Robust and flexible hydroinformatics to account for rainfall space–time variability in a data-sparse region

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Abstract
Rainfall is a major meteorological factor in water assessment in semi-arid basins. For mesoscale basins, the rainfall space–time variability is high and has a major influence on hydrological dynamics. A geomorphology-based rainfall–runoff approach is developed to account for rainfall space–time variability in a robust and flexible manner, according to changing available raingauging configurations. The approach is based on a two-step hydroinformatics protocol, firstly to analyse geomorphometry, and secondly to account for and benefit from available rainfall data.

Key words rainfall–runoff; geomorphology-based transfer function; rainfall space–time variability; isochrone

INTRODUCTION
In semi-arid regions, variability of rainfall inputs is high at different time and space scales. Thus, intense and highly variable hydrometeorological events, which generate both potential resource and hazards, are of major interest. However, raingauge networks are rarely dense and stable enough to observe space–time variability and structures precisely, and to feed rainfall–runoff modelling accurately. A robust and flexible method is proposed to account for the available event space–time variability of rainfall in a rainfall–runoff model. The transfer function used is a geomorphology-based unit hydrograph, with an explicit territorial significance which allows enrichment of the convolution through accounting for a variability matrix. This variability matrix can be built differently depending on the available raingauge network. This allows it to be adapted to evolving network configurations, even in data-sparse contexts, such as through historical changes, breakdown episodes, designed optimization schemes or local changes of design storm events following climatic changes. Such a robust and flexible hydro-geomorphology-based modelling approach is enabled by a dedicated two-step informatics protocol and is illustrated with a Tunisian basin.

ILLUSTRATIVE BASIN
This approach is illustrated with the Skhira basin (192 km\textsuperscript{2}; Fig. 1), part of the major central-Tunisian Merguellil basin (Cudennec \textit{et al.}, 2005, 2006a, 2007; Lacombe \textit{et al.}, 2008). The semi-arid region is characterized by strong rainfall variability (Kingumbi \textit{et al.}, 2005; Jebari \textit{et al.}, 2007; Slimani \textit{et al.}, 2007): the rainfall gradient is globally north–south; the role of topography is major; Atlantic and Mediterranean influences are combined with strong seasonal effects; and rainfall is episodic with major storm seasons at the beginning of autumn (September, October) and at the end of winter and beginning of spring (February–May).

MODELLING PRINCIPLES
Modelling is based on two steps, the former dealing with the geomorphological analysis of the basin and the deduction of the rainfall–runoff transfer function, and the latter dealing with the enriched convolution through the accounting for rainfall space–time variability.
Geomorphology-based transfer function

Geomorphology-based rainfall–runoff transfer functions were proposed, either from hierarchy-based considerations, or from whole-basin functions (Rodriguez-Iturbe & Rinaldo, 1997; Cudennec et al., 2004; Cudennec, 2007). The explicit observable geomorphometric basis of such approaches is of major interest for hydrological modelling in data-sparse contexts where heavy calibration cannot be implemented. Moreover, the conceptualisation of water transfers can be adjusted according to available data and knowledge on flows, allowing development of methods for assessing design floods (e.g. Nasri et al., 2004; Rodriguez et al., 2005), or for transposing discharges between outlets (Boudhraa et al., 2006). A robust approach consists in observing the geomorphometry of water paths down to the outlet from sampling the basin area and to assess the experimental probability density function of the length $L$ run by water, $\text{pdf}(L)$. Transforming this into a probability density function of water travel times $\text{pdf}(t)$, through the simple application of an average velocity, is a simplifying hypothesis which is supported by the literature (Naden, 1992; Beven & Wood, 1993; Blöschl & Sivapalan, 1995; Robinson et al., 1995; Yang et al., 2002; Giannoni et al., 2003). Furthermore, $\text{pdf}(t)$ can be used as a transfer function of the unit hydrograph type through the following convolution:

$$Q(t) = \frac{S}{\Delta t} \sum_{\tau=1}^{\Delta t} \bar{R}(t-\tau) \cdot \text{pdf}(\tau)$$

where $S$ is the surface of the basin, $\Delta t$ the time step, $Q(t)$ the discharge at the outlet at time $t$; and $\bar{R}(t)$ the average net rainfall over the basin at time $t$.

