Runoff response at different spatial scales: moving from small experimental areas to mesoscale catchments

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Abflussreaktion in verschiedenen räumlichen Maßstabsbereichen: von Experimentalflächen zu mesoskaligen Einzugsgebieten

Introduction

One of the classical goals of catchment hydrology is the identification of the basin response in terms of timing and volume of flood production. In this context, small experimental catchments can offer valuable information at different levels. They constitute preferential areas for field observations, collection of high quality hydro-meteorological data (which are also required for detailed model development), usefulness when monitoring actual ecological changes in environmental variables, represent essential operational tools to conceptualize the main hydrological processes occurring at the hillslope and watershed scale and provide insights that allow one to deal with uncertainties throughout the observation-conceptualization-modelling sequence (SCHUMANN et al., 2010). Further potential de-

Zusammenfassung

Kleine Testeinzugsgebiete sind wichtige Quellen für die Gewinnung hydro-meteorologischer Daten und der Konzeptionierung hydrologischer Vorgänge. Mit Hilfe geeigneter Upscaling-Ansätze können auch Erkenntnisse der bestimmenden Niederschlags-Abfluss-Relationen für größere Gebiete erzielt werden. In diesem Beitrag wird untersucht, inwieweit der beobachtete Abflussbildungsmechanismus an kleinen Testgebieten für größere, übergeordnete Gebiete übertragbar ist. Es wurden vier „verschachtelte" Gebiete in den italienischen Dolomiten untersucht, die den mikroskaligen bis zum mesoskaligen Bereich abdecken. Dabei wurden 54 Niederschlagsereignisse analysiert. An beiden Maßstabsbereichen traten ähnliche Schwellenwerteffekte in der Bodenfeuchte-Abfluss-Beziehung auf, welche den Schluss nahelegen, dass Bodenfeuchtemessungen an Hangstandorten universell als Indikatorgrößen verwendet werden können. Die ereignisbezogenen Abflussbeiwerte können gut mittels einer Beta-Verteilung beschrieben werden. Sie zeigen deutlich eine Verringerung bei größeren Einzugsgebieten. Die Variabilität der Abflussbeiwerte zwischen den Gebieten ist möglicherweise auch durch unterschiedliche Topographien und Pufferzonen bedingt.

Schlagwörter: Upscaling, geschachtelte Einzugsgebiete, Abflussbeiwert, Schwellenwerte.

Summary

Small experimental catchments represent valuable tools for collection of detailed hydro-meteorological data and conceptualization of hydrological behaviour. Following an upscaling approach, they can also offer insights about the main rainfall-runoff processes occurring at larger scales. This paper aims at assessing whether the runoff generation mechanisms observed in small areas are representative of those occurring in larger basins. We compare the response of four nested catchments ranging from micro-scale to meso-scale in the Italian Dolomites analyzing 54 rainfall-runoff events. A similar threshold effect in the soil moisture-runoff relationship suggests the same processes operating at different scales and denotes the possibility of using hillslope-scale soil moisture measurements as indicators of the moisture conditions of larger areas. The event runoff coefficients are well described by the beta distribution, which reflects the decrease of stormflow with the increase of the watershed size. The catchment inter-variability of runoff coefficients are probably related to the watershed topographic properties, mostly in terms of extent of the buffering riparian zone.

Key words: Upscaling, nested catchments, runoff coefficient, threshold relation, riparian zone.

rived from detailed hydro-meteorological monitoring in small experimental sites, is the possibility to make predictions about the hydrological behaviour of ungauged watersheds (Bonell et al., 2006) or of larger basins. In the latter case, the runoff response of micro-scale catchments may be used as an indicator of the hydrological behaviour of larger areas (Zillgens et al., 2007). Furthermore, upscaling the observations and the knowledge gained over small research catchments (< 1–10 km^2) to larger (> 100 km^2) watersheds, where detailed analyses and monitoring are usually more difficult to obtain, is extremely valuable for flood modelling and prediction, risk assessment and mitigation intervention (Soulsby et al., 2004, 2006). This requires a sequential methodological approach beginning with the effort to identify the dominant processes that control the hydrological response at different scales and then to develop models based on such mechanisms (Blöschl, 2001; Sivapalan, 2003).

