Response to Anonymous Referee #2
(Comment received and published 3 August 2020)

We are very grateful for the constructive comments of anonymous referee #2 on the manuscript. We believe that they will help increasing substantially the scientific quality of the manuscript. We agree with most recommendations and we give in this note our responses to all remarks.

Comment 2a)

The authors present an interesting study about karst characteristics of catchments at storm-event timescale. The merit of the study is the treatment of multiple sites and the storm-event time-scale, where the case study region in France provides a good example and good data.

Thank you.

The overall article is well written and of scientific interest, but the scientific argumentation should be improved. The literature study is very short and lacking some other approaches, the research question is not clearly stated, the concept is not sufficiently brought into the context of other methods, and the benefits and shortcomings of the developed method against other methods should be better elaborated in the theoretical part, and later on discussed based on the results.

Thank you. We propose to modify the manuscript according to your remarks as detailed below. Your review will allow several improvements such as a more complete literature review making more understandable the originalities of the study, and a better justification of our choice to work with topographic catchments as a spatial reference.

Comment 2b)

In the literature study, other concepts for describing the hydrological characteristics of larger scale karst systems should be mentioned. Gárfias-Soliz et al. (2010) found system memory, response time and mean delay between input and output as indicators for karstification but emphasized that the physically founded regionalization needs to account for structural complexity, heterogeneity of the lithology and the degree of karstification. Hartmann et al. (2013) described the responsive behavior of large-scale karst systems by system signatures derived from hydrodynamic and hydrochemical observations based on data from five different karst systems. Basha (2020) presented six recession curves for the classification of karst aquifers, describing the dichotomy of the dual flow characteristics between the fissured matrix and the conduit system. How do the descriptors found in this study relate to the indicators and signatures found by other authors? Is there a clear difference between daily and storm-event resolution at the size of catchment under consideration?

Our literature study mostly highlights lacks of research on karst hydrology when the studied object is the stream (rather than the spring). We agree that it can be improved by including some references to existing works related to the developed methodology, such as some relevant articles proposed. To this end, we propose to reshape the introduction and include the following paragraphs (see also our response to referee #1 for other literature review improvements).

→ ***Suggested change in manuscript (Introduction section):*** *The diversity of observed processes during storm event in karst catchments does not allow drawing a straightforward analysis on the control of karst in flood runoff generation. In the purpose of understanding the mechanisms involved in this control, there is a need for regionalized studies, covering a large-scale analysis of karst impact over short time periods when the catchment reacts after storm events. It is reasonable to think that karst can alternately increase or decrease storm impacts, depending on its capacity to infiltrate precipitation or to release stored water, i.e. depending on the direction of IGF it promotes. Despite the early conceptualization of IGF (Eakin, 1966), its major role in karst hydrological processes is tackled by very few studies (Le Moine et al., 2007; Lebecherel et al., 2013). Some authors tried to improve model capacities to reproduce karst-based IGF, such as Nguyen et al. (2020) with SWAT, Le Moine et al. (2008) with GR4J or Scanlon et al. (2003) comparing a distributed and a lumped model. Nevertheless, those studies dedicated to the improvement of model performance are not devoted to describe and understand all flood components in karst catchments.*

On one hand, most studies including karst system descriptors are based on a purely hydrogeological point of view, and are very integrative, as they tend to characterize karst aquifer as a whole, by analysing daily spring discharge. Gárfias-Soliz et al. (2010) fond that system memory, response time and mean input-output delay are relevant indicators for karstification, in addition to a necessary consideration of the structural complexity and heterogeneity of the lithology. Hartmann et al. (2013), using 10 system signatures, performed a model parameters sensitivity analysis to investigate their links with hydrological processes on five Europe and Middle East karst sites. Basha et al. (2020) proposed six recession curve equations for the classification of karst aquifers, depending on their flow characteristics. On the other hand, spatialized studies mostly focus on low-flow issues and surface-water/groundwater interaction (e.g., Covino et al., 2011, Mallard et al., 2014). Moreover, most regionalization studies tend to spatialize annual indices (Sivapalan et al., 2011) or model parameters (Parajka et al., 2005; Oudin et al., 2008), and usually exclude catchments with identified IGF (Merz and Blöcshl, 2004) or karst areas (e.g., Laaha and Blöschl, 2006).

Comment 2c)

"Despite some studies describing significant IGF in karst areas (Le Moine et al., 2007; Lebecherel et al., 2013), the specific issue of IGF in karst has not been addressed as such." There have been studies dealing with IGF, in particular the modelling of IGF at catchment scale or adding IGF to hydrological catchment models. Even if karst-based IGF is often neglected, it found attention among hydrological modelers, introducing or enhancing karst capabilities of e.g. SWAT (e.g., Nguyen et al., 2020). Apart from modelling and data analyses, geo-chemical methods based on analysis of chlorides and stable isotopes has been used to characterize karst systems.

