) Mountain Range in the region of the Petrohan locality and is characterised by a moderate continental climate and an average altitude of 1200 m above sea level. The annual amount of precipitation is 1060 mm, with April-May maximum and January minimum. The average length of the vegetation period is 6-7 months, from May till October.

The hydrological investigations at the Petrohan EWB are conducted in four temporary experimental water catchments with their characteristics shown in Table 2. The precipitation rates are metered according to the commonly applied methodology by means of the Vild rainfall meter and the runoff by means of Ponsele-type overflow devices, located at the bottom end of the water catchments.

Table 2: Characteristics of the water catchments at the Petrohan EWB (Management of water-bearing zones, Research team)

Indicators	K1	K2	K3	K4
Area, ha	38.1	30.7	28.6	59.2
Mean altitude above sea level, m	1200	1400	1200	1100
Terrain gradient, ^{o}	32	28	29	24
Forest stand composition	Beech	Beech	Beech	Beech

Comparative monitoring studies have been carried out on the EWB since 1986 with the aim of finding out the changes in the chemical composition and the acidity of precipitation when passing through the spruce and beech-tree crown, using natural and plastic trees for that purpose (Ignatova et al., 1997). In 1992 G. Gergov studied the formation of the surface water runoff for the purposes of water supply and energy generation. Regional water balances have been compiled and an assessment was made of the impact of human intervention on the state of the environment and water resources in the area.

Other problems, related to forest research, have been studied in the EWB as well. They comprise the rate of natural recovery, the influence of logging on the water-bearing and soil protection functions of forests, the impact of acidic precipitation on an open area and the area under the canopy, the lysimetric runoff, etc. The dynamics of heavy metal migration and environmental pollution has been studied as well for the period after 1926 on the basis of dendrological analysis. For additional or comparative investigations meterings are conducted, whenever necessary, at the nearby Barziya EWB.

2.3 Experimental river section of the Forestry University, Sofia along the River Darvenishka

The River Darvenishka takes its source from the Vitosha Mountain and flows north, crossing the south-eastern quarters of Sofia and discharging its water in the River Slatinska, a tributary of the River Iskar. Its total catchment area is 20.9 km^2. Investigations have been carried out along the river course to determine the organic pollution by means of oxygen parameters:

amount of dissolved O_2, saturation with O_2 in accordance with the accepted standard methods, etc. The leaching of K, Na, Ca and Mg from the adjacent bank strips has been studied as well. The content of heavy metals such as Cd, Pb, Cu and Zn has been recorded and studied using an atom adsorption spectrophotometer, etc.

The river section is situated close to densely populated residential areas and this provides the possibility of performing new specialised investigations on the formation of river pollution under urban conditions and on the migration of pollutants and their transformation as a result of self-purification.

2.4 EWB of the Forest Research Institute in the Leeve locality

The EWB is situated within the boundaries of the "Yakoruda" forest farm in the Leeve locality, on the southern slopes of the Rila Mountain at an altitude 1400-1650 m. The soil cover is brown forest soil. The predominant type of rock is granite.

The main topic of the investigations carried out on the EWB is to determine the water balance in areas of limited size occupied by uniform representative vegetation, predominantly Scots pine. The investigations include the precipitation, interception and runoff from tree trunks. Regular observations and measurements of surface and interstitial soil underground runoff have been organised and carried out for this purpose.

Descriptions of the investigations conducted and their major findings are given in articles by Serafimov (1974), Raev (1983), etc..

2.5 Gabra EWB of the Forest Research Institute

Coniferous plantations which were established for erosion-prevention purposes in the past three to four decades represent a large part of the forest ecosystems at altitudes below 800-900 m in Bulgaria. The investigations in these plantations have been carried out because of the interest in the plantations' ecological importance, their hydrological and soil-protecting roles, in particular.

The investigations of Scots and Austrian pine plantations, grasslands and fallow plots were started in the EWB of Gabra which was established for this purpose in the Sredna Gora (Central Mountains). It is situated on the south-facing slope, at an altitude of 850-900 m. The parent materials are mainly schist and the soil is Luvisol.

The investigations were carried out on drainage plots built up especially for this purpose. Their areas were of 150 and 300 m^2. Different trial variants were applied: pure and mixed plantations of Scots pine (*Pinus sylvestris* L.), Austrian pine (*Pinus nigra* Arn.), Norway spruce (*Picea abies* (L.) Karst), birch (*Betula sp.*). Grass and fallow lands were left as reference plots.

The main results refer to interception, surface runoff and soil-losses. The effectiveness of anti-erosion afforestation and the ways of managing the plots (grass-covered land and fallow land) has been evaluated based on a coefficient obtained as a ratio between the actual soil loss and the tolerable one under the same edaphic conditions. The amounts of eroded soil in the investigated forest plantations and grasslands were considerably smaller than the tolerable soil loss - the coefficient's values were lower than 0.1. For the fallow plots, the amounts of tolerable soil losses were larger than 5.0 times.

2.6 EWB of the Forest Research Institute on the Malashevska Mountain

The EWB is situated in south-west Bulgaria near the village of Igralishte, in the Blagoevgrad district. It is situated on the southern slopes at the upper end of the Malashevska Mountain at an altitude of about 700 – 800 m (Fig. 4). The EWB is intended for the determination of the conditions of water and solid runoff formation and its quantitative characteristics in representative small catchment areas of the hydrographic network.

Fig. 4: Snapshot of part of the experimental sites

The EWB comprises four field plots, conventionally marked 1 to 4 and featuring different vegetation cover and duty cycle of land-use. Their major characteristics are shown in Table 3 (according to Mandev, 1984).

The major objective of the investigations is to identify the dynamics of the water and solid runoff, its quantitative and duty cycle characteristics, and to determine the maximum and mean coefficient of the water runoff and the runoff turbidity. A study was conducted of soil erosion intensity under natural conditions at different gradients of the sites, under different agricultural crops and forest plants, different technologies of cultivation and fertilising of the surface cover, etc.

The quantity of surface water and solid runoff is established by means of permanent metering with genuine runoff collection devices. The floating solid runoff is determined on the basis of averaged water samples along the river course, while the summary quantity of river-bottom sediments is determined by means of precision metering of the sediments in specifically set-up “tanks”. The rainfall quantity is metered by means of raingraphs and conventional rainmeters installed in the open, as well as below and among the tree crowns.

Table 3: Geomorphological characteristics and distribution of the basin in the water catchment areas by soil and relief indicators

Indicators	Water catchment no.			
	1	2	3	4
Water catchment area in km^2	0.648	0.135	0.075	0.551
Coefficient of development of the watershed line	1.31	1.05	1.16	1.37
Average width of the water catchment area in km	0.703	0.330	0.152	0.388
Mean riverbed gradient in %	13.5	12.2	15.2	9.3
Hydrographic network density in km/km^2	5.0	9.33	9.0	7.35
Average surface gradient of the water catchment area in %	33	30	33.6	25.9
Altitude above sea level:				
700 m	11.0			
800 m	89.0	100	100	100
Humus				
a) humus-deficient	71.8	77.7	93.7	57.3
b) humus-saturated	28.2	22.3	8.3	40.7

There are several publications devoted to the results of the investigations conducted by A.Mandev (1980, 1982, 1984, etc.) in the EWB of the Forest Research Institute in the region of the Malashevska Mountain.