Accounting for the rainfall space–time variability

Cudennec et al. (2005) proposed the following enrichment of the convolution in terms of the accounting for the net rainfall space–time variability:
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\[ Q(t) = \frac{S}{\Delta t} \sum_{\tau=0}^{\max(k,\tau)} R_i(t-\tau+1) \text{pdf}(\tau) \]  
(2)

where \( R_i(t) \) is the average net rainfall over the isochrone area \( \tau \) at time \( t \), which can be turned into:

\[ Q(t) = \frac{S}{\Delta t} \sum_{\tau=0}^{\max(k,\tau)} R_i(t-\tau+1)V_j(t-\tau+1) \text{pdf}(\tau) \]  
(3)

where \( V_j(j) = \frac{R_j(j)}{R(j)} \) is a variability factor which forms a hydrologically significant space–time variability matrix when \( \tau \) ranges over the whole basin up to the ultimate isochrone area \( K \) and \( j \) over the whole event duration.

Cudennec et al. (2005) implemented this method by using image processing (Fig. 2). Firstly a series of net rainfall field raster images is generated by interpolation – linear interpolation was used since sparse data do not justify more elaborate methods – between available raingauge measurements for each time \( t \), with time step \( \Delta t \). Then a crossed analysis of the rainfall field raster images series and the vector map of the basin isochrone areas allows to assess \( R_i(j) \) and thus to build the variability matrix. Results appear to be encouraging (Fig. 3) and the following alternate matrix approach was developed both to gain calculation time and space, and to allow flexibility in terms of accounting for raingauge networks.

**OPERATIONALITY AND FLEXIBILITY**

**Matrix implementation**

Given a configuration of \( n \) available raingauges \( G_i \), building the rainfall space–time variability matrix \( V_j(j) \), to be introduced in the convolution, through a linear interpolation of net rainfall depth can be achieved as follows.

For each raingauge \( G_i \), a matrix of geometric distance \( d_i \) is built for each raster element \((x,y)\) of the whole basin, based on the same raster discretization scheme than the geomorphological analysis. For each raingauge \( G_i \), a matrix of weight is deduced through the application of the following expression for each raster element \((x,y)\):

\[ \alpha_{ij} = \frac{\sum_{j=1}^{n} d_j - d_i}{(n-1)\sum_{j=1}^{n} d_j} \]  
(4)

![Fig. 2 Vector and raster data management and crossing. (a) Isochrone vector map of the Skhira basin. (b) Overlapping of the interpolated rainfall field raster image with the isochrone vector layer. Example of 10 May 1996, 20:39–20:44 (Cudennec et al., 2005).](image)
Then a combination of these $n$ weight matrices and of the isochrone matrix allows to assess the matrix of the weight of each raingauge $G_i$ for each isochrone area $\tau$, $\alpha^i_\tau$.

At each time $t$, rainfall over the isochrone area $\tau$, $R_\tau(t)$ is then assessed as the following linear combination of rainfall observed by the raingauges of the available configuration:

$$R_\tau(t) = \sum_{j=1}^{n} \alpha^i_\tau R^j(t)$$

Parallel to this, the average rainfall over the whole basin $\bar{R}(t)$ is obtained by the linear combination, equivalent to the Thiessen averaging method:

$$\bar{R}(t) = \sum_{j=1}^{n} \beta^j R^j(t)$$

where $\beta^j = \sum_{\tau=1}^{K} \alpha^i_\tau . \text{pdf}(\tau)$ is the global weight of raingauge $G_i$ over the basin, itself deduced from its weights over isochrone areas $\tau$ ($K$ being the last existing one) combined with their density distribution as observed from the geomorphological analysis.