Thank you for this constructive comment. We will include a discussion on model improvements accounting for karst-based IGFs, such as the already cited work of Le Moine et al. (2008) and the study of Nguyen et al. (2020). Is also of interest the works of Scanlon et al. (2003) which modelled IGF in a karst aquifer using an equivalent porous media.

→ ***Suggested change in manuscript (Introduction & discussion sections):*** Please refer to our response to comment 2b for the proposed modifications.

Comment 2d)

The authors correctly mention that many hydrological studies neglect the characteristics of karst regions, but their own catchment delineation follows the “classical” orographic approach using surface water divides instead of trying to derive subsurface catchments based on hydrogeological data/maps. This is a major shortcoming of the method. In particular, the water balance descriptors could be more meaningful if the overall contributing area including the subsurface catchment would be regarded. Whenever catchment sizes and rainfall amounts are related with stream flow, there would be a mismatch in karst regions and it is unclear for me how the authors have regarded that aspect. A detailed discussion is missing. In particular, for the description of storm peak flow, I would expect water balance descriptors, which include the areas connected by IGF. For arid basins, Wolaver et al. (2008) developed a method to delineate karstic aquifers based on data. Applying such delineation beyond the usage of surface catchments might help to improve the results of the characterization of the flow response to storm events. Here, one could think that the method is inconsistent and I ask the authors to explain why they did not try to delineate the karstic aquifers and include them into the water balance considerations.

We fully agree on the fact that the hydrogeological catchment should be considered in groundwater studies. Yet, we draw attention on the fact that our spatial reference scale is not the aquifer, but the river reach (at a gauging station or at a reach delimited by two stations). For this reason, and as our study accounts for IGF, the topographic catchment appears to be the right reference, even in the case of karst catchments. This comment 2d) is very similar to the comment 1b) of Referee #1, thus we invite readers to see our response to this last comment. We propose to modify Figure 1 and to add the following paragraph to our introduction for a better understanding of our strategy.

→ ***Suggested change in manuscript (Introduction section):*** *Regional spatial analyses need to be based on reliable data at the highest resolution available. For this purpose, the scale of the elementary catchment - i.e. subdivision of a basin following available gauging stations – appears to be the best resolution for long-term monitoring. Elementary catchment can be either the drained area of a headwater catchment controlled by a gauging station, or the drained area between two gauging stations (intermediate catchment). When considering surface and groundwater components, the delineation method of elementary catchments is questionable (topographic vs. hydrogeological boundaries). Despite the importance of groundwater processes in karst areas, topographic catchment delineation remains a more robust reference, for several methodological reasons. First, IGF can be defined as groundwater flow crossing topographic divides, as this concept emerged with the evidence of certain groundwater systems extending beyond the limits of valleys (Eakin, 1966). A perfectly delineated groundwater basin would then show IGF equal to zero. For this reason, studies related to IGF use the topographic catchment spatial reference (Genereux et al., 2005; Schaller and Fan, 2009; Bouaziz et al., 2018; Nguyen et al., 2020; see also a synthesis in Fan, 2019). Second, although in karst catchments groundwater contributes to flood flow, surface runoff has to be considered as an important component of flood flow. Consideration of hydrogeological catchments could thus lead to wrong surface contribution assessment depending on their surface drainage network. Third, as some groundwater flows are aligned with the main surface drainage axis, hydrogeological catchments would encompass the whole river, making it impossible to study the spatial variability of parameters along the river, at the elementary catchment scale. Finally, topographic delineation is reliable and easily reproducible, while groundwater delineation is characterized by a strong uncertainty and variability in karst areas.*

→ ***Suggested change in manuscript (Figure 1):*** Add schematic delineations of topographical and groundwater basins.

Comment 2e)

The conclusions seem to ignore the efforts done in karst research over the last decades: “Existence of karst hydrological specificities has been known for decades, but is poorly quantified and documented.”. Here, I disagree. The authors should explicitly say, where their method provided methodological innovation and which characteristics of karst regions could be now better described.

This statement refers to large scale works focusing on hydrological processes at the stream scale. Our purpose was not to ignore numerous works carried out in karst hydrogeology. However, the stream/river scale is not as much documented as the spring one. We agree that the text can be improved, especially in the light of the added references to advances in karst hydrology.

→ ***Suggested change in manuscript (Conclusion section):*** We propose to replace the cited sentence by a brief summary of what are the innovations of our study compared to existing works (storm-event time scale, spatialized quantification of karst impact on river reaches, effects on flood processes).

