Dear Reviewer #1,

We highly appreciated your review and constructive comments for our manuscript. We provide our responses to your queries below.

Kind regards, all authors

Comment #1: *The manuscript proposes a Unit Hydrograph estimating travel times including also the time-varying rainfall intensity and soil moisture content information.*

The topic is surely interesting although is well crystallized in literature and in practical hydrology.

Unfortunately, the manuscript has some drawbacks that do not allow me to suggest its publication. I see practical, technical, and theoretical issues to be addressed.

Firstly, the text (language, structure, figure captions, typos) should be significantly improved since presently, it does not allow a full understanding of described methods.

Response:

Thank you for your comments. The language of this paper will be revised by a native English-speaker. The skeleton of the methodologies is summarized as follows.

I) The velocity formula was discussed.

The Soil Conservation Service (SCS) formula (Haan et al., 1994) is expressed by

$$V = k \cdot S^{\frac{1}{2}} \tag{1}$$

where k is the coefficient of the flow velocity which is related to the land use of the grid cell; and S is the slope of the grid cell. This equation was used by NRCS (1997), Grimaldi (2010), and Gimaldi (2012) et al., which versified the rationality of this equation.

The SCS flow velocity formula is time invariant. The time-varying rainfall intensity should be considered. The usage of the theory has been proved by Wong (1995), Muzik (1996), Bedient and Huber (2002), Gironas et al. (2009), Du et al. (2009) and Kong et al., (2019) et al.

$$V_t = k \cdot S^{\frac{1}{2}} \cdot \left(\frac{I_t}{I_c} \right)^{\frac{2}{5}} \tag{2}$$

where I_t represents the excess rainfall intensity at time t; and I_c represents the reference excess rainfall intensity of the basin.

Several velocity formulas were commonly used for deriving the spatially distributed unit hydrograph (DUH), such as the Manning' formula (Chow et al., 1988), Soil Conservation Service (SCS) formula (Haan et al., 1994) and Maidment et al. (1996) uniform flow equation. However, these formulas assumed that equilibrium in individual grid cell can be reached before the end of the rainfall excess pulse (Bunster et al., 2019), which yields slower travel times, shorter times to peak, and higher peak discharges.

A factor w_t was first introduced to characterize the soil moisture content in unsaturated areas. This new factor (w_t) was added to the current time-varying flow velocity formula. The proposed flow velocity formula is expressed by

$$V_t = k \cdot S^{\frac{1}{2}} \cdot \left(\frac{I_t}{I_c} \right)^{\frac{2}{5}} w_t^{\gamma} \tag{3}$$

where γ is an exponent smaller than unity, which can be used to improve the applicability of the formula. Hence, the soil moisture content w_t that contributes to the value of velocity decreases as w_t increases. The sensitivity analysis of Parameter γ to the flow velocity formula will be added to the revised manuscript. More details can be seen in Section 2.2.

Actually, hillslope flow velocity in each grid is related to soil moisture content. Fast subsurface velocities and quick runoff responses to precipitation has been observed in many hillslopes (Hutchinson & Moore, 2000; Peters et al., 1995; Tani, 1997). The exact mechanisms that cause water to move through the preferential network are not well known, but it is often assumed that saturated soil provides the connection between preferential features (Sidleet al., 2001; Steenhuis et al., 1988). Many studies have also shown that antecedent moisture condition, precipitation intensity, precipitation amount, topography and so on play a significant role in this phenomenon (Sidle et al., 2000; Tsuboyama et al., 1994; Anderson et al., 2009).

If the entire basin is saturated, the flow velocity will reach its maximum value. Thus, a soil moisture factor should be introduced to improve the flow velocity formula. Otherwise, the flow velocity calculation can be lager under the assumption of saturation. In order to test the influence of soil moisture content on flow velocity, we applied different parameters to Equation (3). Take a specific grid cell for example, whose slope of the grid cell is set to 0.34 m/m. The coefficient of the flow velocity *k*, reference rainfall intensity *Ic* and γ are assumed to be 1.5 m/s, 20mm/h and 0.5 correspondingly. The hillslope flow velocity values corresponding to different rainfall and soil moisture content using Equation (3) are given in Figure 1.