2.7 EWB of the Forest Research Institute in the Parangalitsa locality

The EWB is located within the boundaries of the Parangalitsa nature-protected area. It has been set up with the aim of investigating the quantitative and qualitative characteristics of the water balance components in spruce forests in a high-mountain locality. The area is situated on the western micro-slope of the Rila Mountain in the upper part of the River Blagoevgradska Bistritsa, the catchment of which spreads from 1450 to 2490 m a.s.l. in highly productive spruce ecosystems (altitude of 1450-1650 m a.s.l.), mean annual temperature 4.9^{o} C in the open and 4.5^{o} C inside the forest, precipitation rate about 933.7 mm (Fig. 5). The site is situated on the borderline between areas of cool and moderate mountainous climate and part of the "optimum zone" for development of coniferous vegetation.

The components of the water balance are metered and reported as follows:
Liquid precipitation is metered via 12 standard rain gauges and one rain graph, solid precipitation via snow-metering snapshots at every fresh snowfall. The strength of the snow cover is determined daily through seven snow-metering racks, set at each experimental field. The runoff from the tree trunks is collected by means of spirals. The interception is determined depending on the difference between the precipitation in the open and inside a forest. The evaporation of the soil surface is determined by means of weight evaporators inside the forest and in the open, using soil monolites (500 cm^2). The surface water runoff is measured by means of water balance sites (size 20x50 m or 1000 m^2) and a Valday-type limnigraph. The infiltration under the ryzospherical soil layer and soil humidity are also metered. The meteorological components, such as air and soil temperature, air humidity, wind velocity and direction, etc. are also metered (Raev, 1986).

Fig. 5: View of the experimental basin

The information accumulated in the course of the years in the protected and other EWBs of the Forest Research Institute has been collected and reported in detail by Nedyalkov and Raev (1988).

2.8 EWB of the Forest Research Institute in Govedartzi

The EWB is situated in spruce stands on the northern slopes of the Rila Mountain in the altitude zone of 1400-1600 m as part of the technical section of the Samokov Forestry Department in the village of Govedartzi. The climate is mountainous with continental influence, the annual precipitation is 999 mm with a spring maximum of 560 mm. The soil is dark brown forest soil, average to strong, clay-sand, formed on vaporised gneiss products. The favourable soil properties in combination with adequate hygrothermical conditions of the location of growth create a favourable ecological environment for the formation of highly productive spruce plantations.

The following topics have been studied in the EWB: the variations in the physical properties of the forest cover under the influence of the forest vegetation, the water balance and the water-retaining effect of the shrub-herbaceous and moss cover, the soil hydrological properties, etc. (Raev, 1973, 1974, 1976, 1978, etc.).

2.9 Laboratory of Marine Ecology (LME) of the Institute of Ecology

The LME is a field EWB of the Central Laboratory of General Ecology. It is located in the town of Sozopol on the coast of the Black Sea. LME is specialised in coastal ecosystems and wetland investigations (Hiebaum, 1993).

A laboratory of general ecological investigation, a chemical-analytical laboratory, an instrumental laboratory, a radio isotopic laboratory, a workshop, stores and a kitchen are situated on an area of 230 m^2. The basic scientific instrumentation comprises a spectrophotometer and the corresponding devices for water analysis; an oxymeter and pH-meter, microscopes and devices for phytoplankton and microbiological investigations; a luminometer; a liquidscintillation counter for radio-izotopic measurements. There is a "microcosm" construction for investigations of water/sediment interactions in combination with the techniques applied in the laboratory for the fluxes of oxygen, organic carbon, and nutrients and polluted environment. In the coastal zone "mezocosm" constructions (50-200 I) can be used in investigations on the impact of different nutrients and other substances on the planktonic community.

The main measurements (techniques/analyses) applied by the laboratory are directed to fix the abiotic parameters of the environment: temperature, wind, oxygen concentration, concentrations of NH_4, NO_2, NO_3, PO_4, N_{tot}, N_{org}, C_{org} in sediment as well as functional parameters of the planktonic community: primary productions of glucose, amino acids, carbonic acids and other substrates.

2.10 The River Iskar area

The River Iskar is the longest Bulgarian river and the largest Bulgarian tributary of the River Danube. The catchment of the river from its springs to the town of Novi Iskar near Sofia covers part of the central western part of Bulgaria and extends over an area of 3660 km^2. Its average multi-annual runoff is Wav = 737 million m^3 (Fig. 6). Observations on the runoff of the river and its tributaries have been carried out in the course of a period of 40-80 years by means of 20 meteorological and five hydrometric gauges. The homogeneity of the statistical hydrological series has, in the meantime, been disturbed by the construction of numerous water abstraction facilities. The construction of the biggest dam on the Balkan Peninsula, the Iskar Dam (effective capacity: 634 million m^3), which provides the major portion of the water supply for the city of Sofia and the surrounding area, was completed in 1954. Other dams, water power plants, derivations for water transfer, drinking water treatment plants and other facilities have been built throughout the years. Some of them transfer water from the Struma river basin to the Iskar river basin and others from the River Iskar valley to the River Maritsa catchment.

The monitoring network in the River Iskar catchment is under the direction of the National Institute on Meteorology and Hydrology and partially of the Ministry of Environment and Water. The river has been subjected to continuous specific and complex investigations by different teams which have most often been connected with the effective management of water resources and their protection against pollution.

There are also other temporary field plots for stationary or temporary investigations, which are of no interest for the study of the natural processes and the effect of anthropogenous impacts.

The collected diverse information from the EWB investigations described above allows higher attention to be paid to the development of the ecological models for assessment of the river environment in Bulgaria and other related issues. The experimental activities in the field of water quality in Bulgaria is advancing well, also under laboratory conditions, performed by the Modelling and Ecosystematic Approach team at the Institute of Environmental Protection. The subject of its activity is evaluation of the self-treatment and assimilation capacity of water ecosystems and the major trends in the dynamics of water quality, quantitative assessment of anthropogenous impact on water ecosystems, including point and diffuse pollution sources (Diadovski and Hristova, 2000; Diadovski, 2002).

Fig.6 – The River Iskar area

A physical laboratory model of a river course ("microcosm" system) with an automatic microprocessor oxymeter (OXI 96) has been constructed in the laboratory. The model may be used for investigations of the dynamics of organic and non-organic pollution, of the interaction between biotic and abiotic components of the river ecosystems and the dynamics of the individual components under different degrees of impact. Investigations have been made on the dynamics of nitrogen and phosphorus compounds and the state of water biocenosism characterised by quantitative and qualitative indicators. The "macrocosm" system may be used also for assessments of the impact of river current velocity on the processes of dissolution of organic matter. Studies have been conducted to evaluate the impact of harmful substances on the parameters of water biocenosis. A concept for the sustainable management of water quality and protection of the ecosystems has been developed. Protection of waters from point and diffuse pollution is an important and indispensable requirement for sustainable water management. The ecological assessments of water quality and the dynamics of the ecosystems have been carried out by means of hydro-physical, hydro-chemical and hydro-biological standards, toxicity indexes and biotic parameters. Ecological criteria and indexes for quantitative evaluation of the interaction between man and the water ecosystems were taken into consideration.

3 Hydrological investigations of the liquid runoff at Yundola EWB

Systematisation of the available hydrological information in the Yundola EWB was performed in a specially set-up information database, which contains data about the daily water discharges and precipitation, air temperature and annual sediment runoff.

It was found out that:

- A downward trend was observed in the water quantities after 1980 (83) till 1994 (95) (Fig.7).
- The absence of active anthropogenous activity in the water catchment because of its experimental nature creates conditions for homogeneity of the statistical information, which is tested by appropriate statistical criteria, etc. Field plot no. 2 is the only exception because of its deforestation in 1985 as a consequence of a tornado and the following clear cutting.

