Investigation of the hydrologic response of three experimental basins across Europe

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Untersuchung des Abflussverhaltens dreier europäischer Testeinzugsgebiete

Introduction

Notwithstanding the large number of experimental studies at different catchment scales, our knowledge of processes controlling the basin hydrological response is still limited, especially when this information has to be extended over larger areas (SIVAPALAN, 2005; KIRCHNER, 2009). Understanding the hydrological behaviour of a catchment can be considered as a first step toward a better assessment and prediction of possible impacts of land use modifications and climate change affecting the catchment itself. Studies undertaken in small experimental watersheds, where detailed and high-quality hydro-meteorological variables are relatively easily recorded, can help to address this issue (SCHUMANN et al., 2010). In this context, rainfall-runoff models allow one to link the runoff response observed at the catchment outlet to the corresponding runoff generating mechanisms. This approach is useful both for a better comprehension of the main processes driving the catchment hydrological response and, at the same time, for a more accurate development and performance assessment of the models themselves. Complex distributed rainfall-runoff models may provide insights into the relevant processes operating at the hillslope scale (CAMPORESE et al., 2010;

Zusammenfassung

Die Modellierung des hydrologischen Abflussverhaltens eines Einzugsgebiets ist durch zahlreiche Faktoren erschwert. Aufgrund der Unsicherheiten der Inputdaten, der Komplexität des Systems, der Modellparameterisierung und der Überprüfbarkeit ist die Beschreibung der hydrologischen Einzugsgebietscharakteristik nicht immer einfach. Der Einsatz von Niederschlags-Abfluss- (NA-)Modellen bei gut beobachteten Testeinzugsgebieten kann daher sowohl für das verbesserte Verständnis der Abflusskomponenten verwendet werden, aber auch um die Modelle selbst zu überprüfen. In diesem Beitrag wurden in drei verschiedenen Testeinzugsgebieten, die jeweils unterschiedliche klimatische und physiographische Gegebenheiten reflektieren, NA Modelle angewendet. Die Ergebnisse zeigen eine gute Eignung der Modelle um die Abflussdynamik wiederzugeben. Als besonders wichtig zeigte sich die Beziehung zwischen Bodenfeuchte und Abflussbildung unter Berücksichtigung eines Schwellenwertansatzes.

Schlagwörter: NA-Modell, Testeinzugsgebiet, Bodenfeuchte, hydrologische Prozesse, Schwellenwerte.

Summary

Modelling the catchment hydrologic response is hampered by many factors. Due to large uncertainties of input data, structural complexity, model parameterization and validation data, frequently the prediction of catchment behaviour is not a straightforward task. Therefore, the use of rainfall-runoff models into small catchments, where detailed data are available, may not only contribute to a better understanding of the rainfall-runoff processes, but also allows to assess the reliability of the models themselves. In this study, a continuous rainfall-runoff model, based on an intense hydro-meteorological monitoring activity in research watersheds, was applied to three European experimental catchments characterized by different climatic and physiographic conditions. Results show that the model can be considered as a useful tool to investigate runoff dynamics within these catchments and highlight the importance of the soil moisture-runoff threshold relationship in characterizing the catchment hydrological behaviour.

Key words: Rainfall-runoff model, experimental basin, soil moisture, hydrological processes, threshold.

Loague et al., 2010), but problems related to their parameterization and application limit their use. On the other hand, simple conceptual rainfall-runoff models, due to their ease-of-use and flexibility, represent a valid alternative that can be easily adopted following the more pragmatic "downward approach" aimed at simulating only the most relevant processes (GRAYSON and BLOSCHL, 2000; SIVAPALAN et al., 2003). Along this vein, BROCCA et al. (2010a) developed a parsimonious continuous rainfall-runoff model, named MISDc ("Modello Idrologico Semi-Distribuito in continuo"). The model development was based on the results of an intense hydro-meteorological monitoring activity in an experimental catchment located in central Italy (Vallaccia catchment) which allowed the description of the most important processes controlling the runoff generation (BROCCA et al., 2008; 2010a). Indeed, for a proper evaluation of the assumptions behind the development of a specific rainfall-runoff model, the use of auxiliary data (e.g. soil moisture, groundwater level, soil resistivity, water isotopic composition, etc.) along with the classical rainfall-runoff data is of particular importance (BEVEN, 2008).