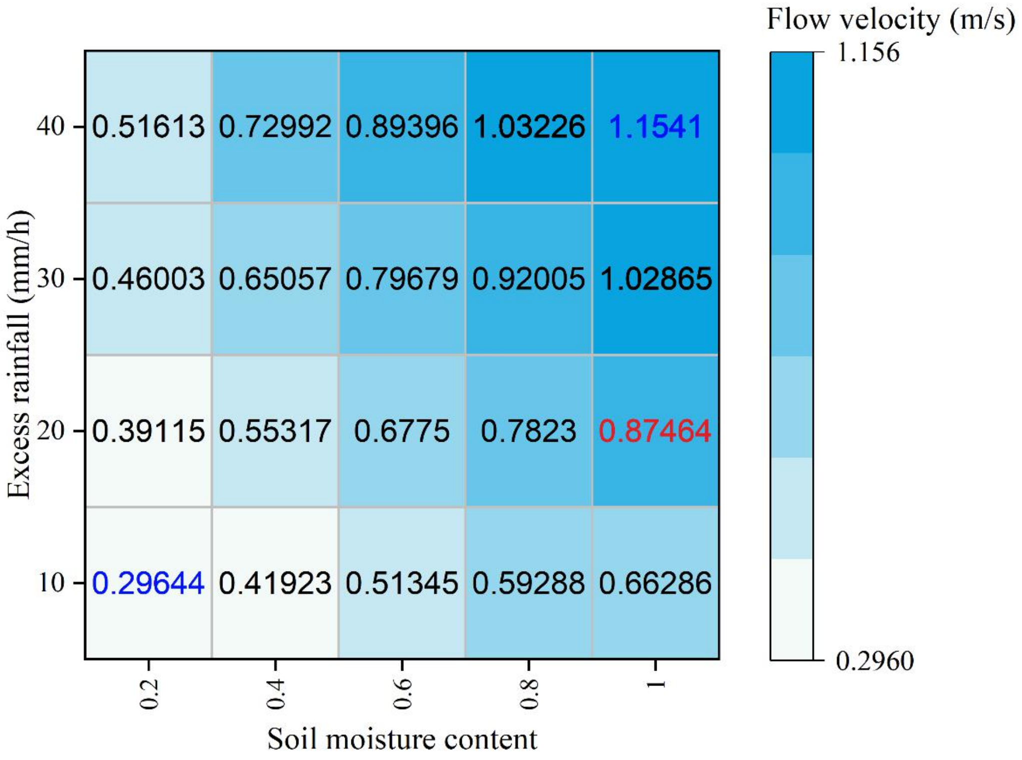

Figure 1. Time-varying flow velocity values corresponding to different parameters

It can be seen from Figure 1 that when w_t equaling to 1, the proposed equation turns to Equation (2). The flow velocity values are ranging from 0.663 to 1.154 m/s, if only considering the time-varying excess rainfall.

When I_t equaling to the reference rainfall I_c, Equation (2) turns to Equation (1), and the flow velocity is 0.875 m/s.

After introducing a soil moisture content factor to the flow velocity formula, the flow velocity values range from 0.296 m/s to 1.154 m/s. The velocity of the grid cell has greater flexibility to better reflect the time-varying characteristics of the routing process.

II) We adopted the proposed flow velocity formula to derive the time-varying distributed unit hydrographs (TDUH), which considers both rainfall intensity and soil moisture content based on the above analysis.

The traditional DUH method can rout the variant spatially distributed rainfall to the watershed outlet (Grimaldi et al., 2010), and such a method is a lumped linear model of watershed response. However, many watersheds may display a nonlinear behavior over a wider range of net rainfall and discharge (Du et al., 2009). Muzik (1996) stated that a family of unit hydrographs should be derived for a considered watershed, with each unit hydrograph being applicable within a certain range of excess rainfall.

The rainfall intensity and soil moisture content were introduced to improve the flow velocity formula. Therefore, we can obtain a family of unit hydrographs corresponding to different rainfall intensity and soil water content. The general schematic of the TDUH method considering rainfall intensities and soil moisture contents is given in Figure 2.