This work focuses on the first step of this methodological sequence. We present a comparison among four nested catchments ranging from 0.03 km^2 to 109 km^2, with the aim to assess how the dominant hydrological processes observed in detail at the micro-catchment scale can be deemed representative of the runoff generation mechanisms occurring in larger basins.

Study area and methodology

The study area (Figure 1) is localized in the Upper Cordevole River Basin (Italian Dolomites, Eastern Alps) and comprises Larch Creek Catchment (LCC, 0.033 km^2), Bridge Creek Catchment (BCC, 0.14 km^2), Cordevole Catchment at La Vizza (7.3 km^2) and Cordevole Catchment at Saviner (109 km^2).

The analysis period spans from mid-May to mid-October 2007–2009. Continuous data collection in the snow-free months at LCC and BCC includes precipitation, water stage and discharge measured at two V-notch weirs, groundwater level monitored over a net of approximately 50 piezometric wells and volumetric soil moisture measured at 0–30 cm depth by four Time Domain Reflectometry (TDR) probes. Moreover, during four one-month field campaigns (2005–2008), daily or twice-a-day soil water content measurements were taken manually at 0–6 cm, 0–12 cm and 0–20 cm at two 26-point grids and a 64-point grid at BCC and LCC, respectively. Sampling was carried out by means of an impedance probe (for measurements at 0–6 cm) and a portable TDR probe (for the deeper layers), calibrated for the local soil conditions. Analyses of these datasets demonstrated a marked spatial and temporal stability of soil moisture spatial patterns (Penna et al., 2007, 2009). Moreover, the average of the four measurements at 0–30 cm showed a good agreement with the temporal patterns of soil moisture on the experimental grids. This allowed us to consider the mean soil water content at 0–30 cm as representative of the wetness conditions of the hillslope zone at LCC and BCC. For La Vizza and Saviner, precipitation data from three and seven rain gauges, respectively, were available. The mean areal precipitation was calculated using the Thiessen polygon method. The main topographic properties of the four study catchments and the instruments used for this work are summarized in Table 1.

We selected 54 rainfall-runoff events with precipitation depth ranging from 4 mm to 65 mm. For each event, the flood hydrograph was separated into baseflow and stormflow using the constant-k method (Blume et al., 2007). Baseflow was subtracted from total flow to compute the event runoff coefficients, defined as the ratio between event stormflow and total rainfall. We investigated the runoff response at different spatial scales across the four study basins by i) the analysis of the antecedent soil moisture-runoff relationship and ii) the inter-comparison of runoff coefficients.

Results and discussion

3.1 Soil moisture-runoff relationship

Figure 2 shows the relationship between antecedent soil moisture (defined as the average of the four 0–30 cm measurements taken immediately before the event start) measured at LCC and runoff coefficients of the four experimental catchments.

Despite the existence of some scatter, it is interesting to note that a similar pattern is observable for the various basins, with a threshold behaviour which highlights the control exerted by soil moisture on runoff of all study watersheds. This agrees with previous findings of Penna et al. (2011), who analyzed 40 rainfall-runoff events at BCC. During dry periods, low runoff coefficients were likely generated mainly by the response of the wet riparian zone. Conversely, during wet conditions, when a threshold of soil moisture (approximately 51%) was exceeded, hillslopes released water and started to contribute to runoff. Therefore, the similar patterns displayed in Figure 2 suggest that i)