In this study, the MISDc model was applied to three experimental catchments characterized by very different climatic and topographic conditions: Colorso in central Italy (BROCCA et al., 2005), Cordevole in northern Italy (Penna et al., 2009) and Bibeschbach in Luxembourg (HEITZ et al., 2010). This work mainly aims at: i) assessing the MISDc model reliability under different physiographic and climatic conditions; and ii) comparing the hydrologic behaviour of three experimental catchments in Europe through the eyes of the MISDc model. Particular attention was given to the threshold-like behaviour existing between soil moisture and runoff (ZEHE and SIVAPALAN, 2009; Graham and McDonnell, 2010), since this relationship can be considered one of the most striking hydrological signatures of a catchment (SPENCE, 2010).

Rainfall-runoff model

The MISDc model is based on an extended formulation of the semi-distributed conceptual model developed by CORRADINI et al. (1995) for rainfall-direct runoff transformation. The event-specific model is coupled with a module for time continuous soil water balance, as proposed by BROCCA et al. (2008), for taking into account the variable antecedent wetness conditions. The model structure reflects some of the hypotheses of catchment behaviour inferred by investigating the response of experimental catchments to external inputs. Particularly, rainfall-runoff observations at different scales as well as soil moisture recordings were taken into consideration (BROCCA et al., 2009). The model structure includes only seven parameters and uses as input the hydrometeorological variable usually available: rainfall and air temperature. A full description of the model can be found in BROCCA et al. (2010a). In this study, we used the lumped version of the model and added a simple component for the simulation of baseflow in order to simulate the discharge during non-flood conditions.

Study catchments and data set

Three experimental catchments were compared: Colorso, Cordevole and Bibeschbach (Figure 1).

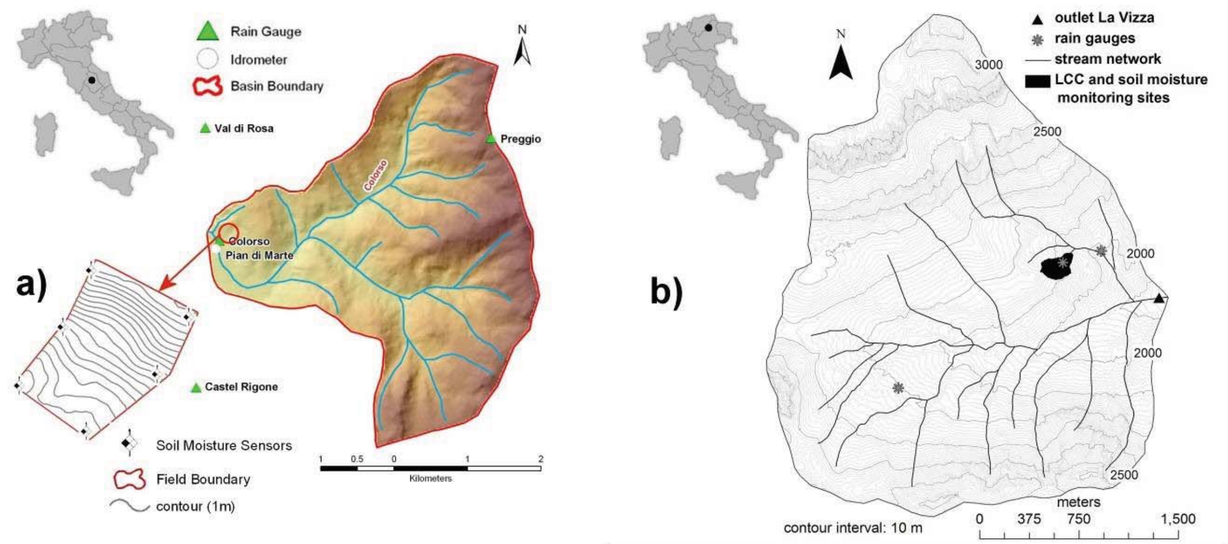
The Colorso experimental catchment, COL, is located in an inland region of central Italy and covers an area of 12.9 km^2 (Figure 1a). Elevations range between 312 and 798 m a.s.l. with a mean slope of 28.2%. The lithology is a flysch formation and the land use is mainly comprised of forest and pasture. Four rain gauges are operating within the basin, which is characterized by a Mediterranean climate with a mean annual rainfall of 930 mm. Since July 2002, an experimental plot (~1 ha) with six probes for continuous volumetric soil moisture monitoring has been set up in the western part of the catchment near its outlet. The soil moisture probes are based on the Frequency Domain Reflectometry (FDR) technique (Enviroscan^{TM}) and measure continuously volumetric soil moisture values in the soil column at 10 cm, 20 cm and 40 cm depth, providing at each depth the average volumetric soil moisture for a layer thickness of nearly 10 cm. The average value of the six probes at 10 cm depth for the period 2002-2004 was used in this study.