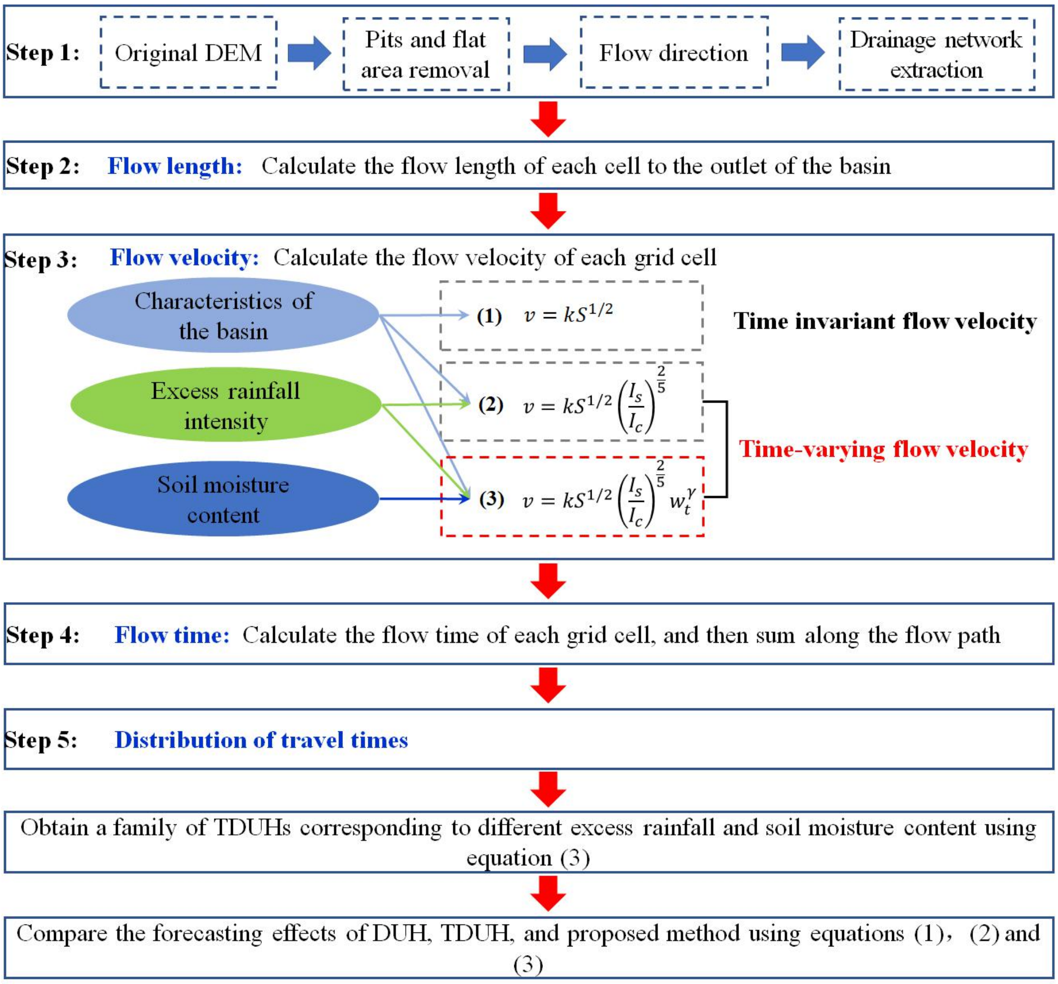

Figure 2. Flow chart of the TDUH method considering rainfall intensity and soil moisture content, in which Equations (1), (2) and (3) means the time invariant flow velocity, time-varying flow velocity considering excess rainfall intensity and time-varying flow velocity considering both excess rainfall intensity and soil moisture content. The unit hydrograph derived from the three flow velocity equations correspond to DUH, TDUH and the proposed method.

The main procedures of this methods are given by

Step 1: Identification of the drainage network using advanced DEM pre-processing techniques. More details can be found in Grimaldi et al (2012).

Step 2: Estimation of flow path, which is measured for each grid cell along the flow directions to the outlet of basins.

Step 3: Calculation of the flow velocity. Three flow velocity equations were adopted to derive the DUHs. Equation (1) is known as SCS formula. Equation (2) is time-varying flow velocity formula considering excess rainfall intensity. Equation (3) is time-varying flow velocity formula considering both rainfall and soil moisture content.

Step 4: Flow length rescales for travel time definition using the above flow velocity formulas.

