

Inferring dominant runoff generation mechanisms through competing modelling hypotheses

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ABSTRACT: Predicting how runoff forms, sustains rivers, and triggers floods is challenging, especially with limited data. We investigate runoff generation in a nested semi-arid catchment using a multiple working hypotheses strategy. Instead of relying on a single model, we test four model structures that represent different process assumptions and assess their transferability to neighboring sub-catchments. Our results show that a good match between simulated and observed streamflow does not necessarily imply realistic processes. Indeed, only when accounting for landscape heterogeneity in the model structure do we observe improvement in both prediction and process consistency. Linking hydrological signatures to model-based diagnostics enables us to infer the dominant runoff mechanisms and quantify the relative roles of surface and subsurface runoff sources across consecutive storm events. This approach offers practical insights into flood generating processes and supports modelling in data-scarce regions.

Keywords: Hypothesis testing; Runoff Generation Mechanisms; Hydrological modelling

1 INTRODUCTION

Depending on the season, climate, and local landscape features, streamflow can arise from a combination of runoff-generation mechanisms, including infiltration-excess or Hortonian overland flow (HOF), saturation-excess overland flow (SOF), among others. Another important mechanism is subsurface stormflow (SSF), which frequently occurs on hillslopes when soil water accumulates above a low-permeability layer (McDonnell et al., 2021). This condition triggers lateral downslope flow once subsurface hydrological connectivity is established, ultimately resulting in soil water exfiltration at the foot slope.

Traditionally, a common approach to identify dominant sources contributing to the hydrograph is the use of hydrochemical data, such as isotopes and geochemical tracers. However, such data are often limited in experimental catchments and typically lack the temporal resolution needed to capture rapid runoff processes.

Today, several established good practices can help us better understand catchment functioning even when data are scarce. These include linking hydrological signatures to process understanding (McMillan, 2020); testing and falsifying process-based hypotheses within a flexible modelling framework (Fenicia et al., 2011); and using spatial transferability tests together with posterior diagnostics to assess the consistency of internal processes

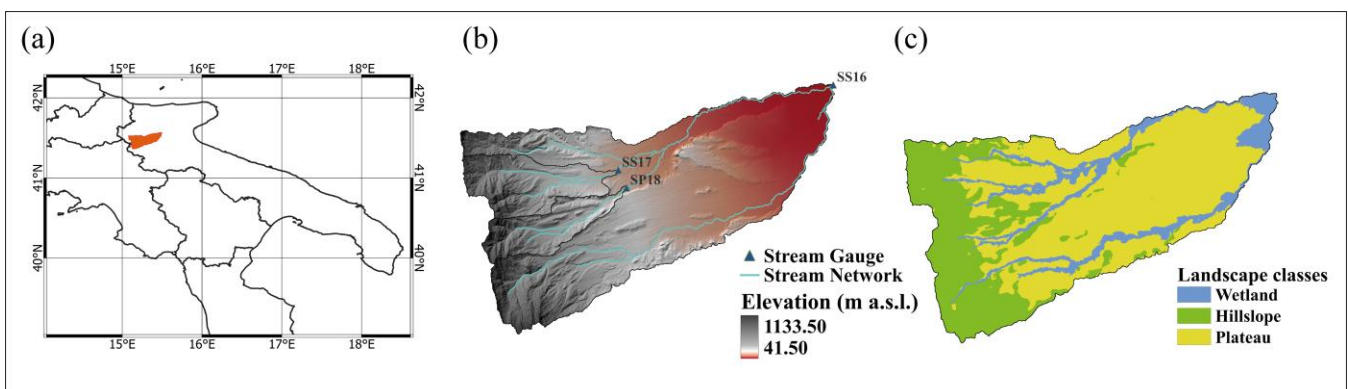


Figure 1. Salsola catchment (a) Southern Italy localization; (b) Elevation, stream network and gauges; (c) Landscape classification

(Fenicia & Kavetski, 2021). These strategies enable models to be used not only for prediction but also as tools for scientific exploration.

In this contribution, building on Perrini et al. (2025), we discuss how these techniques can be applied to infer the dominant runoff-generation mechanisms in catchment-scale event-based modelling applications.

2 STUDY CASE

Our study area is the Salsola catchment in southern Italy (Figure 1). It is a semi-arid basin of approximately 430 km², characterized by an intermittent stream network. The catchment has a nested configuration with three gauging stations, i.e., SS17, SP18, and SS16. Based on the Height Above Nearest Drainage (HAND) landscape classification (Gharari et al., 2011), the two sub-catchments are dominated by hillslope topography, while the entire catchment is predominantly plateau-dominated.