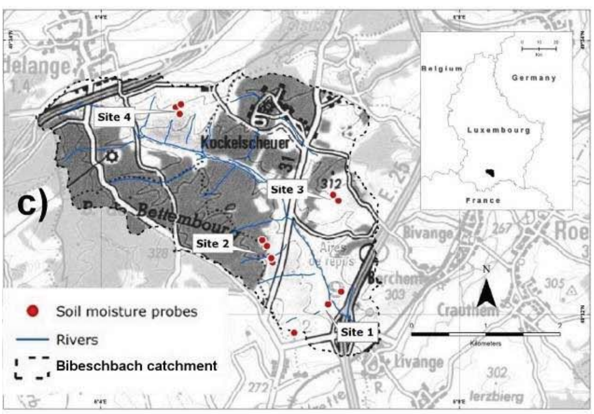
The Cordevole catchment, COR, is located in the central-eastern Italian Alps and covers an area of 7.1 km^2 (Figure 1b). Elevations range between 1835 and 3152 m a.s.l. with a mean slope of 45.4%. The lithology is formed by Triassic dolomite and conglomerate lava and the land use is mainly composed by bare rock in the upper part, pasture and ski fields in the lower portion. Three rain gauges are operating in the basin, which is characterized by a typical alpine climate with a mean annual rainfall of about 1220 mm where 49% falls as snow. Volumetric soil moisture data were collected in the small experimental Larch Creek sub-catchment (LCC, 0.033 km^2) at four locations by using the Time Domain Reflectometry (TDR) technique (Campbell Scientific Inc.). In this study, the 2008 summer data set was used considering the average soil moisture value at 0–30 cm depth.

The experimental Bibeschbach catchment (10.8 km^2), BIB, is located in the southern part of the Alzette River basin, Luxembourg (Figure 1c). Elevations range between 268 and 350 m a.s.l. with a mean slope of 6.4%. The site is mainly characterized by forest and agriculture (i.e. cropland and pasture) on loamy soils. Two rain gauges are operating in the vicinity of the basin which is characterized by a typical humid temperate climate with a mean annual rainfall of about 860 mm. Since 2005, the basin has been equipped with a set of 40 classic ECH2O Decagon^{TM} soil moisture sensors, which measure the permittivity, in terms of voltage, of the topsoil layer at a depth of 4 to 7 cm over four sites (Figure 1c). The soil probes were installed at different locations in accordance with land use, geology and pedology. The sensors were connected to data loggers where an hourly dielectric constant of the medium was stored. A calibration with regular TDR point measurements is performed to convert the signal into volumetric soil water content. For this study, the temporal pattern of the average soil moisture over all sites was used on the 2007–2008 period.

Results and discussions

For each catchment, the seven parameters of the MISDc model were calibrated considering the same range of vari-





Catchment	Area (km^2)	Period of analysis	Mean elevation (m a.s.l.)	Mean slope (%)	Mean annual rainfall (mm)	Soil moisture sampling depth (cm)
Colorso	12.9	2002-2004	533	28.2	930	5-15
Cordevole	7.1	2008 (summer period)	2341	45.4	1220	0-30
Bibeschbach	10.8	2007-2008	298	6.4	860	4-7

Figure 1: Morphology and hydrometeorological network for the three study catchments. In the table the main characteristics of each catchment are also reported