Step 5: Develop a cumulative travel time map of the watershed based on cell by cell estimates for hillslope and channel flow velocities. The cumulative travel time map is further divided into isochrones which can be used to generate a time-area curve and the resulting unit hydrograph (Kilgore, 1997).

References:

Anderson, AE, Weiler, et al., Hudson Subsurface flow velocities in a hillslope with lateral preferential flow. Water Resour Res, 45, pp. W11407, 10.1029/2008WR007121, 2009.

Bedient P. B., Huber W. C.: Hydrology and Floodplain Analysis. (3rd ed.), Prentice-Hall, Upper Saddle River, NJ, pp. 763, 2002.

Bunster, T., Gironás, J., Niemann, J. D.: On the Influence of Upstream Flow Contributions on the Basin Response Function for Hydrograph Prediction. Water Resources Research, 55 (6), 4915-4935, https://doi.org/10.1029/2018WR024510, 2019.

Chow, V. T., Maidment, D. R., and Mays, L. W. Applied hydrology, McGraw-Hill, New York, 1988.

Du, J., Xie, H., Hu, Y., Xu, Y. P. and Xu, C. Y.: Development and testing of a new storm runoff routing approach based on time variant spatially distributed travel time method. Journal of Hydrology, 369(1-2):44-54, https://doi.org/10.1016/j.jhydrol.2009.02.033, 2009.

Gironás, J., Niemann, J. D., Roesner, L. A., Rodriguez, F., & Andrieu, H. A morpho-climatic instantaneous unit hydrograph model for urban catchments based on the kinematic wave approximation. Journal of Hydrology, 377(3-4), 317–334. https://doi.org/10.1016/j.jhydrol.2009.08.030, 2009.

Grimaldi, S., Petroselli, A., Alonso, G., Nardi, F. Flow time estimation with spatially variable hillslope velocity in ungauged basins. Advances in Water Resources, 33 (10), pp. 1216-1223, 2010.

Grimaldi, S., Petroselli, A., Nardi, F. A parsimonious geomorphological unit hydrograph for rainfall-runoff modelling in small ungauged basins. Hydrological Sciences Journal, 57 (1), pp. 73-83, 2012.

Haan, C.T., Barfield, B.J., Hays J.C.: Design hydrology and sedimentology for small catchments Academic Press, New York, 1994.

Hutchinson, D. G., and R. D. Moore, Throughflow variability on aforested hillslope underlain by compacted glacial till, Hydrol. Processes,14(10), 1751-1766, doi:10.1002/1099-1085(200007)14:10<1751::AID-HYP68>3.0.CO;2-U, 2000.

Kilgore, J. L. Development and evaluation of a GIS-based spatially distributed unit hydrograph model, (Master's thesis). Blacksburg, VA: Virginia Polytechnic Institute and State University. http://hdl.handle.net/10919/35777, 1997.

Kong, F. Z., Guo, L.: A method of deriving time-variant distributed unit hydrograph. Advances in Water Science, 30(04):477-484, https://doi.org/10.14042/j.cnki.32.1309.2019.04.003. 2019. (in Chinese)

Maidment, D. R.: Developing a spatially distributed unit hydrograph by using GIS. IAHS publication, 181-181, 1993.

Maidment, D.R., Olivera, F., Calver, A., Eatherall, A.: Unit hydrograph derived from a spatially distributed velocity field. Hydrol Process, 10, pp. 831-844, 1996.

Muzik, I.: A GIS-derived distributed unit hydrograph. Hydrological Processes, 10(10):1401-1409, https://doi.org/10.1002/(SICI)1099-1085(199610)10:10<1401::AID-HYP469>3.0.CO;2-3, 1996.

NRCS (natural Resources Conservation Service), Ponds Planning, design, construction. Washington, DC: US Natural Resources Conservation Service, Agriculture Handbook no.590, 1997.

Peters, D. L., et al. Runoff production in a forested, shallow soil,Canadian Shield Basin, Water Reso ur. Res., 31(5), 1291– 1304,doi:10.1029/94WR03286, 1995.

Sidle, R. C., et al. Stormflow generation in steep forested head-waters: A linked hydrogeomorphic paradigm, Hydrol. Processes, 14(3),369 – 385, doi:10.1002/(SICI)1099-1085(20000228)14 :3<369::AID-HYP943>3.0.CO;2-P, 2000.