**Hydro-geomorpho-informatics**

The first step is led with the HydroStruct software application (Fig. 4), which is dedicated to combined spatial, topological and scaling analysis of morphometry of river networks, in the frame of the OdefiX java framework (Cudennec et al., 2006a,b; Pouget et al., 2006). Vector data of river networks and basins boundaries, however they are obtained, are analysed through both tree formalisation and spatial sampling. Results are extracted as global, classified and scaled statistics; and in terms of spatial distribution through raster images. Raster images of scaled geometric variables can be combined to assess and explore further structural evidences, and be linked with territorial maps of hydrological parameters and/or socio-anthropic properties. Sub-basins and populations of basins can be easily analysed, by crossing, filtering and merging vector, raster and tree data (Cudennec & Fouad, 2005; Cudennec et al., 2006a). Furthermore, a major prospect is the crossing of hydro-geomorphometric results with spatio-temporal variables of different kinds. The matrix approach presented here is such a development based on the particular geomorphometric interpretation of the basin rainfall–runoff spatial structure. The matrix approach was implemented in the frame of Matlab™ software.
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Fig. 4 HydroStruct software user interface.

Fig. 5 Geometric characterisation raster mapping of the Skhira (outlet) raingauge as regards the basin: (a) distance from the gauge; (b) gauge weight in a three-gauges (Skhira, Kesra and Morra) configuration; and (c) gauge weight in a two-gauges (Skhira and Morra) configuration.
Adaptive and proactive flexibility

Recent rainfall events are mostly observed by two or three recording raingauges only: Skhira, Morra and Kesra gauges, at the outlet, outside of the basin and inside of the basin, respectively (Fig. 1). Figure 5 displays the raster map of the geometric distance from the Skhira gauge, and the maps of its weight for the three-gauges and the two-gauges (with Morra) configurations. For a given basin, and the corresponding set of existing and historical raingauges, all the operational configurations can be considered in terms of weight mapping. For any recorded or real-time event, using the pre-defined set of weight maps corresponding to effectively operational configuration – and even further, switching between configurations in case of a sudden breakdown – is an important aspect in terms of adaptative flexibility. The approach also provides a synthetic view of the hydro-geomorphological vision offered by a raingauging configuration, thanks for instance to multi-gauge weight/isochrone graphs (Fig. 6).

Furthermore, this flexibility can be used in a proactive way, especially in terms of network optimisation based on the search for the best locations to implement new raingauges, in terms of the best hydro-geomorphological added value. As an example of such a perspective, Fig. 6 displays the hydro-geomorphological vision with a fictitious gauge (see Fig. 1 for location), instead of the actual Morra raingauge.

Fig. 6 Weight of raingauges along the Skhira basin isochrone areas for different configurations.

CONCLUSION

The proposed geomorphology-based rainfall–runoff accounting for rainfall space–time variability is promising. Its potential is especially interesting in data-sparse regions where the geomorphology-based approach can be applied in a robust and adaptable manner, and where the accounting for rainfall variability is much flexible. The two-step hydro-geomorpho-informatics protocol is a major assessment, rendering the method robustness and flexibility fully operational. Rainfall–runoff improvement is obvious, in coherence with the results of Cudennec et al. (2005). However, the easy-to-use and adaptable hydro-geomorpho-informatics protocol opens new major perspectives in terms of switching between various raingauges configurations, both through
history and towards network improvement scenarios. Finally, the major perspective consists of feeding the approach, for a given raingauge configuration, with design storms expressed in terms of net rainfall series for each raingauge. Developing such design storms, and further performing the whole rainfall–runoff modelling, for events of diverse rainfall variability and associated intensity and frequency, will be a major step for hydrological engineering in data-sparse basins and areas.

REFERENCES