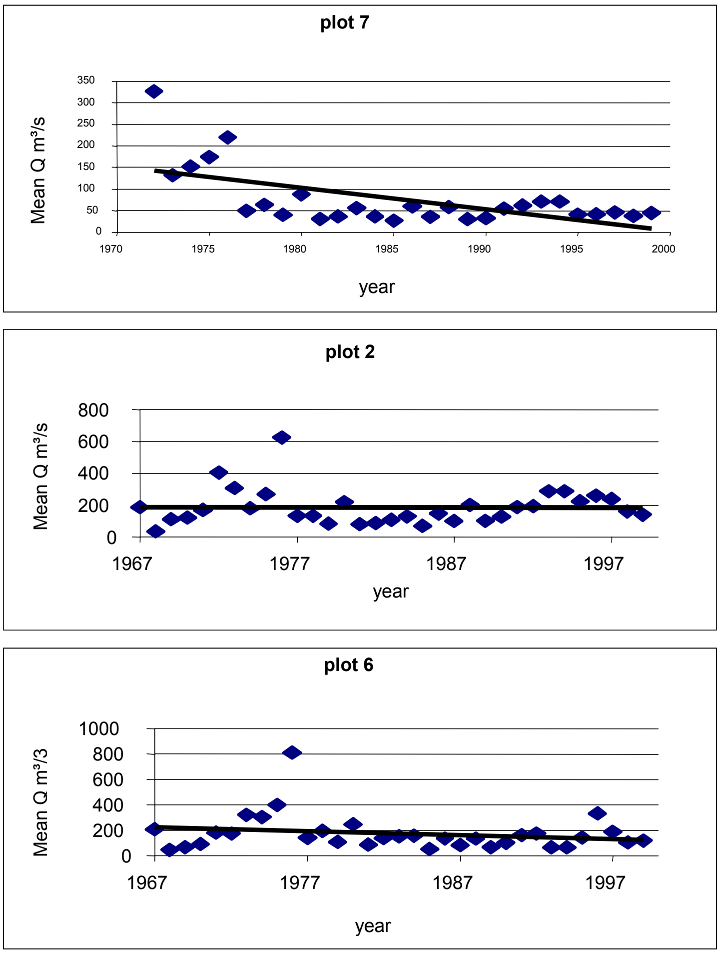

Fig. 7: Trends in the change of the water quantities

The same information has been used for studying the role of preliminary moistening in the water runoff formation because of its poor investigation so far. Preliminary moistening of the catchment (PMC) is a general concept, frequently used in hydrology for qualitative determination of water abundance in the region on the basis of assessment of river runoff, state of soil moisture, air humidity, presence or absence of temporary water streams and puddles on the terrain or of cracked, dry soil cover, presence of easily blown fine dust on the earth's surface, withered vegetation, etc.

Different authors determine PMC quantitatively according to empirical formulas developed by them on the basis of personal experience and intuition. So, for example, there are formulas in the form of linear and parabolic polynomials, which include different percentages of the sum of precipitation during the preceding "n" days. Other authors use the total volume of water accumulated in the riverbed for quantitative determination of PMC. Under the conditions of small mountain rivers in the region this will be a very dynamic characteristic, which could neither be defined and measured correctly nor be used as an index of water abundance or as a measure of the preliminary moistening due to the following considerations. Surface runoff as one of the major moistening sources of the basin ceases rapidly after the end of precipitation or snow thawing; soil runoff ceases rapidly because of insufficient soil cover thickness; underground runoff or the "basic" component of river runoff, is usually low because of the hard volcanic rocks forming the high-mountain massifs and their low "potential" for accumulating surface water.

The lack of clear and generally accepted instructions on how to define the PMC value has forced us to make our own choice in conformity with the object of the present study – the forested high-mountain catchment in the region (Yundola) subjected to Mediterranean climatic influence. Field observations have revealed that 2-3 days after rainfall the surface soil layer has already dried up and within another couple of days the herbaceous cover has become withered. This proves that humidity in the region is very short-lasting and of low "capacity". For this reason, the statement that PMC is not visibly influenced by liquid precipitation in the catchment for many days or even weeks seems to be correct. The duration of this "preceding" period is a variable number of days, which depends on the season and precipitation intensity.

The observations and analyses of the hydrographs for the runoff sites in the explored area reveal that water discharges in the days immediately preceding the "benchmark" moment of investigation are of decisive importance for the magnitude of the formed increase of flow rate or for the flood wave formation (Fig.8). For this reason, we assume the hypothesis that the water discharge in the days preceding the benchmark moment of investigations can be accepted as an integral characteristic parameter or a PMC index.

The sum of daily precipitation has been divided into four classes for convenience of data processing: I – precipitation from 0 to 10 mm; II – from 10 to 20 mm; III – 20-30 mm and IV – precipitation higher than 30 mm.

The graphic dependence in the form of a family of curves has been plotted in the coordinate system Q_{i-n} - ΔQ_i having as third parameter N_i (Fig. 9). It is obvious that the curves are of the power law type, i.e. the ΔQ_i increment of each of them attenuates when rainfall increases.

The three-parameter graphic presentation of the relationship Q_{i-n} - ΔQ_i – N_i reveals that for an arbitrarily chosen PMC level the greater the fallen precipitation N_i, the greater the change of the river flow rate ΔQ_i; and on the contrary, for a given precipitation N_i, the greater the value of the PMC measure Q_{i-n}, the greater the increase of the water quantity ΔQ_i.

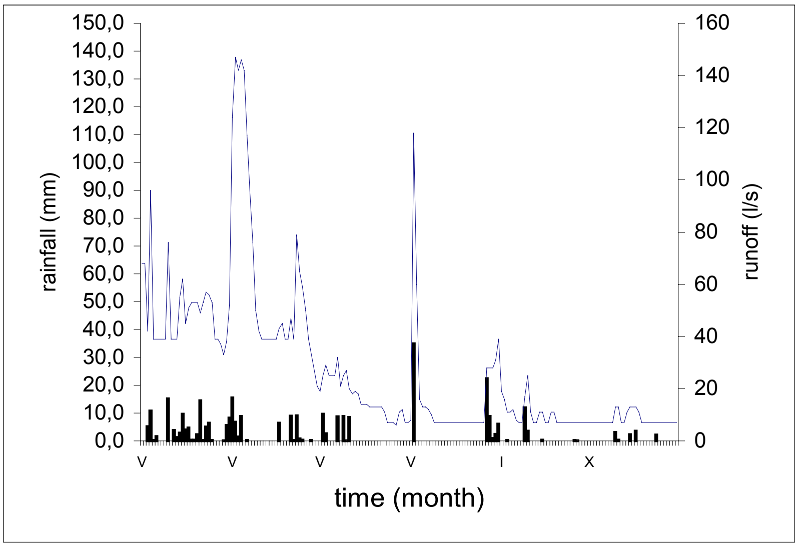

Fig. 8: Rainfall and runoff versus time when PMC is determined for the Yundola case study at field plot No 7 for 1985

