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Controls on event runoff coefficients in the eastern Italian Alps

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SUMMARY

Analyses of event runoff coefficients provide essential insight on catchment response, particularly if a range of catchments and a range of events are compared by a single indicator. In this study we examine the effect of climate, geology, land use, flood types and initial soil moisture conditions on the distribution functions of the event runoff coefficients for a set of 14 mountainous catchments located in the eastern Italian Alps, ranging in size from 7.3 to 608.4 km^2. Runoff coefficients were computed from hourly precipitation, runoff data and estimates of snowmelt. A total of 535 events were analysed over the period 1989–2004. We classified each basin using a "permeability index" which was inferred from a geologic map and ranged from "low" to "high permeability". A continuous soil moisture accounting model was applied to each catchment to classify 'wet' and 'dry' initial soil moisture conditions. The results indicate that the spatial distribution of runoff coefficients is highly correlated with mean annual precipitation, with the mean runoff coefficient increasing with mean annual precipitation. Geology, through the 'permeability index', is another important control on runoff coefficients for catchments with mean annual precipitation less than 1200 mm. Land use, as indexed by the SCS curve number, influences runoff coefficient distribution to a lesser degree. An analysis of the runoff coefficients by flood type indicates that runoff coefficients increase with event snowmelt. Results show that there exists an intermediate region of subsurface water storage capacity, as indexed by a flow–duration curve-based index, which maximises the impact of initial wetness conditions on the runoff coefficient. This means that the difference between runoff coefficients characterised by wet and dry initial conditions is negligible both for basins with very large storage capacity and for basins with small storage capacity. For basins with intermediate storage capacities, the impact of the initial wetness conditions may be relatively large.

Introduction

Predicting flood response in ungauged catchments is emerging as one of the major issues in the hydrological science (Sivapalan et al., 2003). Predictions are particularly difficult to make in alpine regions where data are sparse and the spatial variability of both precipitation and physical controls on runoff generation is huge. The event runoff coefficient, defined as the portion of rainfall that becomes direct runoff during an event, is a key concept in hydrology and an important diagnostic variable for catchment response, particularly if a range of catchments and a range of events are to be compared by a single indicator (Merz and Blöschl, 2009). Analysis of event runoff coefficients may provide essential insight on how different landscapes 'filter' rainfall to generate runoff and how the observed differences can be explained by catchment characteristics (Blume et al., 2007). Quantifying process controls on space and time variability of runoff coefficients may therefore contribute to isolate flood-generating mechanisms both in time (summer vs. winter, rainfall vs. snowmelt, etc.), and also in space (different climate, geology, soils, vegetation, etc.) (Fiorentino and Iacobellis, 2001).

There exists a substantial body of work on controls of runoff coefficient variability at the regional scale (Merz and Blöschl, 2003). The scale dependency of runoff coefficients to plot and catchment area has been examined by Wainwright and Parsons (2002) and Cerdan et al. (2004), who both identified a significant decrease in the runoff coefficient as area increases. Furthermore, Cerdan et al. (2004) was able to show that at the scale of 10 km^2 the percentage of arable land is a driving factor for runoff response. Gottschalk and Weingartner (1998) examined runoff coefficients for 192 flood events in 17 Swiss catchments, which they used in a derived flood frequency model. They fitted a Beta function to the distribution of runoff coefficients in each catchment and interpreted the parameters for different hydrologic regions in Switzerland. They concluded that the differences in runoff coefficients can be explained by topographic characteristics such as altitude and slope and to some degree by stream network density and

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geology. A larger flood events data set was examined by Merz and Blöschl (2009), who analysed a total of about 50,000 events in 337 Austrian catchments with catchment areas ranging from 80 to 10,000 km^2 over the period 1981–2000. They found that, in the type of climate and at the scale of the catchments examined in their work, the main controls on event runoff coefficients were the climate and the runoff regime through the seasonal catchment water balance and hence antecedent soil moisture conditions in addition to event characteristics. Catchment characteristics such as soils, land use and geology affected runoff coefficients to a lesser degree.

In this paper, we characterise the distribution of event runoff coefficients for 14 catchments in the eastern Italian Alps. The size of the catchments ranges from 7.3 to 608.4 km^2. In this region, interaction of orographic structure with large scale atmospheric patterns results in large spatial variability in the precipitation and flood regime, and translates into marked differences of the distribution of event runoff coefficients. There is, however, considerable spatial variability in the degree to which runoff coefficients reflects the precipitation pattern. Specifically, we address the following research questions: (a) What are the main controls on the spatial variability of event runoff coefficients? (b) How variability in climate, geology and land use can be related to spatial differences in runoff coefficient distributions? (c) How is the influence of antecedent soil moisture conditions filtered by geo-hydrologic characteristics of the catchments?