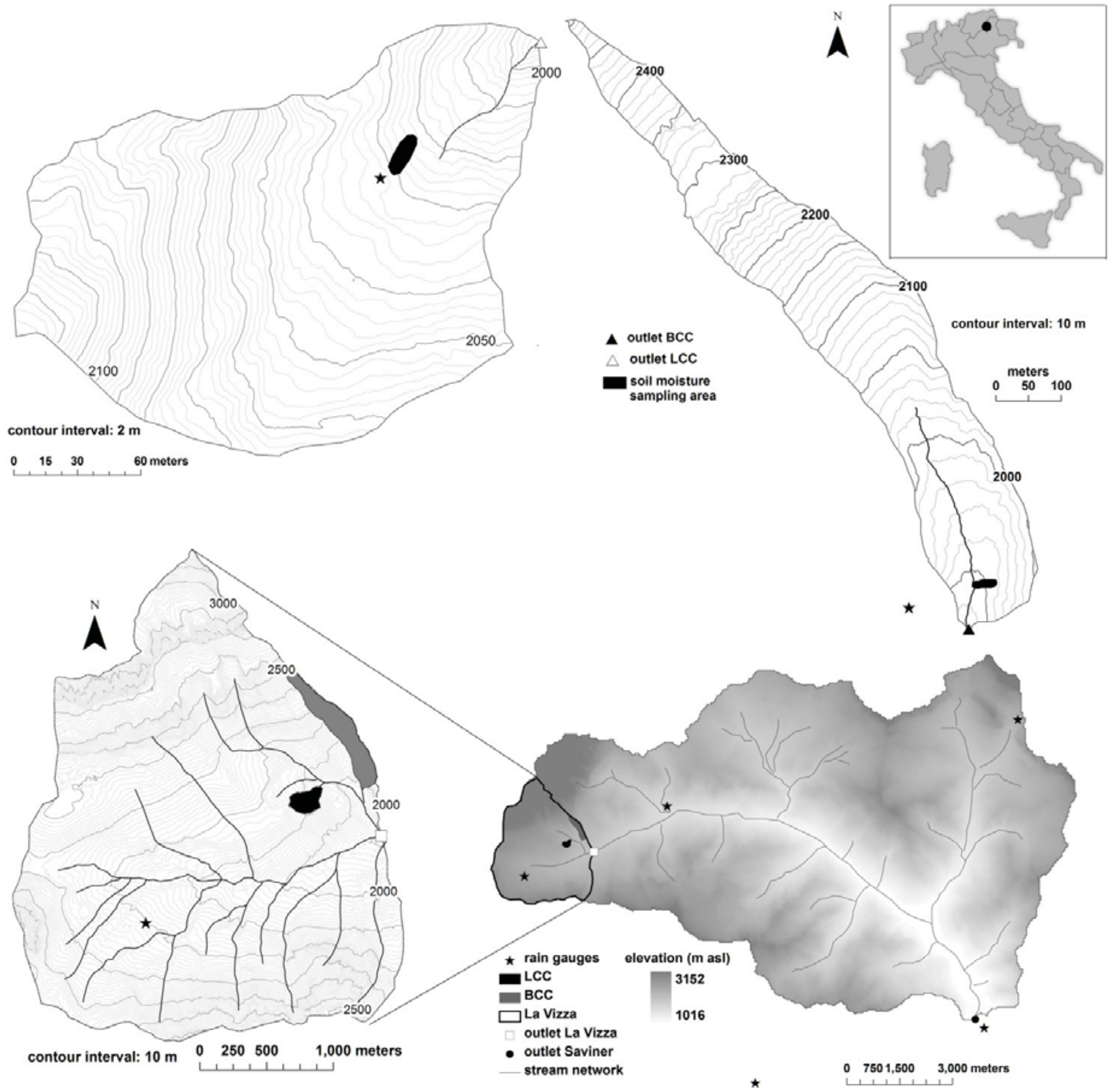

Figure 1: Study area with the four experimental catchments
Abbildung 1: Untersuchungsbereich mit den vier Testeinzugsgebieten

Table 1: Main morphological properties and instrumentation of the four experimental catchments
Tabelle 1: Gebietskenngrößen und Anzahl der installierten Messgeräte

Catchment name	Area (km^2)	Elevation range (m a.s.l.)	Mean slope (°)	N. of rain gauges	N. of soil moisture sensors
LCC	0.03	1970-2128	25.4	1	4
BCC	0.14	1932-2515	29.9	1	-
La Vizza	7.3	1843-3152	28.0	3	-
Saviner	109	1016-3152	25.9	7	-