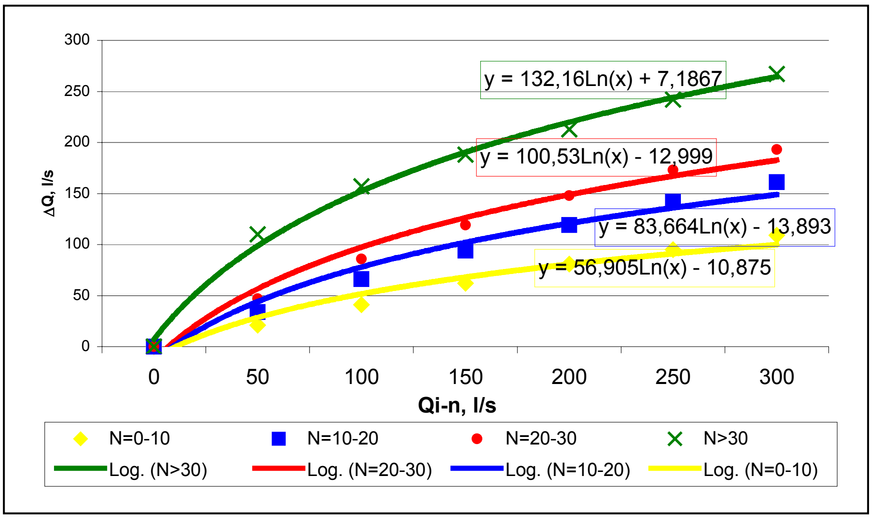

Fig. 9: The increment of discharge affected by the rainfall, taking into account the PMC

The described relationships are represented by the following equations:

$\Delta Q_{1i} = 56{,}905\ln(x) - 10{,}876$ for N_{1i} = 0-10 mm
$\Delta Q_{2i} = 83{,}644\ln(x) - 13{,}893$ for N_{2i} = 10-20 mm
$\Delta Q_{3i} = 100{,}53\ln(x) - 12{,}999$ for N_{3i} = 20-30 mm
$\Delta Q_{4i} = 132{,}16\ln(x) + 7{,}1867$ for N_{4i} = >30 mm

Finally, the following statements and conclusions could be made. The role of preliminary moistening of the catchment area for the river runoff formation has been revealed; the mechanism of flood wave formation due to precipitation has been described depending on the preliminary moistening of the catchment; a mathematical model has been composed for the river runoff formation depending on the precipitation and the preliminary moistening of the catchment.

4 Investigations of the solid load of rivers

In hydrology the solid runoff is considered an integral component part of the river runoff. Its investigation is of great importance for engineering, geological, ecological and economic practice. The availability of vegetation diminishes the destructive effect of rainfall drops. To summarise, one may say that vegetation cover and trees play the role of buffer for the impact of rain on the soil particles.

On the basis of the available information collected in the course of almost 40 years at the EWB, some empirical relationships between the annual sum of precipitation and the resulting total sediment load (TSL) have been developed. In this way we have found out that the total quantity of suspended sediments in the river waters in the EWB is low and does not change within broad limits at the different points, which indicates even development of soil erosion and homogeneity of the natural conditions in the area.

It has been discovered that the fluctuations of the module of the total annual sediment load for each separate watershed basin usually oscillate around a permanent value, typical for the respective field plot, as follows:

$$MR(B1)_m = 0.10 \text{ m}^3/\text{ha.an}$$
$$MR(B3)_m = 0.32 \text{ m}^3/\text{ha.an}$$
$$MR(B2)_m = 0.21 \text{ m}^3/\text{ha.an}$$
$$MR(B4)_m = 0.67 \text{ m}^3/\text{ha.an}$$
$$MR(B6)_m = 0.20 \text{ m}^3/\text{ha.an}$$

Evidently, the annual production of the sediment load remains constant for long periods of time and in reality it is not affected by the precipitation. This may serve as an indicator for effective long-term biological consolidation of the terrain to an extent which makes it non-susceptible to soil erosion. Provided this conclusion is corroborated by other studies, it may become an example for the perfect protection of the soil layer as a result of the consolidating and regulating impact of afforestation activities.

The indicated values for MR_m have been used to construct the empirical relationship $MR_m - I_{max}$ because of its specific role, which helps identify the role of the maximum gradient of the water catchment basin and permits the prior definition of the anticipated sediment runoff of the rivers and the intensity of soil erosion in the case of high precipitation rates. This may have practical application in the performance of erosion-prevention activities.

If we assume that because of the closeness of the field plots to each other within the limited boundaries of a mountainous area the natural conditions in all of them (geology, soil cover, percentage of vegetation cover, state of the surface cover, meteorological conditions) and anthropogenous impact (absence of any engineering and communication facilities, construction activities, residual products from manufacturing activities, etc) are almost identical, then the main reasons for any possible differences in the MR values may be said to be related to the orientation of the slope, the length of the slope and the maximum gradient of the field plot.

The use of GIS for the area gave us the opportunity to ascertain that among the three possible sources of differences indicated it is the maximum gradient of the slopes of the water catchment basins that changes within the broadest possible limits. The reason is that the high gradient predetermines a higher velocity and an increased transportation capacity of the current, which in turn causes more intensive erosion and evacuation of larger quantities of sediment matter from the watershed basin to the river.

5 Instead of conclusion

EWB creates conditions for carrying out multi-annual investigation work which comprises the collection of information and its consistent processing and storage as a modern database. Opportunities are provided for the launching and conducting of active experiments with broad foreign participation, thus creating conditions for more profound penetration into the mechanism of the formation of surface runoff and soil erosion, which will help reveal more clearly the influencing factors and the interaction between them.

EWBs are natural areas for the work and contribution of young researchers. They are an effective operating school for the training of young professionals.

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Influence of land use changes on peak discharges - Two case studies, Upper Tanaro River and Dora Riparia River, Piedmont, Italy

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Abstract

The aim of this study is to evaluate the effect of land use changes which occurred in the last two centuries, particularly forest increase, on peak flows. The attention is focused on the impact on extreme flood events in two rivers in Piedmont (Italy), Tanaro and Dora Riparia. The Rivers Tanaro and Dora Riparia were severely affected by major floods during the last ten years. The change in land use in the last century was claimed to be one of the likely factors of the disaster.

The hydrologic model of the basins was built using Hec-1 and the precipitation losses simulated according to the SCS method. Stream topology was derived from a DEM with a 50x50 m grid using the Boss-WMS® code. Hec-1 was run with two land use schemes, respectively corresponding to the actual land use and to the land use derived from maps and data of about one century ago for Tanaro and two centuries ago for Dora Riparia. For both the basins the present land use evidences an increase of forested areas compared to the past (from 30 to 39% of the whole basin area for Dora Riparia and from 52 to 69% for Tanaro).

Results seem to show that the peak flow response to forest increase is low. The reduction of peak flow at the outlet catchment on the occasion of major floods, like those that happened in November 1994 and in October 2000, is small.

1 Introduction

The Rivers Tanaro and Dora Riparia (Piedmont, Italy) were severely affected by major floods during the last ten years. The change in land use which occurred in the last century has been claimed as one of the likely factors of the disaster. In particular, it is the general opinion that abandonment of the mountains and deforestation are the main causes of those extreme events. The general concern that climate change, urbanisation and forest loss in uplands can increase flooding is widespread (DeWalle, 2003).

The contribution of forests in runoff generation was investigated during the past century in the USA and in Europe. The results of American experience was summarised on several occasions (Hibbert, 1967; Colpi and Fattorelli, 1985). In the USA many experimental areas were established to study the effects of forest management on watershed hydrology, but the analyses were not focused on the impact of forests on large flood events. Only in recent years have a few authors revisited those data to investigate the peak flow response to forest practices, focusing on large peak flow events (Beschta et al., 2000; Jones 2000). Their analyses “do not support the concept that relatively large peak flows are increased by forest practices” (Beschta et al., 2000).

Recently, European field researches (Cosandey, 1993, 1995) and official general reports (Calder, 2000; Fao, 2003) support the opinion that "extreme hydrological events are the result of natural processes of erosion and sediment motion interacting with human systems" (Davies, 1997). Ives and Messerli (1989) outline that "the scale approach is a key issue in the understanding of highland-lowland linkages. Whereas on a micro-scale (small watershed) the effects of human interventions such as forest cutting can be directly documented in terms of higher discharge peaks or higher sediment load, on a large scale natural processes are dominant".

