Response to Anonymous Referee #1
(Comment received and published 19 July 2020)

We are very grateful for the constructive comments of anonymous referee #1 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 1a)

The study analyzed stream flow observations at 108 gages in three regions with varying karst area, focusing on event-scale hydrologic response to 20 large storm events. Using 15 descriptors on catchment water balance, hydrograph shape, and difference between an upstream and downstream gage, the study compared the catchment response in karst (K), middle (M) and non-karst (NK) catchments. It is concluded that (1) karst promotes high infiltration but (2) slows down flood response (both rising and falling limb), and the latter behavior is attributed to inter-basin groundwater flow (IGF).

I find the study valuable in that it selected a wide range of catchments under different climatic and geologic conditions, and that it focused on event time-scale response of catchment runoff underlain by karst geology. However, the manuscript can benefit significantly from a clearer and sounder conceptual model, better framing of the questions (what we know and don't know) and the hypotheses to be tested with this particular dataset, how the results speak for or against the hypotheses posed, and a better overall presentation, as expanded below.

Thank you. We propose to modify the manuscript according to your remarks as detailed below. Your review will allow several improvements such as a better justification of our choice to work with topographic catchments as a spatial reference, a more complete literature review, and a clearer definition of what is the lateral flow Q_L in comparison to IGF.

Comment 1b)

First, there are some conceptually ambiguities.

(a) My understanding is that groundwater flow, particularly trans-catchment groundwater flow, or inter-basin flow (IBF), does not follow surface drainage structure in karst terrain as depicted in Figure 1. We cannot delineate groundwater basins based on surface topography, a well-known problem in karst terrain. Figure 1 depicts the IBF as completely defined by, and in parallel with the surface drainage gradient. While this may be fine for unconsolidated materials without strong geologic structure, it is hardly the case for karst terrain, where the extensive underground conduit networks do not follow the topography. The authors' finding that the strongest lateral inflow is in inter-mediate catchments in NK, that is, there is more IBF in non-karst areas, is counterintuitive and confusing, and points to this conceptual flaw. The reason may well be that in NK areas the surface and subsurface drainage system are more aligned, and such an assumption is more valid, allowing the detection of IBG inflow. The authors need to clarify and justify this assumption, because it also underlies the methodology used in the study, with the analyses entirely based on streamflow.

First, we propose to keep the term IGF in the manuscript (instead of IBF) as it is a term dedicated to the study of Interbasin Groundwater Flow.

Figure 1 represents all identified inputs and outputs at the scale of an elementary catchment (drained area between two gauging stations). They are composed of three main flows: input streamflow Q_I, output streamflow Q_O and lateral flow Q_L. Q_L is composed of several flows corresponding to different processes, which are numbered from 1 to 4 on Figure 1. Interbasin Groundwater Flow (IGF) is noted as number 2, and represented by incoming and outgoing arrows of two types. Straight arrows represent IGF in parallel with the surface drainage gradient, while curved arrows represent IGF from/towards other directions (outside upstream or downstream elementary catchments).

→ ***Suggested change in manuscript (Figure 1):*** Modify IGF arrows to make clearer the fact that IGF can be in different directions than the main surface drainage direction, and to differentiate them from other Q_L flows.

We fully agree on the comment stated that groundwater basins cannot be delineated based on surface topography, especially in karst areas. However, our spatial reference is the stream catchment for which the topographic catchment is the relevant spatial reference, even when accounting for groundwater flows in addition to surface flows. 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 1c)

(b) The methodology infers IBF into and out of a catchment by comparing the inflow QI and outflow Qo of a stream reach (Fig 1). The authors need to clarify to what extend one can infer IGFs from streamflow alone.

Considering the topographic elementary catchment as our reference for all water balance calculations, IGF is inferred from inflow Q_I, outflow Q_o and effective rainfall P_{eff} (obtained by subtracting the estimated evapotranspiration to measured rainfall, see Appendix C of the submitted manuscript). Knowing that this term also accounts for potential aquifer level variations, it is noted IGF*.

The difference reflects inflow from local precipitation falling on its topographic catchment and subsequent infiltration and surface and subsurface runoff (local source), the inflow from upstream catchments via IBF (remote source), minus the loss to local aquifers (local sink, recharging local aquifers, increasing groundwater storage) which may or may not leave the catchment via IBF (remote sink). But without an explicit aquifer water balance to track all the terms during the events, it is difficult to separate these terms. To arrive at quantitative results, the authors need to explicitly quantify these terms, incorporating aquifer water level observations, spring discharges.

As explained in lines 93 to 97 and visible in Figure 1, lateral exchanges may be a combination of (supposed decreasing importance):

- Effective rainfall (precipitation minus evapotranspiration) over the elementary catchment,
- IGF,
- Aquifer storage variation,
- Overbank phenomena.