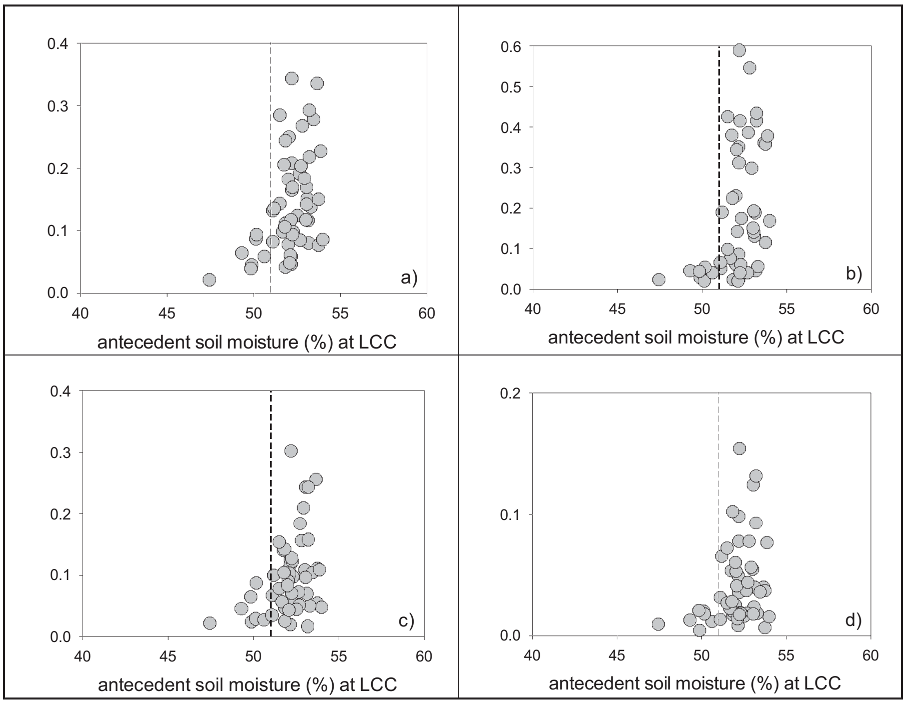

Figure 2: Antecedent soil moisture versus runoff coefficient for the four study catchments. a) LCC; b) BCC; c) La Vizza; d) Saviner. Note the different y-axis scale

Abbildung 2: Vorbefeuchtungsgrad und Abflussbeiwert an den vier Testgebieten. a) LCC; b) BCC; c) La Vizza; d) Saviner

comparable runoff processes controlled by soil moisture within the various landscape units occur at different spatial scales and that ii) few hillslope-scale soil moisture measurements may be used as indicators of the wetness conditions at larger scales even in alpine catchments with rough topography and complex terrain.

3.2 Inter-comparison of event runoff coefficients

Runoff coefficients of the selected events were compared for all study catchments. Summary descriptive statistics are given in Table 2. Overall, runoff coefficients do not exceed 60%, with BCC showing the highest mean, the highest variability and the widest range of values. The largest catchment, Saviner, is characterized by the lowest mean, the smallest range of values and the most skewed distribution. On average, runoff coefficients are relatively low for such steep catchments, likely due to the short study period considered and to the lack of snowmelt-runoff events, which significantly contribute to yearly runoff in this area (Penna et al., 2009). Moreover, the influence of evapotranspiration should also be taken into account, since the study watersheds are densely vegetated.