In Europe, studies of forested catchments generally investigated the impact of presence or absence of forests and forest practices on water yield and water quality (Fohrer et al., 2002; Klöcking and Haberlandt, 2002; Krause, 2002; Naef et al., 2002). The impact of forests on peak and low flows was recently studied in the framework of the FOREX Project (FORest and EXtreme events), collecting data from 28 small basins across Europe (Robinson et al., 2003). The study, in spite of specific local conditions, found a substantial homogeneity of results: the contribution of forests in peak flow reduction of extreme events seems to be smaller than has often been claimed (Robinson et al., 2003).

In Italy, at the beginning of modern hydraulics, Vincenzo Viviani (1684), one of the Galileo's disciples, considered forest clear cutting of the upper Arno to be a main cause of soil erosion and of the sedimentation in the lower part of the basin. The scale concept was also clear in the mind of Carlo Giorgini (1854) whose opinion was that "it is likely that land use changes due to deforestation and the increase of cultivated areas do not affect the volume of major floods which follow long-lasting and extensive rainfalls; […] but they affect the frequency and volume of flash floods of torrents on the occasion of heavy storms of short duration, which occur over small areas in the mountains". The same author outlined (p. 139 and 192) that Florence was severely flooded in 1177 and 1333, before deforestation, and in 1557 when deforestation was not yet so severe as in the following centuries. More recent remarks about the role of forests can be found in the stimulating discussions which took place at the Italian Accademia Nazionale dei Lincei at the end of the 1960s (Susmel, 1967, 1971; Gherardelli and Marone, 1968, 1971; De Philippis, 1971). It was the time of catastrophes: the flooding of Venice and Florence.

The aim of this study is to evaluate the effect of land use changes that occurred in the last two centuries, particularly forest increase, on peak flows. The attention is focused on the impact on extreme flood events in two rivers in Piedmont (Italy), Tanaro and Dora Riparia. Unprecedented flows in 1994 (in the River Tanaro) and 2000 (in the River Dora Riparia) seriously affected both the tributaries and the main stream, causing the collapse of some bridges, severe erosions of main road embankments (in Tanaro) and extensive flooding in the lower catchment of Dora Riparia including Torino city centre. These events were characterised by long-lasting and heavy rainfalls.

The hydrologic model of the basins was built using Hec-1 and the precipitation losses simulated according to the SCS method. Stream topology was derived from a DEM with a 50x50 m grid using the Boss-WMS® code.

Hec-1 was run with two land use schemes, respectively corresponding to the actual land use and to the land use derived from maps and data of about one century ago for Tanaro and two centuries ago for Dora Riparia.

2 The investigated basins: past and present land use

The River Tanaro headwater is located in the lower part of the Western Alps, near the border of France (Fig 1): two mountain torrents Tanarello and Negrone make up the Tanaro River which flows in a narrow valley between steep side slopes, generally wood-covered with abandoned pastures at the higher elevations. Soil is shallow over limestone bedrock. The study related to the upper part of the basin and the outlet was fixed at the Nucetto section, where discharges were measured by the *Ufficio Idrografico* of the River Po in the period 1933-1965. There are three cross sections of interest: Ormea, Garessio and Nucetto (Fig. 1)

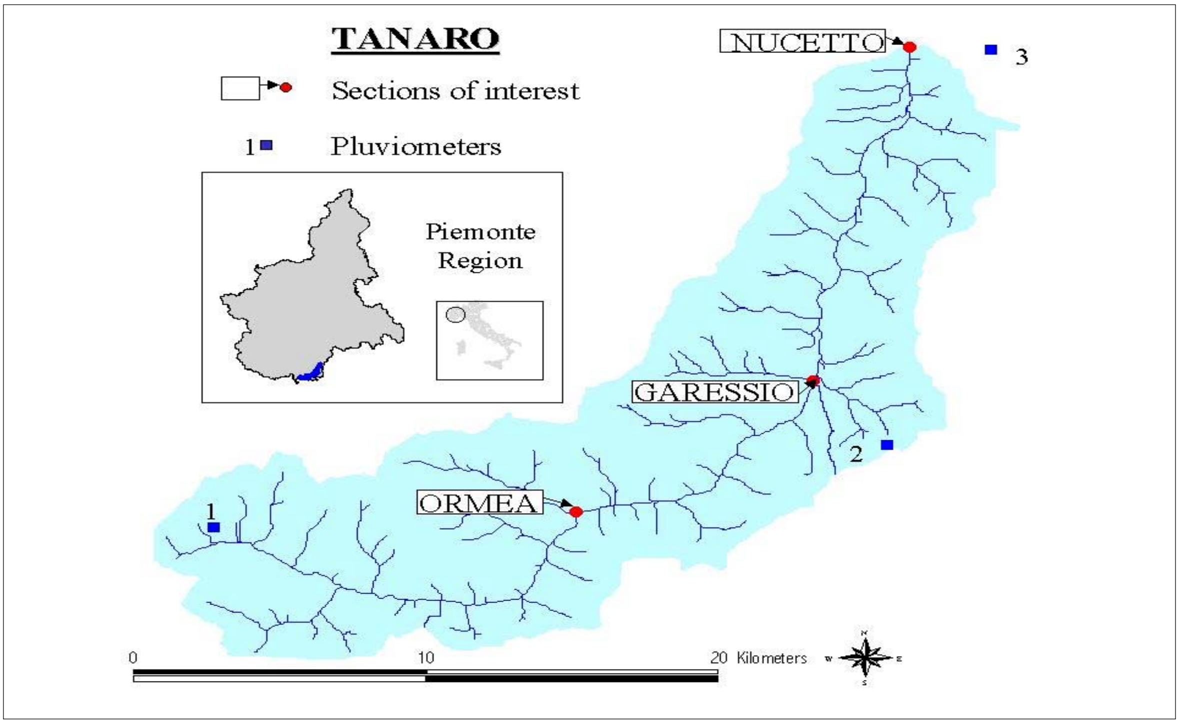

Fig. 1: Tanaro basin location with cross sections of interest and recording stations

The Dora Riparia basin (Fig. 2) is located West of Torino (1300 km^2 at Torino city and 1060 km^2 at the foot of the mountains) and originates from two torrents (Dora of Bardonecchia and Dora Riparia) which join at Oulx. The basin outlet, for this study, is located at Susa, just upstream of the confluence with the Cenischia torrent, where the basin area is 694 km^2. There are four cross sections of interest: Dora Riparia (D1), Dora of Bardonecchia (D2), the confluence of the two reaches at Oulx (D1+D2) and the outlet at Susa (Fig. 2)

The main catchment characteristics are shown in Table 1.