Abbildung 1: Morphologie und hydro-meteorologisches Beobachtungsnetz der drei Untersuchungsgebiete. Die Tabelle zeigt die wichtigsten Gebietskenngrößen (Fläche, Beobachtungsdauer, mittlere Seehöhe, mittlere Hangneigung, mittlere Jahresniederschlag und Sondentiefe) ability and applying a standard gradient-based automatic optimization method (the low number and the independence of the parameters do not require a more sophisticated method). The maximization of the Nash-Sutcliffe efficiency index, *NS*, was used as performance measure for discharge, whereas the determination coefficient, R^2, was considered for soil moisture. Calibration was performed using only discharge observations. Additionally, soil moisture simulations were compared with observations to evaluate the internal state simulated by the model. As such, it has to be noticed that the optimal layer depth simulated in the MISDc model was found ranging between 1.5 and 2.0 m. Since measurement depths are shallower (5–30 cm), a surface layer was created with the same depth as the observations, the same characteristics (parameters) of the whole soil layer and then included into the model. Therefore, the comparison between the simulated and observed soil moisture was carried out for this surface soil layer. Figure 2 shows the comparison in terms of discharge and saturation degree (computed from soil moisture data) for each catchment. For COL and BIB a clear seasonal soil moisture pattern is detected. COR shows a narrower range of variation for the saturation degree compared to the others and this is likely related to the shorter summer period analyzed.