For this modelling exercise, we selected four consecutive rainfall–runoff events from January 2023 that occurred within a two-week window (Figure 2). These events provide a valuable opportunity to test different model structures under varying rainfall conditions and antecedent soil moisture. Rainfall forcing was constructed by merging spatiotemporal precipitation fields from the National Civil Protection radar platform with in-situ pluviometer measurements; the latter were used as a reference for bias correction via kriging with external drift. For further details on the dataset used in this study, see Perrini et al., (2025).

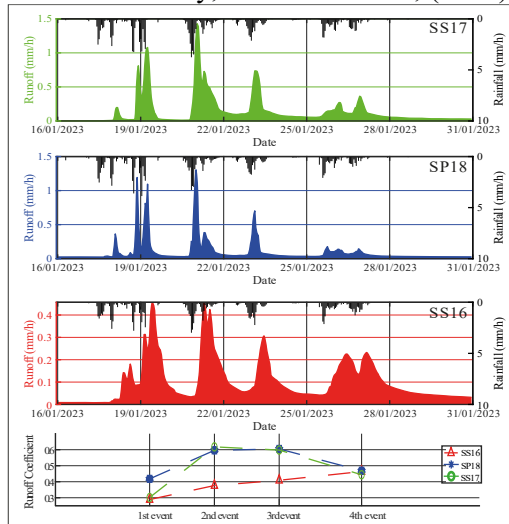


Figure 2. Rainfall and streamflow at each streamflow gauge station. The bottom panel shows the runoff coefficients for each storm event

3 COMPETING HYPOTHESES

Based on hydrological signatures, we established a set of prior modelling hypotheses. First, given the semi-arid context, the temporary stream network, and the very

small baseflow indices identified at the long-term scale, we chose to neglect baseflow in the event-based modelling application. Second, we found that the two headwater catchments display predominantly Hortonian behaviour, with runoff coefficients primarily dependent on rainfall intensity. At the outlet, by contrast, multiple runoff mechanisms are likely at play. Here, runoff coefficients increase consistently from one event to the next, beyond rainfall amounts alone. Consequently, no single catchment functioning could be excluded a priori.

Building on the distributed hydrological model proposed by Manfreda et al., (2005), we defined four bucket-type model structures to represent competing hypotheses on different runoff-generation processes. All structures share the same climatic inputs, soil–vegetation–land-use parameterizations, and common modules for interception, surface depression storage, and actual evapotranspiration. To keep the modelling parsimonious and limit parameter equifinality, we used regularization functions that link local parameters to catchment-scale super-parameters, a standard practice for distributed modelling. The four competing hypotheses (Figure 3) are:

- *HORTONIAN*; each grid cell can produce only HOF first, while local SOF occurs only once saturation is reached.
- *DUNNIAN*; both SOF and SSF can occur, while HOF is not considered.
- *DREAM*; a combination of the *HORTONIAN* and *DUNNIAN* concepts, allowing HOF, SOF, and SSF to occur in each grid cell.
- *FLEXDREAM*; an extension of the FLEX-Topo concept (Savenije, 2010) applied to the *DREAM* structure, in which each runoff mechanism depends on the main landscape classes.

Because our focus is on event-scale modelling, where surface routing should not be oversimplified, each model structure was coupled with Iber+, a 2D hydrodynamic model (Cea & Bladé, 2015), via the Runoff-on-Grid approach (Perrini et al., 2024).

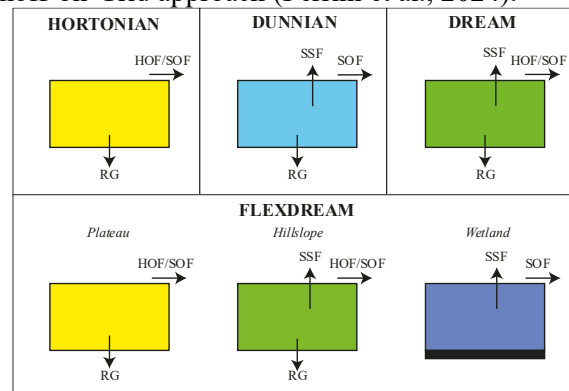


Figure 3. Bucket-type model structures representing different hypothesis on runoff generation (RG is the percolation out of the soil).