Table 1: Main characteristics of Dora Riparia and Tanaro Rivers

	DORA RIPARIA	TANARO
AREA (km^2)	694	390
Average elevation (m a.s.l.)	1613	1227
Maximum elevation (m a.s.l.)	3627	2651
Minimum elevation (m a.s.l.)	385	450
Mean annual precipitation (mm)	752	1060

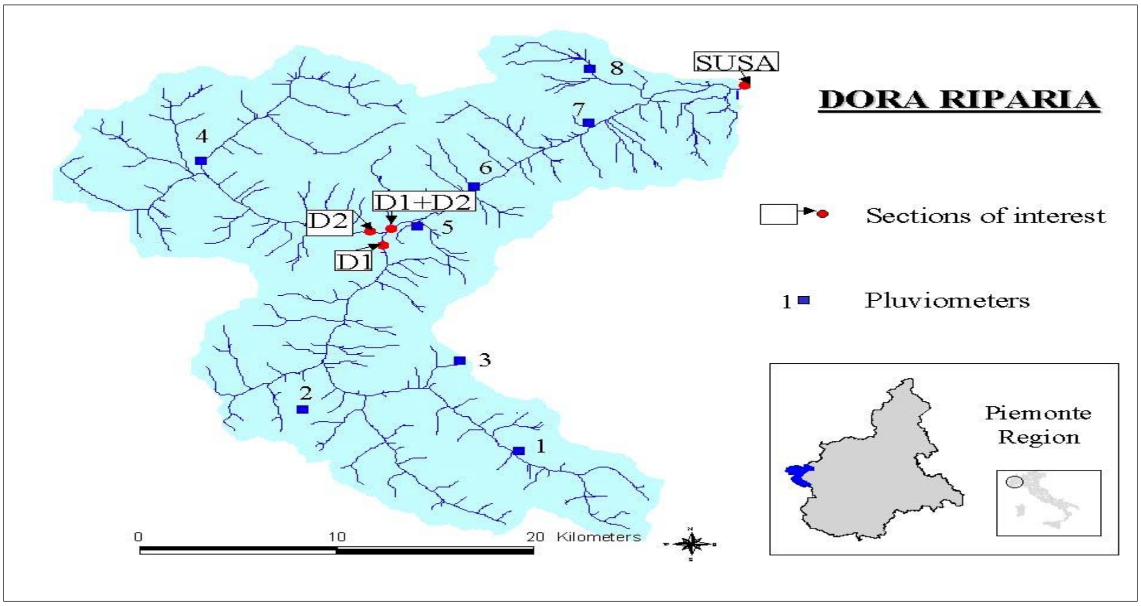

Fig. 2: Dora Riparia basin location, with cross sections of interest and recording stations

Information on past land use in the Tanaro valley derives from different sources. Documents were found at local archives and at the Torino State Archive, reproducing the map of public forests. Moreover, the official maps of the Geographic Military Institute (1923, scale 1:25000) show the extension of forests, pastures and cultivated lands. This information was integrated with some old prints showing the terraced lands near Garessio and Ormea and with engravings dating from the beginning of the 20th century (Fig. 3). The combination of these documents produced a map of the land use in Tanaro about a hundred years ago, when side slopes were densely cultivated and population was distributed in minor villages.

Fig. 3: Ormea, view of urbanised area and terraced slopes

A very detailed historic map (Fig. 4), dating from the beginning of the 19th century and divided into nine parts, was found for the Dora Riparia basin at the Torino State Archive. The maps, on a scale of about 1:8750, allow forests, pastures, bare soil, cultivated and terraced lands, grasslands, lakes and villages to be distinguished. Moreover, they overlap quite accurately the present-day cartography, so that it was possible to draw a map of the past land use in GIS environment.

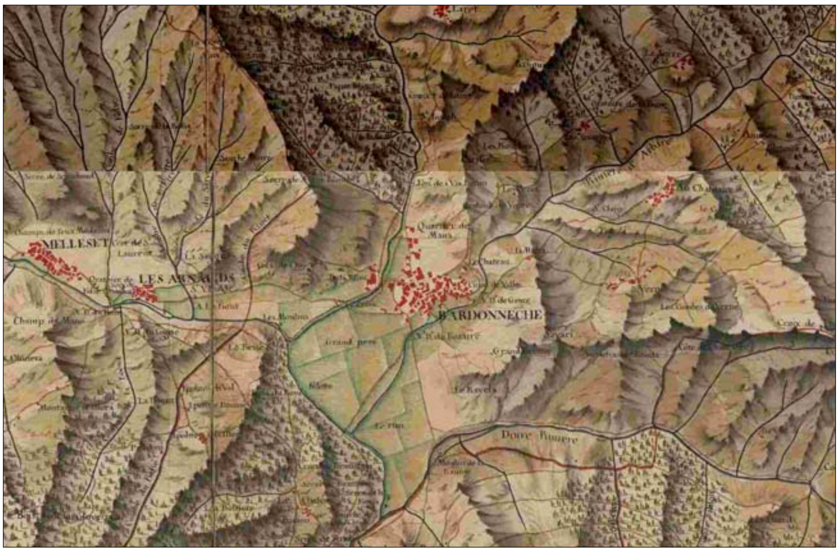

Fig. 4: Extract from the historic map of Dora Riparia Valley (from Torino State Archive) showing in detail the land use at the beginning 19th century. The original scale is about 1: 8750.

For both the Tanaro and Dora Riparia basins the present land use shows an increase of forested areas compared to that in the 19th century: from 30 to 39% of the whole basin area for Dora Riparia and from 52 to 69% for Tanaro (Table 2). This increase seems to be caused by the decrease of alpine pasture and bare soil at the highest elevations and of vineyards (terraced cultivation) at the lowest elevations in the Dora Riparia catchment (Fig. 6). In the Tanaro catchment the present forest cover is a main result of the abandonment of pastures (Fig. 5). In the Dora Riparia basin the increase of urban areas is fairly evident. Growth produced not only more developed areas but also a higher density of homes in residential areas.

Table 2: Comparison between past and present land use in Dora Riparia and Tanaro River basins (% of coverage)

LAND USE	Dora Riparia		Tanaro	
	Past	*Present*	*Past*	*Present*
Bare soil and alpine pastures	33.29	23.84	3.82	3.77
Pastures	31.19	30.49	33.19	22.94
Forests	30.37	38.85	52.31	68.82
Grasslands	2.49	4.89	5.18	3.86
Terraced cultivation	2.38	0.43	5.09	0.10
Lakes	0.04	0.04	-	-
Urban areas	0.25	1.45	0.41	0.62