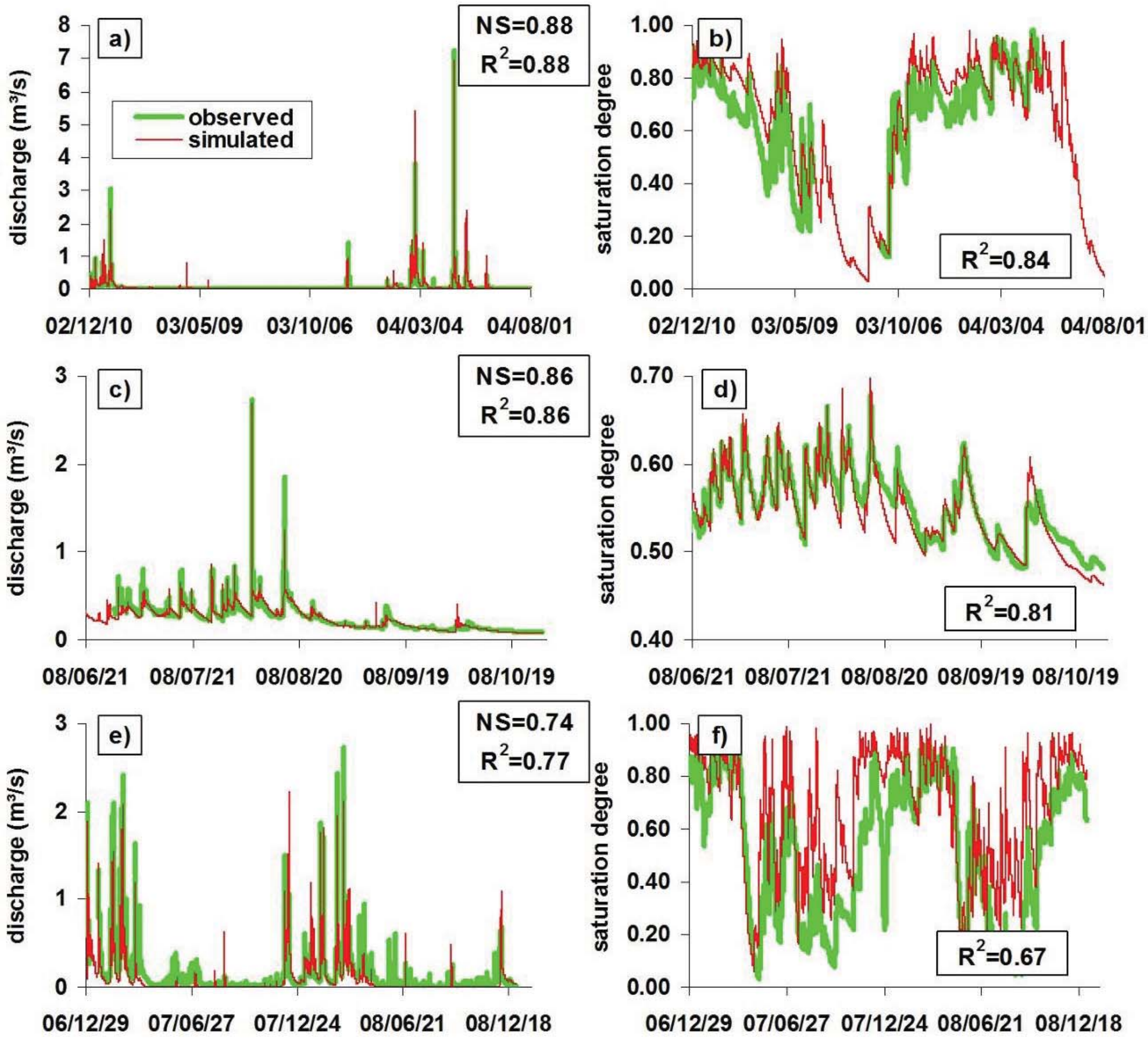


Figure 2: Observed versus simulated discharge (left) and surface saturation degree (right) for : a, b) Colorso, c, d) Cordevole, and e, f) Bibeschbach catchment

Abbildung 2: Beobachtete und simulierte Werte des Abflusses (links) und des Bodensättigungsgrades (rechts) der Gebiete a, b) Colorso, c, d) Cordevole und e, f) Bibeschbach

On the other hand, COL catchment is characterized by a faster and more significant runoff response compared to the two other sites. Indeed, considering that catchment areas of the three basins are quite similar, COL site shows a runoff response twice as significant.

As expected, the best results in terms of discharge simulations were obtained for COL (*NS* = 0.88), for which the model was first developed and tested. However, the model also shows a good performance for COR (*NS* = 0.86), while a slight decrease of *NS* was observed for BIB (*NS* = 0.74), mainly for low flow conditions. Considering the saturation degree simulations, the same model performance rank resulted, i.e. the best performance was found for COL (R^2 = 0.84), and the worst one for BIB (R^2 = 0.67). These discrepancies between observed and simulated data are likely due to model inconsistencies and/or input/output data errors, but further detailed investigations are needed to address these issues. Overall, the model can be considered fairly accurate in the simulation of both discharge and soil moisture and can be used as an appropriate tool to investigate catchment hydrological behaviour.

Furthermore, the simulated saturation degree for the whole soil profile was related to the observed and simulated discharge. Figure 3 displays a clear threshold effect for both observed and simulated discharge. Moreover, COL and BIB show a non-linear response that is more pronounced and visible than for COR. In addition, the same plot is presented in Figure 4, where the surface layer was

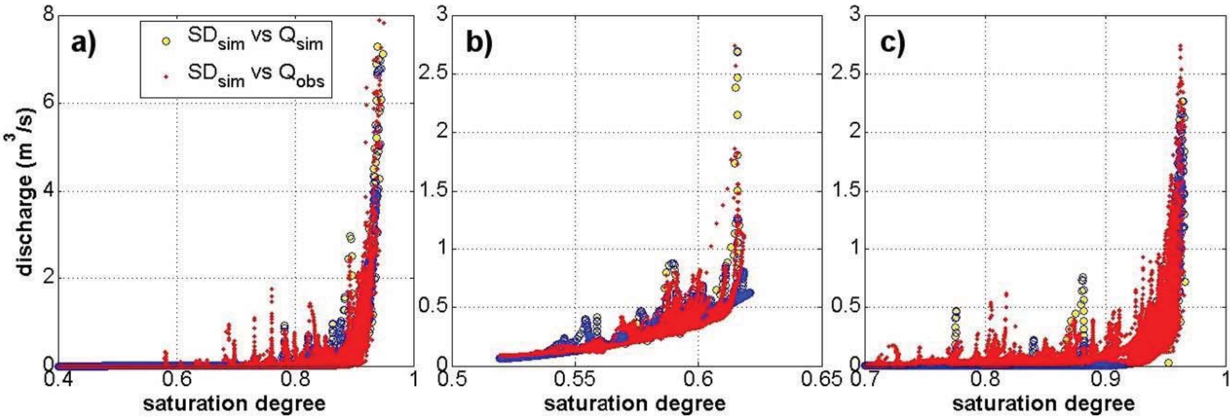


Figure 3: Relation between the simulated saturation degree, SD_{sim}, and the observed and simulated discharge (Q_{obs} and Q_{sim} respectively), for: a) Colorso, b) Cordevole, and c) Bibeschbach catchment