We consider overbank flow to be negligible, assuming that the overflow water returns to the river after a relatively short time during the recession. We propose an assessment of evapotranspiration (explained in Appendix C) which allows estimating the effective rainfall on the elementary catchments. Thus, combined to inlet streamflow Q_I and outlet streamflow Q_O data, our methodology allows calculating the remaining term of the water balance, noted IGF*, which includes IGF and the potential aquifer storage variation during the considered event (noted δ). δ can either be positive, corresponding to an aquifer recharge, or negative, corresponding to an aquifer draining. Aquifer draining is unlikely during storm events, as important rainfalls generally occur. In case of an aquifer recharge, and as our analysis is performed on the whole storm-event period (including the entire recession), a substantial part of the infiltrated water should be released. For these reasons, δ is assumed to be a minor component on the IGF* term compared to IGF. This is discussed in lines 182 to 195, and calculation of IGF* is presented in equation 8.

→ ***Suggested change in manuscript (Methodology section):*** the text will be made clearer to show how all water balance component are considered in our study.

The diffusive wave model for surface water propagation appears to be an over-kill in comparison to a complete lack of first-order water balance in the subsurface.

We precise that the diffusive wave model is used to analyse the flow dynamics during floods through the simulation of lateral hydrographs. It is not used in the lateral flow estimation for water balance calculations (see our response above).

Comment 1d)

Second, the authors should provide a more thorough literature review, discuss what we know and do not know in terms of event-scale catchment runoff generation in karst terrain, and pose a set of testable hypotheses. For example, it is expected that in karst area, infiltration is high, and storm flow is flashy due to the open conduits in the subsurface, but after a threshold when the groundwater builds up to the spring overflow point. Then as the results are opposite (slow hydrograph response), one can reason why this hypothesis must be rejected. For another example, one can hypothesize that in karst catchments, streamflow can be lower or higher than expected from calculations based on infiltration over the surface catchment area alone (local source), or there is mass imbalance, and thus IGF must be invoked. Then the analyses can be targeted to test these hypotheses, and the results discussed with clarity surrounding these hypotheses.

Thank you for this comment. We will develop the literature review (see also our response to referee #2 regarding this aspect), and especially discuss in a larger extent what are the main findings on karst impacts on flood processes and runoff generation. We propose to include the following paragraph to the introduction. This more detailed analysis will also be used to better interpret and discuss our results.

→ Suggested change in manuscript (Introduction section): *Karst impacts on flood processes are mostly documented through case studies. As an example, Zanon et al. (2010) showed that during a flash flood in 2007 in Slovenia, karst area reduced flooding, which was more important in a non-karst neighbouring zone, receiving less precipitation. Likewise, Delrieu et al. (2005) observed, for an exceptional storm event in 2002, lower runoff coefficient values for the karstic catchment compared to the hard-rock catchment in the eastern zone of the Cévennes Mountains. De Waele et al. (2010) and Charlier et al. (2015, 2019) determined that, depending on the location on the river profile, karstification could result in streamflow losses or gains due to the high spatial variability of the hydrogeological karst features. Other frequently described processes are groundwater rising leading to reduced infiltration and important surface runoff (Lopez-Chicano et al., 2002; Bonacci et al., 2006), and backflooding/sinkhole flooding due to conduit constriction (Maréchal et al., 2008; Bailly-Comte et al., 2009).*

Comment 1e)

Third, in addition to the above, a few other things can be done to reduce the length, enhance focus, clarify terminology and make it easier for readers to follow the central theme and take-home messages.

(a) Move “Section 3 The Study Area” to before “Section 2 Methodology”

We prefer to keep the methodology section before the study site one in order to put more emphasis in the genericity of our methodology, which could be applied elsewhere. Nevertheless, if the final decision is to switch those sections, this modification will be done.

(b) List all variables in a table with definitions. It is hard to remember the 10s of mathematical symbols mentioned later – one has to go back and find their definitions.

A list of all variables, their symbols and definition is proposed in Appendix D. We will make sure that this is clearly indicated and visible in the manuscript.

(c) In presenting results, please use plain English of the meaning of the variable, rather than the ratio of 2 variables defined earlier, so the reader can grasp the meaning of the results.

→ ***Suggested change in manuscript:*** We propose to replace the ratios by plain English in the manuscript. We also propose to remind the meaning of variables more frequently in the text.

(d) Is the lateral hydrograph, QL, the same as IGF? Both appeared in the text frequently, and it appeared that they are used in the same context. If so, please unify the terminology. If not, please make it more clear by using a conceptual model diagram.

The lateral hydrograph Q_L is the association of all lateral flows occurring at the elementary catchment scale (P_{eff} + IGF + δ, see our response to Comment 1c).