Sidle, R. C., et al. A conceptual model of preferential flow systemsin forested hillslopes: Evidence of self-organization, Hydrol. Processes,15(10), 1675-1692, doi:10.1002/hyp.233, 2001.

Steenhuis, T. S., et al. Preferential flow influences on drainage ofshallow sloping so ils, Agric. Water Manage., 14(1–4), 137–151,doi:10.1016/0378-3774(88)90069-8, 1988.

Tani, M. Runoff generation processes estimated from hydrologicalobservations on a steep forested hillslope with a thin soil layer, J. Hydrol.,200(1 – 4), 84 – 109, doi:10.1016/S0022-1694(97)00018-8.

Tsuboyama, Y., et al. Flow and solute transport through the soilmatrix and macropores of a hillslope segment, Water Resour. Res., 30(4),879-890, doi:10.1029/93WR03245, 1994.

Wong, T. S. W. Time of concentration formulae for planes with upstream inflow. Hydrological Sciences Journal, 40(5), 663-666. https://doi.org/10.1080/02626669509491451, 1995.

Comment #2: *It is not clear (although the title is clear) if the manuscript proposes an IUH model, that is a rainfall-runoff method, or a simplified routing approach. Reading the title and the introduction it seems the first option, looking the case study the second one.*

Response:

Thank you for your comments. In this manuscript, we proposed an IUH model by improving the flow velocity formula. Spatially Distributed Unit Hydrograph model proposed by Maidment (1993), is a semi-analytical form of the WFIUH identified by Rigon et al (2016). In this study, a family of unit hydrographs corresponding to different excess rainfall intensities and soil moisture contents were derived. In practical flood forecasting, for each time interval, we are supposed to select a TDUH suiting to a certain range of rainfall and soil moisture content.

In Section 4.1.2 of the case study, the parameters for deriving the unit hydrographs were determined. To make the proposed method more applicable and reduce the number of unit hydrographs, we have simplified the method. The TDUH considering time-varying soil moisture content can be obtained in a certain range of rainfall intensities and soil moisture contents, and the division ranges of which are presented in Tables 4 and 5. For a specific basin, there will be 20 (4 times 5) unit hydrographs according to the discrete range of excess rainfall and soil moisture content using our methods.

Table 4. The rainfall intensity It of each period corresponds to the discrete rain intensity I_s

Net rainfall intensity I_t (mm/h)	$0 < I_t \leq 15$	$15 < I_t \leq 25$	$25 < I_t \leq 35$	$I_t > 35$
Discrete rainfall intensity I_s(mm/h)	10	20	30	40

Table 5. The soil moisture content w_t of each period corresponds to the discrete soil moisture content w_s

Soil moisture content w_t	$0 < w_t \leq 0.2$	$0.2 < w_t \leq 0.4$	$0.4 < w_t \leq 0.6$	$0.6 < w_t \leq 0.8$	$w_t > 0.8$
Discrete soil moisture content w_s	0.1	0.3	0.5	0.7	0.85

References:

Maidment, D. R.: Developing a spatially distributed unit hydrograph by using GIS. IAHS publication, 181-181, 1993.

Rigon, R., Bancheri, M., Formetta, G., & de Lavenne, A. The geomorphological unit hydrograph from a historical-critical perspective. Earth Surface Processes and Landforms, 41(1), 27–37. https://doi.org/10.1002/esp.3855, 2016.

Rigon, R., Bancheri, M., & Green, T. R. Age-ranked hydrological budgets and a travel time description of catchment hydrology. Hydrology and Earth System Sciences, 20(12), 4929–4947. https://doi.org/10.5194/hess-20-4929-2016, 2016.