Abbildung 3: Gegenüberstellung von simuliertem Bodensättigungsgrad SD_{sim} und beobachteten und simulierten Abflüssen (Q_{obs} bzw. $Q_{sim)}$ für die Gebiete a) Colorso, b) Cordevole und c) Bibeschbach

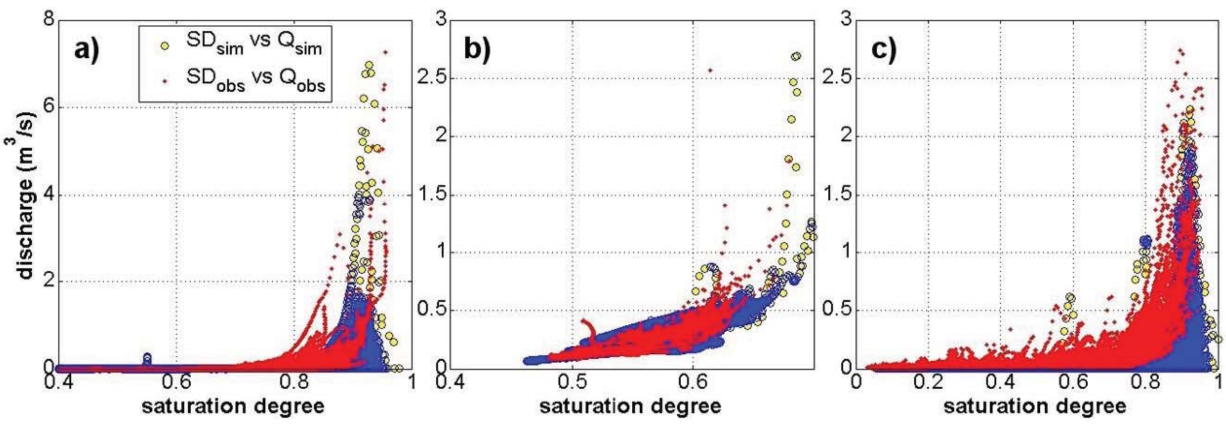


Figure 4: Relation between the observed and simulated surface saturation degree (SD_{obs} and SD_{sim} respectively), and the observed and simulated discharge (Q_{obs} and Q_{sim} respectively), for: a) Colorso, b) Cordevole, and c) Bibeschbach catchment

Abbildung 4: Gegenüberstellung von beobachteten und simuliertem Bodensättigungsgrad (SD_{obs} bzw. SD_{sim}) und beobachteten und simulierten Abflüssen (Q_{obs} bzw. $Q_{sim)}$ für die Gebiete a) Colorso, b) Cordevole und c) Bibeschbach considered. This allows a comparison between the actual observed and simulated surface saturation degree with observed and simulated discharge. The scatter on these relationships becomes more pronounced, particularly for wet conditions.

Figures 3 and 4 also highlight a stronger non-linearity for COL and BIB compared to COR. This is in contrast with the behaviour expected by looking at the complex catchment topography of COR that is supposed to play a major role on the runoff response. A possible explanation for such a difference can be related to thinner soils and higher slopes, which reduce the dampening effect of soil in alpine catchments (e.g., less storage capability and reduction of buffer effect, especially in the riparian zone). Investigations are ongoing to check these hypotheses.

Conclusions

The application of the MISDc model to three different experimental catchments in Europe provided insights both on model reliability and on the catchments' hydrological behaviour. In particular, the MISDc model performed reasonably well when simulating discharge and soil moisture for the three study areas. The model was able to reproduce a clear threshold-like behaviour existing between wetness conditions and runoff, highlighting the difference in the hydrological response of the three experimental catchments. Based on these preliminary results, further investigations about the functioning of these basins (response time of runoff, input/output data uncertainty) as well as on the possibility to use soil moisture observations for model calibration and improvements will be conducted (Brocca et al., 2010b).

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