Expressing the water balance gives: $Q_I + Q_L = Q_O$ (a)

Replacing Q_L in (a) gives: $Q_I + P_{eff} + IGF + \delta = Q_O$ (b)

As δ is not measured, it cannot be differentiated from IGF: $IGF + \delta = IGF^* = Q_O - Q_I - P_{eff}$ (c)

A definition of Q_L is given when this term is first cited, lines 118 to 119. It is also reminded in the legend of Figure 1.

→ ***Suggested change in manuscript (Methodology section):*** We propose to make the distinction between IGF and Q_L clearer by introducing an explicit equation.

(e) The authors talk about losing reach vs gaining reach, in the context of losing water to other catchments via IGF. The terms “losing streams” or “gaining stream” have been understood as stream and local groundwater exchange, regardless of the source/sink is local or remote (IGF). Perhaps use “losing catchment” vs “gaining catchment” because here the authors refer to IGF?

Thank you, we agree with this remark and will implement it to the manuscript.

(f) in Fig 1, catchments include headwater, intermediate, but is it intermediate between a headwater and a tailwater catchment? Is there another catchment below the intermediate?

Our spatial scale of work is the elementary catchment, defined as the drained area between two gauging stations. In case of a headwater catchment, the elementary catchment corresponds to the whole topographic catchment, as there is no gauging station to delineate the upstream divide. In other cases, the elementary catchments are intermediate catchments (with upstream and downstream gauging stations), knowing that a basin could have a succession of intermediate catchment if there are several stations on the river.

In Figure 1, there is another intermediate catchment below the presented one. We do not use the term tailwater catchment, as there are other gauging stations downstream of our study zones.

→ ***Suggested change in manuscript (Introduction & Figure 1):*** We propose to make Figure 1 clearer by adding an “intermediate catchment” label to the third catchment, and an “elementary catchment” label for all three catchments. See also suggestions when defining elementary catchments in the Introduction section (response to comment 1b)

Line 296. Is this stream loss, or simply that the infiltration over the surface catchment drained elsewhere, to neighboring catchments? IBF is not just a result of stream flow loss; infiltrated water may not go to the streams at all in its own catchment but may enter streams in other catchments.

We agree on the fact that IGF can be the result of both streamflow losses and surface infiltration. Nevertheless, the terms cited in line 296 (V_S and V_U) only regard streamflow losses. Indeed, they are obtained by difference of inlet and outlet streamflow, regardless of precipitations. On the opposite side, the parameter IGF* can be interpreted by local streamflow losses or diffuse infiltration.

Cited literature:

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Bonacci, O., Ljubenkov, I., Roje-Bonacci, T., 2006. Karst flash floods: an example from the Dinaric karst (Croatia). Natural Hazards and Earth System Science 6, 195–203.

Charlier, J.B., Moussa, R., Bailly-Comte, V., Danneville, L., Desprats, J.F., Ladouche, B., Marchandise, A., 2015. Use of a flood-routing model to assess lateral flows in a karstic stream: implications to the hydrogeological functioning of the Grands Causses area (Tarn River, Southern France). Environmental Earth Sciences 74, 7605–7616.

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De Waele, J., Martina, M.L.V., Sanna, L., Cabras, S., Cossu, Q.A., 2010. Flash flood hydrology in karstic terrain: Flumineddu Canyon, central-east Sardinia. Geomorphology 120, 162–173. https://doi.org/10.1016/j.geomorph.2010.03.021

Delrieu, G., Nicol, J., Yates, E., Kirstetter, P.-E., Creutin, J.-D., Anquetin, S., Obled, C., Saulnier, G.-M., Ducrocq, V., Gaume, E., 2005. The catastrophic flash-flood event of 8–9 September 2002 in the Gard Region, France: a first case study for the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory. Journal of Hydrometeorology 6, 34–52.

López-Chicano, M., Calvache, M.L., Martín-Rosales, W., Gisbert, J., 2002. Conditioning factors in flooding of karstic poljes—the case of the Zafarraya polje (South Spain). CATENA 49, 331–352. https://doi.org/10.1016/S0341-8162(02)00053-X

Maréchal, J.C., Ladouche, B., Dörfliger, N., 2008. Karst flash flooding in a Mediterranean karst, the example of Fontaine de Nîmes. Engineering Geology 99, 138–146. https://doi.org/10.1016/j.enggeo.2007.11.013

Zanon, F., Borga, M., Zoccatelli, D., Marchi, L., Gaume, E., Bonnifait, L., Delrieu, G., 2010. Hydrological analysis of a flash flood across a climatic and geologic gradient: The September 18, 2007 event in Western Slovenia. Journal of Hydrology 394, 182–197. https://doi.org/10.1016/j.jhydrol.2010.08.020