Comment #3: *As recalled by the authors in the Introduction the IUH approach assumes some hypotheses (i.e. linear system, time invariant, rainfall spatially homogeneous) that of course are far from the watersheds real behavior, however this is an accepted compromise in challenging hydrological studies (i.e. ungauged basins). In my opinion there is a contradiction in trying to make non-linear a linear approach, maybe it is better to use a non linear approach or an other approach. If a time-varying rainfall and spatial distribution information are introduced, the nature of IUH is lost and we do not know any more what we are implementing. In my experience I also tried to force the IUH concept, however I limited it to the estimation of the hillslope velocity cell by cell indeed further adaptation (i.e. empirical estimation of channel velocity) would have been in contrast to the IUH theoretical definition (Grimaldi et al. 2010; 2012).*

Response:

We appreciate for this general comment. The IUH is the probability density function for the arrival time of a randomly chosen drop to the trapping state (Rodríguez-Iturbe et al., 1982). The IUH approach assumes some hypotheses (i.e. linear system, time invariant, rainfall spatially homogeneous) in the application. Contrary to the linear assumption, basins have been shown to exhibit nonlinearity in the transformation from excess rainfall to stormflow (Bunster et al., 2019). Of course, this is an accepted compromise in challenging hydrological studies over the past few decades, especially for the ungauged basins. Nevertheless, many hydrologists have made great efforts to it.

Minshall (1960) showed that different rainfall intensities significantly correspond to different UHs for a small watershed. After that, Rodríguez-Iturbe et al. (1982) extended the GIUH to the geomorphoclimatic IUH (GcIUH) to cope with this nonlinearity by incorporating excess rainfall intensity in the determination of the IUH. Lee et al. (2008)

proposed a variable Kinematic wave GIUH corresponding to time-varying rainfall intensity for the calculation of the runoff concentration, which warrants consideration for rainfall-runoff modelling in ungauged catchments that are influenced by high intensity rainfall. Du et al. (2009) proposed a GIS based simple and easily performed routing approach to simulate the storm runoff process with consideration of spatial and temporal variability of runoff generation and flow routing through hillslope and river network. In addition, many similar works have been done by Muzik (1996), Gironás et al. (2009), and Bunster et al. (2019).

References:

Bunster, T., Gironás, J., Niemann, J. D.: On the Influence of Upstream Flow Contributions on the Basin Response Function for Hydrograph Prediction. Water Resources Research, 55 (6), 4915-4935, https://doi.org/10.1029/2018WR024510, 2019.

Du, J., Xie, H., Hu, Y., Xu, Y. P. and Xu, C. Y.: Development and testing of a new storm runoff routing approach based on time variant spatially distributed travel time method. Journal of Hydrology, 369(1-2):44-54, https://doi.org/10.1016/j.jhydrol.2009.02.033, 2009.

Gironás, J., Niemann, J. D., Roesner, L. A., Rodriguez, F. and Andrieu, H.: A morpho-climatic instantaneous unit hydrograph model for urban catchments based on the kinematic wave approximation. Journal of Hydrology, 377(3-4), https://doi.org/10.1016/j.jhydrol.2009.08.030 317–334, 2009.

Lee, K. T., Chen, N. C., Chung, Y. R.: Derivation of variable IUH corresponding to time-varying rainfall intensity during storms. International Association of Scientific Hydrology Bulletin, 53(2):323-337, https://doi.org/10.1623/hysj.53.2.323, 2008.

Minshall, N. E.: Predicting storm runoff on small experimental watersheds. J. Hydraul. Engng ASCE, 86(HY8), 17-38, https://doi.org/10.1061/JYCEAJ.0000509, 1960.

Muzik, I.: A GIS-derived distributed unit hydrograph. Hydrological Processes, 10(10):1401-1409, https://doi.org/10.1002/(SICI)1099-1085(199610)10:10<1401::AID-HYP469>3.0.CO;2-3, 1996.

Rodríguez-Iturbe, I., González-Sanabria, M., Bras R. L.: A geomorphoclimatic theory of the instantaneous unit hydrograph. Water Resources Research, 18(4):877-886, https://doi.org/10.1029/WR018i004p00877, 1982.

Comment #4: *Most importantly, it should be clarified the practical context on which we are referring. Personally, I consider the WFIUH approach particularly brilliant in small and ungauged basin application since it optimizes the topographic information and since* *the IUH approximations are coherent with by the basin dimension. In other contexts, maybe, other approaches should be preferred (semi-distributed or fully distributed models).*

Response:

Thank you for your comments. It is not doubt that the WFIUH provided a useful methodology for runoff routing in small and ungauged basin (Grimaldi et al., 2010; Grimaldi et al., 2012). As mentioned above, Spatially Distributed Unit Hydrograph model is a semi-analytical form of the WFIUH identified by Rigon et al (2016). The DUH is also well used in small and ungauged basin as described in the introduction. A fully distributed models use routing methods to completely remove the linearity assumption, but they are usually computationally intensive because they solve the momentum equation (Bunster et al., 2019). DUH method is an alternative approach that allow the use of distributed information in a much more efficient manner.