Literature cited:
Basha, H.A.: Flow Recession Equations for Karst Systems. Water Resources Research 56(7), 2020, Article number e2020WR027384
Gárfias-Soliz, J., Llanos-Acebo, H., Martel, R.: Time series and stochastic analyses to study the hydrodynamic characteristics of karstic aquifers. Hydrological Processes24(3), January 2010, Pages 300-316.
Hartmann, A. et al.: Process-based karst modelling to relate hydrodynamic and hydro-chemical characteristics to system properties. Hydrology and Earth System Sciences17(8), 2013, Pages 3505-3521.
Nguyen, V.T., Dietrich, J., Uniyal, B.: Modeling interbasin groundwater flow in karst areas: Model development, application, and calibration strategy. Environmental Modelling and Software 124, 2020, Article number 104606.
Wolaver, B.D. et al.: Delineation of regional arid karstic aquifers: An integrative data approach. Ground Water 46(3), 2008, Pages 396-413.

Anaya, R., Wanakule, N., 1993. A Lumped Parameter Model for the Edwards Aquifer (Technical Report). Texas Water Resources Institute.

Barrett, M.E., Charbeneau, R.J., 1997. A parsimonious model for simulating flow in a karst aquifer. Journal of Hydrology 196, 47–65. https://doi.org/10.1016/S0022-1694(96)03339-2

Bouaziz, L., Weerts, A., Schellekens, J., Sprokkereef, E., Stam, J., Savenije, H., Hrachowitz, M., 2018. Redressing the balance: quantifying net intercatchment groundwater flows. Hydrology and Earth System Sciences 22, 6415–6434. https://doi.org/10.5194/hess-22-6415-2018

Covino, T., McGlynn, B., Mallard, J., 2011. Stream-groundwater exchange and hydrologic turnover at the network scale: Hydrologic turnover at the network scale. Water Resources Research 47. https://doi.org/10.1029/2011WR010942

Eakin, T.E., 1966. A regional interbasin groundwater system in the White River Area, southeastern Nevada. Water Resources Research 2, 251–271. https://doi.org/10.1029/WR002i002p00251

Fan, Y., 2019. Are catchments leaky? Wiley Interdisciplinary Reviews: Water 6. https://doi.org/10.1002/wat2.1386

Genereux, D.P., Jordan, M.T., Carbonell, D., 2005. A paired-watershed budget study to quantify interbasin groundwater flow in a lowland rain forest, Costa Rica. Water Resources Research 41. https://doi.org/10.1029/2004WR003635

Hartmann, A., Barberá, J.A., Lange, J., Andreo, B., Weiler, M., 2013. Progress in the hydrologic simulation of time variant recharge areas of karst systems – Exemplified at a karst spring in Southern Spain. Advances in Water Resources 54, 149–160. https://doi.org/10.1016/j.advwatres.2013.01.010

Laaha, G., Blöschl, G., 2006. Seasonality indices for regionalizing low flows. Hydrological Processes 20, 3851–3878. https://doi.org/10.1002/hyp.6161

Le Moine, N., Andréassian, V., Mathevet, T., 2008. Confronting surface- and groundwater balances on the La Rochefoucauld-Touvre karstic system (Charente, France): CLOSING THE CATCHMENT-SCALE WATER BALANCE-A CASE STUDY. Water Resources Research 44. https://doi.org/10.1029/2007WR005984

Le Moine, N., Andréassian, V., Perrin, C., Michel, C., 2007. How can rainfall-runoff models handle intercatchment groundwater flows? Theoretical study based on 1040 French catchments: Dealing with IGF in rainfall-runoff mode. Water Resources Research 43 . https://doi.org/10.1029/2006WR005608

Lebecherel, L., Andréassian, V., Perrin, C., 2013. On regionalizing the Turc-Mezentsev water balance formula. Water Resources Research 49, 7508–7517. https://doi.org/10.1002/2013WR013575

Mallard, J., McGlynn, B., Covino, T., 2014. Lateral inflows, stream-groundwater exchange, and network geometry influence stream water composition. Water Resources Research 50, 4603–4623. https://doi.org/10.1002/2013WR014944

Merz, R., Blöschl, G., 2004. Regionalisation of catchment model parameters. Journal of Hydrology 287, 95–123. https://doi.org/10.1016/j.jhydrol.2003.09.028

Oudin, L., Andréassian, V., Perrin, C., Michel, C., Le Moine, N., 2008. Spatial proximity, physical similarity, regression and ungauged catchments: A comparison of regionalization approaches based on 913 French catchments. Water Resources Research 44. https://doi.org/10.1029/2007WR006240

Parajka, J., Merz, R., Blöschl, G., 2005. A comparison of regionalisation methods for catchment model parameters. Hydrology and Earth System Sciences 16.

Scanlon, B.R., Mace, R.E., Barrett, M.E., Smith, B., 2003. Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, USA. Journal of Hydrology 276, 137–158.

Schaller, M.F., Fan, Y., 2009. River basins as groundwater exporters and importers: Implications for water cycle and climate modeling. Journal of Geophysical Research 114. https://doi.org/10.1029/2008JD010636

Sivapalan, M., Yaeger, M.A., Harman, C.J., Xu, X., Troch, P.A., 2011. Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. Water Resources Research 47. https://doi.org/10.1029/2010WR009568