In particular we characterise the distribution of runoff coefficients with respect to a broad geologic partitioning of the region according to the permeability characteristics of the lithological units, as inferred from geological surveys. A number of studies identified low correlation between geological indices and the distribution of event runoff coefficients (Merz and Blöschl, 2009 and references therein). A possible reason for the apparent low predictive power of geological indices may be the use of the percentage of catchment area covered by a given geological unit to characterise the process controls on the runoff coefficients. Although this is the type of information typically available for practical applications, it seems not to be representative as even within the same geological unit, the runoff generation can differ vastly, depending on preferential flow through fissures and fractures, as illustrated by many case studies around the world. (Tague and Grant, 2004). Conceptually, our approach follows Winter (2001) and Tague and Grant (2004), who advocate hydrologic comparison based on geologic–geomorphic landscape attributes. We classified each basin using a "permeability index" which ranges from "low" to "high permeability". The classification metric incorporates information on the inferred degree of secondary permeability (i.e. the permeability effects developed in a rock after its deposition, through weathering and fracturing) and on the spatial organisation of the lithological unit with respect to the river network. The lateral contiguity of distinct lithological units provides a unique opportunity to examine geological control on runoff coefficients distributions at the regional scale. Moreover, the geologic partitioning affords characterisation of the impact of initial moisture conditions on runoff coefficients for various permeability classes. To this purpose, a continuous soil moisture accounting model is applied to each catchment to derive soil moisture conditions prior to each event.

The paper is organised as follows. The Section "Study catchments: morphology, climate, land use and geology" describes the study area and the main attributes of catchments according to morphology, climate, land use and geology. The Section "Computation of event runoff coefficients" describes the technique used to estimate the event runoff coefficients, and specifically the baseflow separation method, the event separation method, the estimation of the runoff coefficient and the continuous soil moisture accounting model used to evaluate the initial soil moisture conditions. The analysis of the main controls on the runoff coefficient distributions is reported in the Section 'Results', with focus on the role of climate, geology, land use and initial soil moisture conditions. Finally, the overview of the principal observations from this work is presented in the Section "Conclusions".

Study catchments: morphology, climate, land use and geology

The location of the 14 catchments used in this study is shown in Fig. 1. Table 1 provides more detailed catchment information. For the sake of clarity, catchments are sequentially numbered as indicated in Table 1. Catchment drainage area ranges between 7.3 km^2 and 608.4 km^2. The topography is rather complex with altitudes ranging from 388 m asl (lowest altitude of Posina) to 3600 m asl (highest elevation of Ridanna at Vipiteno). Measured runoff represents the natural runoff variability well, since management activities, such as artificial reservoirs and diversions, do not alter the river regime. Five catchments are included in four larger parent basins (catchments 1 and 3 are included in catchment 2; catchments 5, 9 and 14 are included in catchments 4, 10 and 13, respectively).

Examination of Table 1 shows that these catchments exhibit significant variability in terms of hydrological response. A parameter which describes this variability is the ratio between the mean of maximum annual flood and the average annual discharge. Table 1 shows that catchments with similar drainage area, such as catchment 5 (San Vigilio at Longega), catchment 12 (Posina at Stancari) and catchment 13 (Cordevole at Saviner) (with areas ranging from 105.5 to 116.0 km^2) are characterised by values of the ratio ranging over more than one order of magnitude (from 2.4 to 33.2). This variability implies that different processes are responsible for flood runoff generation across these catchments. Qualitative information gathered during site visits was used to make educated guesses about the hydrological processes driving runoff generation during flood events. According to this information, for example, the response of the Posina catchment is dominated by quick subsurface flow and surface runoff generated on saturated areas, whereas the response of the San Vigilio catchment is delayed and attenuated due to large groundwater storage.

Estimates of catchment-averaged mean annual precipitation (MAP) reported in Table 1 were obtained by the Thiessen technique. The gauge densities range from 1 station per 4 km^2 (catchment 14 – Cordevole at Vizza) to 1 station per 150 km^2 (catchment 1 – Aurino at Cadipietra). Corrections for snowfall catch deficit (Sevruk et al., 1998) were used. Catchment-averaged mean annual precipitation ranges from 900 mm to 1708 mm. Precipitation is larger for the catchment located in the forealpine regions (catchment 12) and for some of the catchments most exposed to the *stau* effect (catchments 3 and 10). It is intermediate for the catchments located in the Dolomite region exposed to humid and warm winds from the Adriatic sea (catchments 13 and 14) and for the other catchments exposed to the *stau* effect (catchments 1, 2, 9 and 11). Precipitation is significantly lower in the catchments of Val Pusteria (catchments 4–8), due to the dual sheltering effect of the mountainous ranges to both the north and the south.

We applied the Budyko's climatic classification scheme (Budyko, 1974) to display the climatic characteristics of these catchments. This is achieved by presenting the specific response of each catchment on the Budyko curve (Fig. 2), which is a plot that expresses E/P, the ratio of average annual evapotranspiration (E) to average annual precipitation (P) as a function of EP/P, the ratio of average annual potential evapotranspiration (EP) to average annual precipitation (P). Actual evapotranspiration (E) for each catchment was derived as the long-term difference between P and R (runoff) for the basins, whereas potential evapotranspiration was