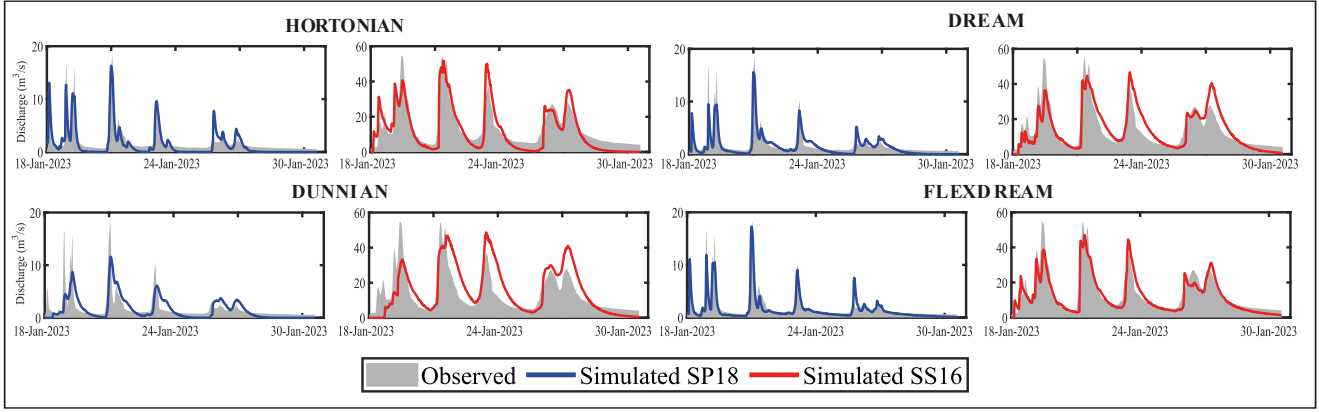


Figure 4. Observed and Simulated hydrographs in the two catchments used for spatial validation

4 RESULTS

4.1 Operational Testing & Process consistency

To evaluate the competing hypotheses, we used a meta-objective function (Perrini et al., 2025) — a composite of statistical metrics that capture different aspects of the streamflow time series, such as high flows, low flows, flow-duration curves, and hydrograph-based dynamics — to calibrate each structure at the SS17 gauge. We then performed a spatial transferability (or spatial validation) test at SP18 and SS16. From an operational standpoint, this assesses whether the optimal parameters identified at a single station can be applied across the nested catchment, thereby revealing model structures that perform well only under calibrated (comfortable) conditions due to overfitting of free parameters. Comparison of simulated and observed hydrographs at the validation stations (Figure 4), together with performance metrics (Table 1), indicates that the two most complex hypotheses perform best.

Table 1. Performance for each model structure across the three stream gauges

Structure	Performance		
	SS17	SP18	SS16
HORTONIAN	0.51	0.34	0.63
DUNNIAN	0.57	0.34	0.50
DREAM	0.76	0.52	0.72
FLEXDREAM	0.85	0.72	0.81

Focusing on *DREAM* and *FLEXDREAM*, we further examined the spatial variability of runoff-generation mechanisms alongside the HAND-based landscape classification (Figure 5). *DREAM* produces SSF across much of the catchment, with a notable contribution from plateau areas feeding the SS16 outlet. This representation appears physically inconsistent because, following Savenije (2010) and the conceptual understanding of plateau areas, SSF and SOF should be minimal on plateaus. *FLEXDREAM* avoids this issue by generating SSF and SOF only in wetlands and hillslopes.

Consequently, *FLEXDREAM* simulates internal catchment processes in a manner consistent with the conceptual understanding of landscape behavior, suggesting that its superior performance reflects more realistic modelling assumptions. Nevertheless, *DREAM* remains a generalization of *FLEXDREAM*, so in hillslope-dominated landscapes the two hypotheses may yield very similar behaviour.

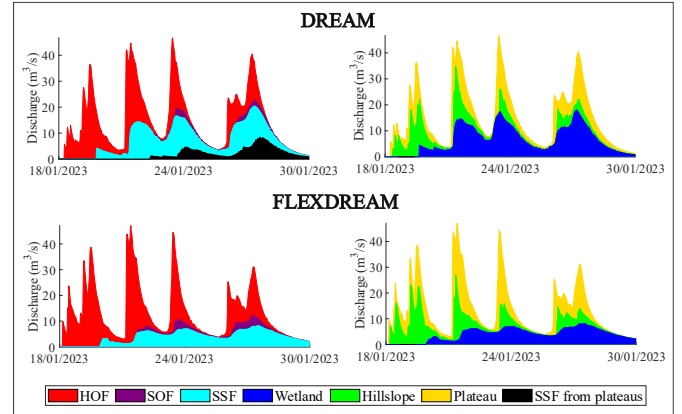


Figure 5. Surface-subsurface and landscape-based streamflow partitioning referred to the *DREAM* and *FLEXDREAM* structures

4.2 Dominant Runoff Mechanisms

Identifying runoff sources typically relies on isotopic or geochemical tracers in rainfall and streamflow. Although such data were unavailable in this study, we retrospectively exposed the dominant runoff processes for each storm event from prior and posterior evidence:

- Event 1; The poor graphical agreement of the *DUNNIAN* model—relative to other models, including *HORTONIAN*—suggests that SOF and SSF were minimal or absent at this stage.
- Events 2 & 3; A combination of surface and subsurface processes is more likely. This is indicated by increasing recession volumes in the headwaters, with hydrograph tails rising above pre-event levels, signaling activation of slower runoff pathways as the catchment became wetter. Nevertheless, peak flows remained strongly associated with intense rainfall.