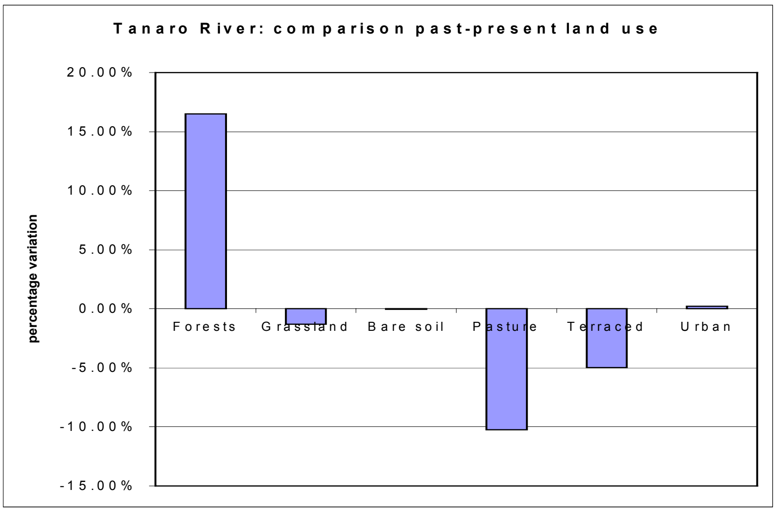

Fig 5: River Tanaro: deviation in % of present from past land use

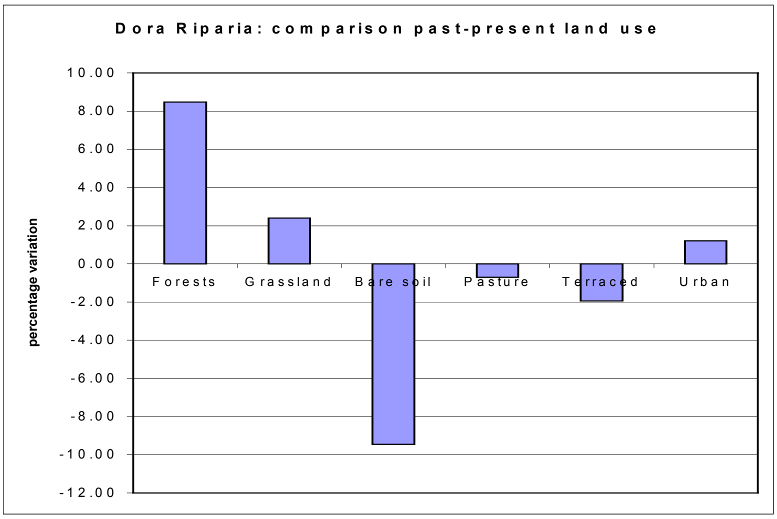

Fig. 6: River Dora Riparia: deviation in % of present from past land use

3 The hydrologic model

A hydrologic model of the two basins was built using Hec-1 and the precipitation losses simulated according to the SCS (soil conservation service) method. Stream topology as well as sub-catchment CN (curve number) values were derived from a DEM with a 50x50 m grid and land use maps in the framework of the Boss-WMS® code.

The SCS runoff method relates accumulated rainfall to an empirical parameter CN. The CN is a function of land use, soil classification, hydrologic conditions and antecedent runoff conditions (Hoggan, 1989).

Soils are divided into four hydrological groups according to different infiltration rates: A, B, C and D, representing soils with high, moderate, low and very low infiltration rates. CN values can vary according to the antecedent moisture condition (AMC). AMC is expressed as a function of rainfall in the last five days (Table 3). CN values are usually given in tables for AMC II and then obtained for AMC I and AMC III with two equations (Ranzi and Rosso, 1994):

$$CN_I = \frac{CN_{II}}{2.3 - 0.013CN_{II}}$$

$$CN_{III} = \frac{CN_{II}}{0.43 + 0.0057CN_{II}}$$

For a given AMC, the CN value depends on hydrologic soil characteristics and land use.

The land use represents runoff-production potential. Seven land use classes were considered for this study: bare soil and alpine pastures (including rocks, landslides and riverbeds), pasture, forest, grasslands, terraced cultivation (vineyards), lakes and urban areas. Table 4 shows CN for these classes and for each hydrologic soil type in AMC II condition (Hoggan, 1989; Ranzi and Rosso, 1994).

Table 3: Definition of AMC classes

Classes AMC	Total rainfall of the last five days	
	Plant dormancy	Growing season
I	< 13 mm	< 36 mm
II	13 ÷ 28 mm	36 ÷ 53 mm
III	> 28 mm	> 53 mm

Table 4: Runoff curve number for considered land use classes

LAND USE	**CN**			
	TYPE A	**TYPE B**	**TYPE C**	**TYPE D**
Forest	36	60	73	79
Pasture	49	69	79	84
Grasslands	30	58	71	78
Terraced cultivation	70	79	84	88
Bare Soil	68	79	86	89
Lakes	100	100	100	100
Urban areas	77	85	90	92

Figure 7 schematises the WMS method to compute hydrographs at the basin outlets. Starting from a DEM of the basin, the WMS computes flow direction and flow accumulation with TOPAZ (TOpographic PArameteriZation programme of USDA-ARS, National Agricultural Water Quality Laboratory). Once the watershed outlet and interior sub-basin outlets are identified, it defines basins and computes basin geometric data such as area, slopes, runoff distances. With geometric data, land use and soil type coverage, WMS computes CN for each sub-basin by taking an area-weighted average of different CN values of different regions for soil type and land use combinations in Table 4 within a basin (BOSS INT., 2000). CN is used to compute the lag time, a parameter defined as the difference in time between the centre of

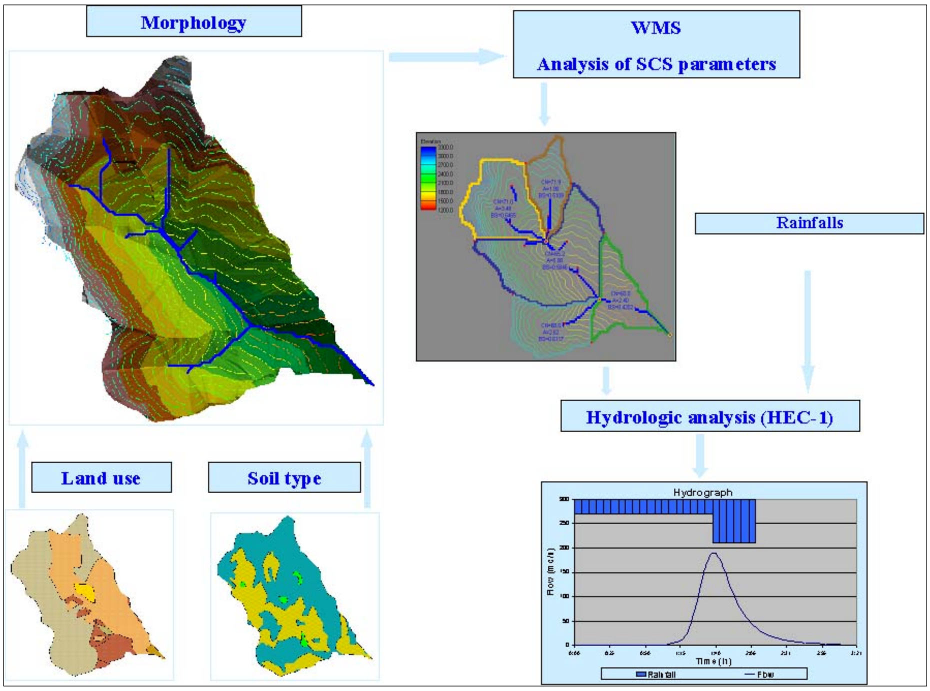

Fig. 7: WMS system for hydrologic analysis

mass of net rainfall and peak rate of flow (Gupta, 1989). The lag time in hours is computed with the well-known relation (Mishra and Singh, 2003) in metric units:

$$TL = 0.342 \cdot Y^{-0.5} \cdot L^{0.8} \cdot (1000/CN - 9)^{0.7}$$

where Y is the watershed slope (%) and L is the hydraulic length of watershed (km).

The last step is to assign precipitation data. Then WMS produces the Hec-1 file that simulates the hydrographs at the basin outlet.

For both Tanaro and Dora Riparia, the present land use is derived from surveys supported and distributed by Regione Piemonte in GIS environment. Past land use was obtained as described above. Hec-1 was run with the two land use schemes. Hydrologic soil type, for want of soil type maps, was inferred by combining information of geological, lithological, pedological maps and local investigations at different scales. For our alpine basins the prevailing soil types are A and B.

The model was run with November 1994 rainfalls for the River Tanaro (Anselmo and Bogo, 2002) and with October 2000 rainfalls for the River Dora Riparia. The event of 2-7 November, 1994 was characterised by long-lasting heavy rainfalls of 300-350 mm within three days (Fig. 8) with hourly maximum values of 30 mm. The hourly rainfalls recorded in three stations spatially distributed over the basin (Fig 1) were assigned to the model. The recurrence time of the 24-hour precipitation evaluated with the Gumbel method was 94 years for station 1, 58 years for station 2 and 193 years for station 3. The event of 13-16 October, 2000 was particularly serious in the River Dora Riparia: up to 320 mm in four days (Fig. 9). The hourly rainfalls recorded at eight stations (see Fig. 2) were assigned to the model. The recurrence time of the 42-hour precipitation is 10-20 years for stations 1-5, 350 years for station 6, 110 years for station 7 and 316 years for station 9.