References:

Bunster, T., Gironás, J., Niemann, J. D.: On the Influence of Upstream Flow Contributions on the Basin Response Function for Hydrograph Prediction. Water Resources Research, 55 (6), 4915-4935, https://doi.org/10.1029/2018WR024510, 2019.

Grimaldi, S., Petroselli, A., Alonso, G., Nardi, F. Flow time estimation with spatially variable hillslope velocity in ungauged basins. Advances in Water Resources, 33 (10), pp. 1216-1223, 2010.

Grimaldi, S., Petroselli, A., Nardi, F. A parsimonious geomorphological unit hydrograph for rainfall-runoff modelling in small ungauged basins. Hydrological Sciences Journal, 57 (1), pp. 73-83, 2012.

Maidment, D. R.: Developing a spatially distributed unit hydrograph by using GIS. IAHS publication, 181-181, 1993.

Comment #5: *The present manuscript does not clarify these aspects. It provides a case study with a large basin, eliminating the hillslopes (including an area threshold of 1 km2), assuming calibration, increasing the number of parameters: without a clear context it disorients the reader. I would expect to see nine case studies (each sub-basin) in order to evaluate the expected improvements of IUH given by the soil moisture content, in ungauged contest. If the practical aim is different (large gauged basins) the comparison should be performed with other models underlying the added value of the proposed approach.*

Response:

Thank you for your comments. The hillslopes were eliminated by assuming an area threshold of 1 km^2 . Many works found that the hillslope runoff may significantly affect hydrologic response at any scale and especially for the small basins (Naden, 1992). In this study, flow directions, and channels were extracted from a 30-m resolution DEM using a single-direction flow algorithm (O'Callaghan & Mark, 1984). We will rescale the hillslope cells by assuming an area threshold of 900 m^2 in the revised manuscript, and a constant flow velocity was adopted for the channel network based on the previous studies (Grimaldi et al., 2010, 2012).

We are trying to apply a more efficient distributed computing method in a large watershed. Due to the lack of observed runoff data in small catchments, we provided a case study with a large basin, which was divided into 9 sub-basins with an average basin area of 175 km^2. Dooge (1973) shown that the term small refers to basins with drainage areas less than 150-200 km^2 , and it is reasonable to accept the linear theory of the IUH. The DUH method was mostly used in small and ungauged basins, and the simulation effects are generally good (Melesse, & Graham, 2004; Gad, 2014). Additionally, the comparisons between traditional unit hydrograph and the proposed method will be added in the revised manuscript based on your suggestions.

References:

Dooge, J,C,I. Linear theory of hydrolofic systems. US Department of Agriculture, Technical Bulletin 1468, 1973.

Gad MA. Flow velocity and travel time determination on grid basis using spatially varied hydraulic radius. Journal of Environmental Informatics 23(2):36–46, 2014.

Grimaldi, S., Petroselli, A., Alonso, G., Nardi, F. Flow time estimation with spatially variable hillslope velocity in ungauged basins. Advances in Water Resources, 33 (10), pp. 1216-1223, 2010.

Grimaldi, S., Petroselli, A., Nardi, F. A parsimonious geomorphological unit hydrograph for rainfall-runoff modelling in small ungauged basins. Hydrological Sciences Journal, 57 (1), pp. 73-83, 2012.

Melesse, A., & Graham, W. Storm runoff prediction based on a spatially distributed travel time method utilizing remote sensing and GIS1. Journal of the American Water Resources Association, 40(4), 863–879. https://doi.org/10.1111/j.1752-1688.2004.tb01051.x, 2004.

Naden P. Spatial variability in flood estimation for large catchments: the exploitation of channel network strucrure. Hydrol Sci J. 37(1):53-71, 1992.

O'Callaghan, J. F., & Mark, D. M. The extraction of drainage networks from digital elevation data. Computer Vision, Graphics, and Image Processing, 28(3), 323–344. https://doi.org/10.1016/S0734-189X(84)80011-0, 1984.