Table 2: Basic descriptive statistics of runoff coefficients of the four experimental catchments

Tabelle 2: Statistische Kenngrößen des Abflussbeiwertes der vier Testgebiete

	LCC	BCC	La Vizza	Saviner
Mean	0.14	0.19	0.10	0.04
Coefficient of Variation	0.57	0.85	0.65	0.83
Skewness	0.75	0.77	1.26	1.52
Minimum	0.02	0.02	0.02	0.01
Maximum	0.34	0.59	0.30	0.15

Inter-comparison of event runoff coefficients is presented in Figure 3. Scatterplots reveal an overall good agreement among the various basins, with the best correlation existing between the two smaller catchments, LCC and BCC ($R^2 = 0.57$). Runoff coefficients significantly decrease with the increase of the watershed area. This different behaviour, which reflects the scale-dependency of event stormflow, is speculatively related to the highest values of slope of the two headwater catchments and the possible deeper soils in the riparian area of large watersheds, which allow for a larger water storage and a lower runoff depth.

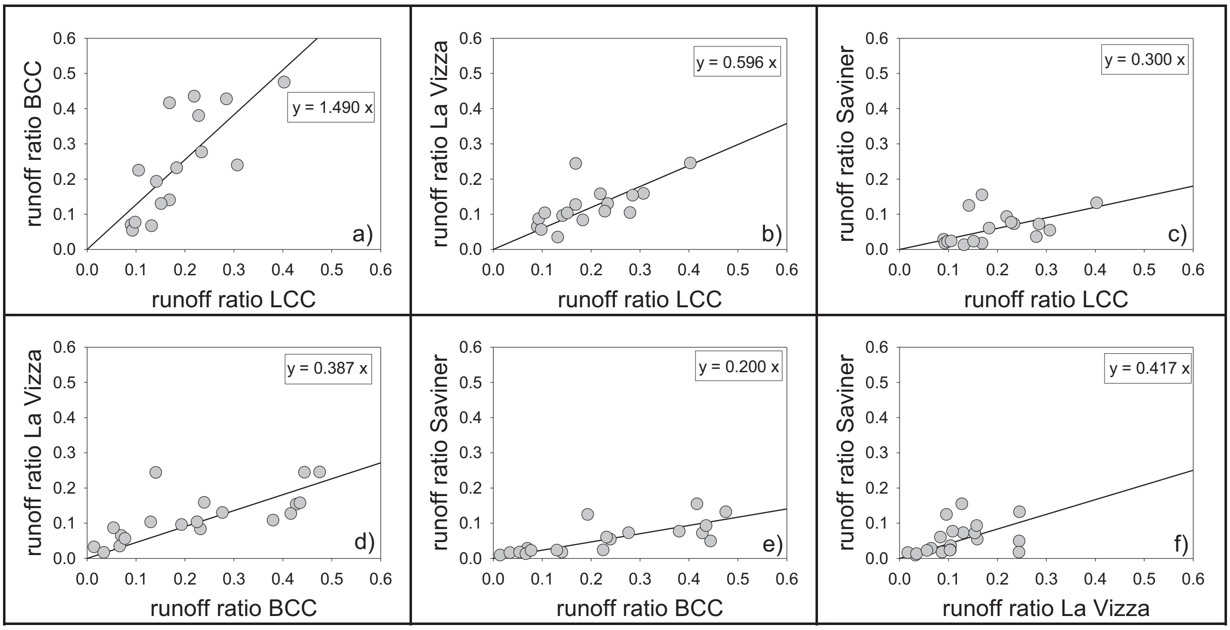

Figure 3: Comparison among the runoff coefficients of the four study catchments. Only the events (20) with comparable precipitation values across the various catchments (mean difference: 17%, minimum difference: 1%, maximum difference: 37%) were considered. a) LCC vs. BCC; b) LCC vs. La Vizza; c) LCC vs. Saviner; d) BCC vs. La Vizza; e) BCC vs. Saviner; f) La Vizza vs. Saviner

Abbildung 3: Paarweiser Vergleich der Abflussbeiwerte der vier Testgebiete. Nur zeitgleiche Niederschlagsereignisse wurden berücksichtigt