The antecedent moisture condition (AMC) was calculated from rainfalls for the two basins, obtaining AMC II for the River Tanaro and AMC I for the River Dora Riparia.

Hec-1 was run with the two land use schemes.

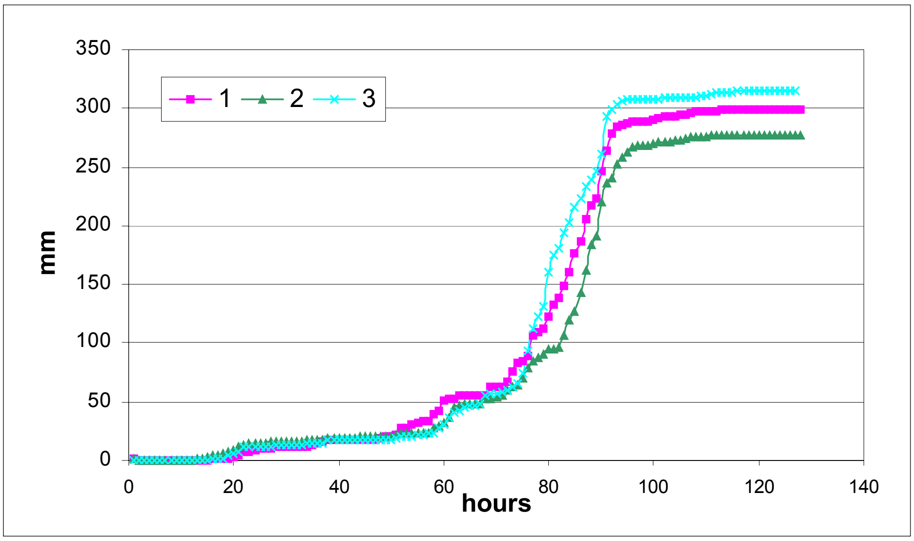

Fig. 8: Cumulated rainfall recorded at three stations (see Fig. 1) in the Tanaro basin for the 2-6 November 1994 event

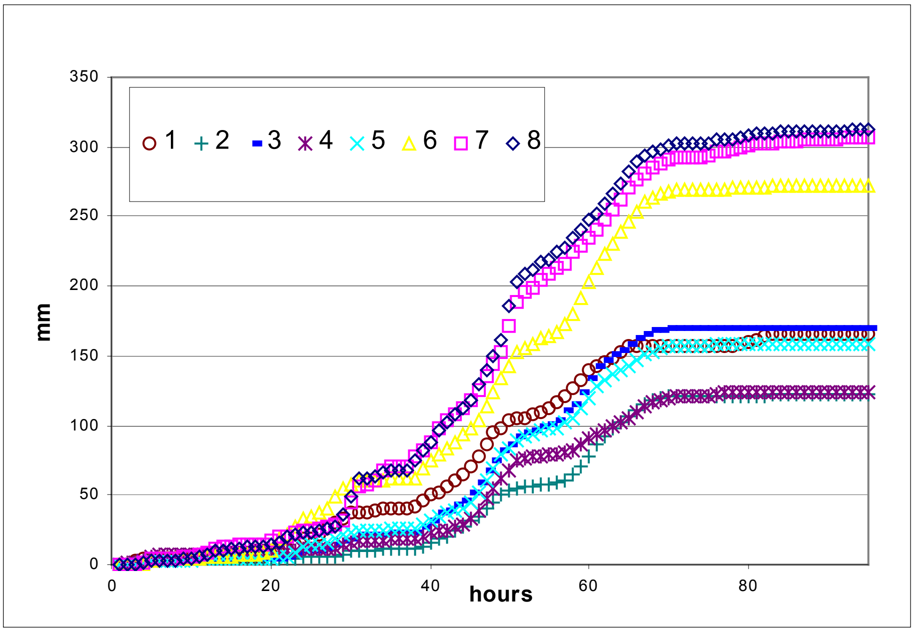

Fig. 9: Cumulated rainfall recorded at eight stations (see Fig. 2) in the Dora Riparia basin for the 13-16 October 2000 event

4 Results: impact of land use changes on peak flow

The results of the Hec-1 simulation with past and present land use do not show any significant difference in peak flow at the outlet catchments (Table 5 and Table 6). The peak flow for the River Tanaro at the outlet of Nucetto is 1158 m^3/s with the past land use and 1118 m^3/s with the present land use, corresponding to a decrease of 3.5%. The Dora Riparia basin shows the same trend: the peak flow at the outlet of Susa is 391 m^3/s with the past land use and 351 m^3/s with the present land use. The decrease in flow is 10%.

Tab. 5: Comparison between peak flows obtained with present and past land use in Tanaro River basin

TANARO RIVER		Peak flow [m^3/s]	
River Station	Catchment area (km^2)	Past land use	Present land use
Ormea	188	707	703
Garessio	255	1027	1010
Nucetto	375	1158	1118

Tab. 6: Comparison between peak flows obtained with present and past land use in Dora Riparia River basin

DORA RIPARIA RIVER		Peak flow [m^3/s]	
River Station	Catchment area (km^2)	Past land use	Present land use
Dora of Cesana (D1)	257.53	137	136
Dora of Bardonecchia (D2)	246.69	91	77
Confluence D1+D2	504.42	212	202
Dora at Susa	694.09	391	351

These results are consistent with the observed flow at the Ceva bridge, downstream from Nucetto, for the River Tanaro during the 1994 event. For the River Dora Riparia a peak flow of 106 m^3/s was measured at Oulx (Dora of Cesana D1) and 400 m^3/s were estimated at Susa during the event of October 2000.

5 Conclusions

Land use changes in the last two centuries have been remarkable for both the Dora Riparia and Tanaro river basins. Mountain depopulation and abandonment of pastures and terraced lands have caused an expansion of forests. Forests increased from 30 to 39 % of the whole basin area in the Dora Riparia basin and from the 52 to 68 % in the Tanaro basin. The reduction of peak flow at basin outlets on the occasion of major floods, like those that occurred in November 1994 and in October 2000, is small.

Results are in agreement with recent studies (Beschta et al., 2000; Jones, 2000; Robinson et al., 2003) and they seem to show that the peak flow response to forest increase is small. Also FAO (2003) concludes that "forests produce low levels of storm flow and greater soil stability than any other vegetation type because of their high infiltration rates, protective ground cover, high consumption of soil water and high tensile strength of roots. These attributes are particularly beneficial in mountainous terrain that is subject to torrential rainfall. Forest removal and road construction are problematic in such areas because they increase the frequency and magnitude of landslides and debris flows (Sidle, 2000). However, there is a limit to the protection that forest cover provides, as was found in Taiwan Province of China, where nearly all mountainous watersheds are forested and managed for slope stabilisation and torrent control (Lu *et al*, 2001). As the amount of rainfall becomes extreme, the extent to which forests can help to prevent landslides, debris flows and flooding diminishes."

Results herein presented show that recent urbanisation effects on runoff are mitigated, at basin scale, by the natural increase of vegetation-covered areas. Anyway, future modelling work is necessary to improve the accuracy of the model and to investigate in more detail the role of forests. The aspects to be taken into account are:

- Further calibration and sensitivity analysis of CN values, particularly for forest cover;
- Investigation of the role of different types of forests, especially the difference between the stages of canopy re-growth;
- Analysis of different land use scenarios, at different scales including sub-basins.

Last but not least, the amount of data collected within the European Representative and Experimental Basin network (ERB) activity may be of valuable interest and help.

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