- Event 4; HOF likely became marginal across the catchment. A reduction in rainfall intensity led to the temporary deactivation of HOF in the two headwater sub-catchments. At the outlet, however, the increasing runoff coefficient despite lower rainfall intensity points to SOF and/or SSF as the dominant processes operating in saturated areas and in soil pathways activated during the preceding events. Accordingly, all models that include HOF produced large overestimates of peaks at SS17 and SP18. By contrast, at SS16 the *DUNNIAN* model alone reproduced a smooth double-peaked hydrograph, whereas all HOF-based models yielded irregular hydrographs closely tracking rainfall intensity, which was evidently no longer the primary runoff-inducing driver.

5 CONCLUSIONS

Simulating rainfall and runoff dynamics in semi-arid catchments is challenging when using streamflow time series alone. However, this study shows that adopting multiple working hypotheses is an effective way to characterize dominant event-scale runoff mechanisms and to partially compensate for the absence of hydrochemical tracers used for hydrograph separation. By jointly analyzing hydrological signatures, model performance, and modeled runoff sources, we identified a rapid alternation of runoff generation processes in the nested Salsola catchment.

Across consecutive storm events, surface processes dominated the initial responses, while subsurface contributions became increasingly important as catchment wetness accumulated. Among the tested hypotheses, FLEXDREAM emerged as the most credible structure, excelling in both in terms of predictive skill and internal process consistency. This finding underscores the central role of landscape organization in shaping hydrological behavior, and it suggests that landscape-aware model structures are essential for robust event-scale modelling.

Overall, our results indicate that both surface and subsurface mechanisms should be included, at least as prior modelling assumptions in semi-arid regions. Although our inference did not use isotopic or geochemical data, integrating such information or using direct hydrological state variables detected by remote-sensing as an external source of information could further improve process-based hypotheses.

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7 REFERENCES

- Cea, L., Bladé, E. 2015. A simple and efficient unstructured finite volume scheme for solving the shallow water equations in overland flow applications, *Water Resources Research* **51**(7), 5464–5486.
- Fenicia, F., Kavetski, D. 2021. Behind every robust result is a robust method: Perspectives from a case study and publication process in hydrological modelling, *Hydrological Processes* **35**(8), e14266. <https://doi.org/10.1002/hyp.14266>
- Fenicia, F., Kavetski, D., Savenije, H. H. G. 2011. Elements of a flexible approach for conceptual hydrological modeling: 1. Motivation and theoretical development, *Water Resources Research*, **47**(11).
- Gharari, S., Hrachowitz, M., Fenicia, F., Savenije, H. H. G. 2011. Hydrological landscape classification: investigating the performance of HAND based landscape classifications in a central European meso-scale catchment, *Hydrology and Earth System Sciences* **15**(11), 3275–3291.
- Manfreda, S., Fiorentino, M., Iacobellis, V. 2005. DREAM: A distributed model for runoff, evapotranspiration, and antecedent soil moisture simulation, *Advances in Geosciences* **2**, 31–39. <https://doi.org/10.5194/adgeo-2-31-2005>
- McDonnell, J. J., Spence, C., Karran, D. J., Van Meerveld, H. J., Harman, C. J. 2021. Fill-and-spill: A process description of runoff generation at the scale of the beholder, *Water Resources Research* **57**(5), e2020WR027514.
- McMillan, H. 2020. Linking hydrologic signatures to hydrologic processes: A review, *Hydrological Processes* **34**(6), 1393–1409.
- Perrini, P., Cea, L., Chiaravalloti, F., Gabriele, S., Manfreda, S., Fiorentino, M., Gioia, A., Iacobellis, V. 2024. A runoff-on-grid approach to embed hydrological processes in shallow water models, *Water Resources Research*, **60**(7), e2023WR036421.
- Perrini, P., Iacobellis, V., Gioia, A., Cea, L., Savenije, H. H. G., Fenicia, F. 2025. Can dominant runoff generation mechanisms be disentangled through hypothesis testing? insights from integrated hydrological-hydrodynamic modeling, *Water Resources Research* **61**(4), e2024WR039394.
- Savenije, H. H. G. 2010. HESS Opinions "Topography driven conceptual modelling (FLEX-Topo)", *Hydrology and Earth System Sciences* **14**(12), 2681–2692.