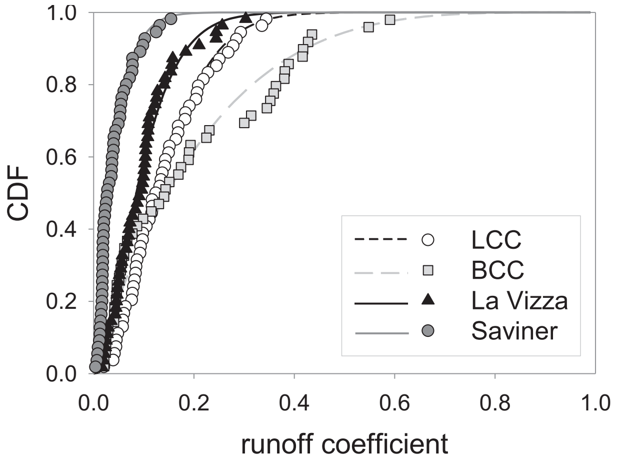

Figure 4: Experimental (dots) and theoretical (lines) cumulative beta distribution functions of runoff coefficients for the four study catchments. Root Mean Square Error: LCC = 0.021; BCC = 0.050; La Vizza = 0.029; Saviner = 0.048

Abbildung 4: Experimentelle (Punkte) und beta-verteilte (Linie) Häufigkeitsverteilung der Abflussbeiwerte der vier Testgebiete

The distribution of runoff coefficients is well fitted by a beta distribution (MERZ et al., 2006; VIGLIONE et al., 2009). The comparison with the theoretical distribution function underlines the different patterns for the four study sites (Figure 4). Generally, the values and the variability of runoff coefficients decrease with the catchment scale increase, in accordance with previous observations on several basins at different spatial scales (La Vizza and Saviner included, NORBIATO et al., 2009). Interestingly, BCC slightly departs from such a trend: it shows the lowest fit to the theoretical distribution (highest Root Mean Square Error), and, particularly, for moderate and big events, runoff coefficients of BCC are greater than those observed for LCC. A possible explanation of such a behaviour lies in the higher extent of thin soils (i.e., more propensity to runoff) in the upper part of BCC compared to LCC and in the different extent of the riparian area in the two catchments. To test this latter hypothesis, starting from a 1 m resolution grid, we followed a DEM analysis threshold method (JENCSO et al., 2009) to define the riparian extent in each catchment. The results were then compared with the real topography observed during field surveys. According to this approach, the riparian zone in LCC and BCC accounts for 3.9% and 2.0% of the total catchment area, respectively. This means that for small events, where the major contribution to runoff likely comes from the riparian area (MCGLYNN and MCDONNELL, 2003; MCGLYNN, 2005; PENNA et al., 2011), BCC, which features a smaller riparian area than LCC, generates lower runoff coefficients compared to LCC. Conversely, for bigger events, where the major contribution to runoff comes from the hillslope zone, BCC, which features a smaller riparian area and therefore a greater hillslope area than LCC, produces higher runoff coefficients.

Conclusions

This study compares the runoff response of four alpine nested catchments ranging from 0.033 km^2 to 109 km^2 over 54 rainfall-runoff events. A similar threshold relation between antecedent soil moisture (measured at a few locations at the micro-catchment scale) and runoff coefficients is found for all basins. This highlights the control exerted by soil moisture on runoff at different scales suggesting that few hillslope-scale soil moisture measurements can be used as indicators of the moisture conditions in larger basins. Inter-comparison of event runoff coefficients shows a good correlation across all scales, with runoff coefficient values significantly decreasing with the increase of the catchment area. Runoff coefficients fit well the beta distribution but their variability at small scales reflects the marked influence of topography (in terms of riparian area/total watershed area ratio) on the catchment runoff response. This work shows evidence that small experimental catchments with detailed data can provide important indications about the main processes operating at larger scales. Nevertheless the intrinsic variability of hydrological behaviours due to local controls has to be taken into account.

References

BLÖSCHL G. (2001): Scaling in hydrology. Hydrological Processes, 15, 709–711.

BONELL M., MCDONNELL J.J., SCATENA F., SEIBERT J., UHLENBROOK S., VAN LANEN H. (2006): HELPingFRIENDs in PUBs: charting a course for synergies within international water research programs in gauged and ungauged basins. Hydrological Processes, 20, 1867–1874.

JENCSO K.J., MCGLYNN B.L., GOOSEFF M.N., WONDZELL S.M., BENCALA K.E., MARSHALL L.A. (2009): Hydrologic connectivity between landscapes and streams: transferring reach- and plot-scale understanding to the catchment scale. Water Resources Research, 45, W04428, doi:10.1029/2008WR007225.

BLÖSCHL G., PARAJKA J. (2006): Spatio-temporal variability of runoff coefficients. Journal of Hydrology 331, 591–604.

BLUME T., ZEHE E., BRONSTERT A. (2007): Rainfall–runoff response, event-based runoff coefficients and hydrograph separation/Réponse pluie-débit, coefficients d'écoulement événementiels et séparation d'hydrogramme, Hydrological Sciences Journal, 52:5, 843-862. DOI: 10.1623/hysj.52.5.843

MCGLYNN B.L. (2005): The role of riparian zone in steep mountain catchments. In Global Change and Mountain Regions: An Overview of Current Knowledge. Adv. Global Change Res. Ser., vol. 23, edited by U.M. Huber, H. K. M. Bugmann and M. A. Reasoner, pp. 331–342, Springer, New York.

MCGLYNN B. L., MCDONNELL J. J. (2003): Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. Water Resources Research, 39(11), 1310, doi:10.1029/2003WR002091.

NORBIATO D., BORGA M., MERZ R., BLÖSCHL G., CARTON A. (2009): Controls on event runoff coefficients in the eastern Italian Alps. Journal of Hydrology, 375, 312–325.

PENNA D., BORGA M., NORBIATO D., DALLA FONTANA G. (2009): Hillslope scale soil moisture variability in a steep alpine terrain. Journal of Hydrology, 364, 311–327.

PENNA D., NORBIATO D., BORGA M., DALLA FONTANA G. (2007): Analisi della stabilità temporale dell'umidità del suolo in un piccolo bacino dolomitico/Temporal stability of surface soil moisture in a small alpine catchment. In G. Bischetti (Ed.): Ricerche ed esperienze di Sistemazioni Idraulico-Forestali (vol. 27, 489–502). Nuova Editoriale Bios, Cosenza, Italy.

PENNA D., TROMP-VAN MEERVELD H. J., GOBBI A., BORGA M., DALLA FONTANA G. (2011): The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. Hydrology and Earth System Sciences 15, 689–702, doi: 10.5194/hess-15-689-2011.

SCHUMANN S., SCHMALZ B., MEESENBURG H., SCHRÖDER. U. (Eds.) (2010): Status and Perspectives of Hydrology in Small Basins. Results of the International Workshop in Goslar-Hahnenklee, 2009 and Inventory of Small Hydrological Research Basins. IHP/HWRP-Berichte 10, Koblenz, Germany.

SIVAPALAN M. (2003): Process complexity at hillslope scale, process simplicity at the watershed scale: is there a connection? Hydrological Processes, 17, 1037–1041.

SOULSBY C., RODGERS P.J., PETRY J., HANNAH D.M., MALCOLM I.A., DUNN S.M. (2004): Using tracers to upscale flow path understanding in mesoscale mountainous catchments: two examples from Scotland. Journal of Hydrology, 291, 174–196.

SOULSBY C., TETZLAFF D., DUNN S.M., WALDRON S. (2006): Scaling up and out in runoff process understanding: insights from nested experimental catchment studies. Hydrological Processes, 20, 2461–2465.

VIGLIONE A., MERZ R., BLÖSCHL G. (2009): On the role of the runoff coefficient in the mapping of rainfall to flood return periods. Hydrology and Earth System Sciences, 13, 577–593, www.hydrol-earth-syst-sci.net/13/577/2009/

ZILLGENS B., MERZ B., KIRNBAUER R., TILCH N. (2007): Analysis of the runoff response of an alpine catchment at different scales. Hydrology and Earth System Sciences, 11, 1441–1454, www.hydrol-earth-syst-sci.net/11/1441/2007/

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