Reply to comment on “Development and testing of a new storm runoff routing approach based on time variant spatially distributed travel time method” by Du et al. [Journal of Hydrology 369 (2009) 44–54]

We enjoyed the comments and discussion provided by Saghafian and Noroozpour and appreciate their interest in our work and their careful reading of our paper. We also acknowledge their introduction of references that were overlooked by us. Our response below follows the order of their comments.

1. The aim of the paper was to propose a distributed storm runoff routing approach that should not only retain the physical basis but also produce acceptable results for operational use and application. Fully physically based models suffer from, among others, the difficulty of large data requirements and the need to estimate parameter values which not only give good results but are also physically reasonable. The main idea of the approach is that a single raster data structure is established for the whole computation process whereas the rainfall process is divided into several time intervals, and for each time interval the following procedure holds: (1) The excess rainfall intensity is computed using the SCS method for each cell (grid or pixel); (2) The accumulated runoff for each cell is estimated using the GIS flow accumulation function; (3) The travel time for each overland flow cell is estimated using Eq. (8); (4) The travel time for each channel cell is estimated using Eq. (20); (5) The travel time to outlet (cumulative travel time) for each cell is calculated using the GIS flow length function; and (6) The runoff hydrograph at the watershed outlet contributed by the excess rainfall over this time interval for all cells is computed (the runoff at each respective arrival time being determined by the sum of the volumetric flow rates with the same arrival time from all contributing cells). When all runoff hydrographs for any time interval have been calculated, the final runoff hydrograph can be estimated easily.

One of the key aspects is the travel time estimation. There are many methods to calculate travel time for overland and channel flow including theoretical equations described in text books (e.g. Singh, 1988) and different variants of simplifications used in hydrological modelling, such as the method based on the concept of time to equilibrium (Chow et al., 1988; Saghafian and Julien, 1995), the method of assigning a velocity as a function of distance from the channel and the outlet (Calver, 1993), the formula presented in the National Engineering Handbook of the US Soil Conservation Service for overland flow velocity as a function of land surface slope, the method in which local velocity in each cell can be estimated by modifying the mean velocity for the watershed by a function of the local slope and the upstream drainage area (Maidment et al., 1996), the method assuming that travel time for each cell in a watershed is simply proportional to the time of concentration (Kull and Feldman, 1998), the method based on the average velocity, the maximum velocity, and average wave velocity for a constant upstream inflow and a uniform net rainfall intensity input (Wang, 2003), and a newly developed aggregated network-response-function (NRF) routing algorithm (Gong et al., 2009), etc.

In our approach, the overland flow travel time in a grid cell was estimated by combining a steady state kinematic wave approximation with Manning’s equation, and the channel flow velocity was estimated using Manning’s equation and the steady state continuity equation for a wide channel. An amendment was made to channel flow velocity by approximating Manning’s equation to remove river width from the original formula which is difficult to estimate. The reason we selected such a method, even though it has some limitations as in many other operational models, was to develop a distributed storm runoff routing approach that should not only retain its physical basis but also produce acceptable results for operational use and widespread application. Simple to use and still having a physical basis, this concept has been applied in some research works with good results (Muzik, 1996; Melesse and Graham, 2004).

2. The K parameter introduced in Eq. (19) accounts not only for some estimation error in the Manning roughness coefficient (n) and the bed slope but also for the simplification error in deriving the velocity formula (with the kinematic wave approximation, the wide channel assumption, and Manning’s equation approximation for removing river width from the original formula). Therefore, a calibrated value of 7.5 for K does not necessarily mean that the channel roughness is under-estimated by a factor of 7.5. The advantage of introducing K to the equation is: (1) it accounts for some error in parameter estimation, such as Manning roughness, river bed slope and overland slope; (2) it compensates for the error in deriving the model structure, such as that arising from the steady state kinematic wave approximation which is a case that seldom happens for storms in natural watersheds; all models being simplifications of nature. Thus, the usefulness of introducing the K parameter (even though it’s physical meaning is less clear than that of the other parameters) is threefold: (1) it facilitates good agreement between the simulated results and the observed ones, (2) it simplifies the calibration process by reducing the number of parameters requiring calibration, and (3) more importantly, it prevents the calibrated values of other parameters from going beyond the scope of reasonable values, i.e. it keeps the magnitudes of the other parameter values within their theoretically feasible range.

3. In our model, the ‘excess rainfall intensity times the grid cell squared’ was calculated as the total input for each overland
cell. Only in computing the travel time (Eq. (8)) the distance \( l \) was set equal to the grid size multiplied by 1.41 for an overland cell having flow in the diagonal direction. Thus, mass balance is maintained.

4. For the steady state kinematic wave approximation in this small mountain watershed, the flow velocity at each overland cell was considered to be independent of the upslope cell inflow. The effect of flow accumulation in overland cells was not considered. In channel river flow, the effect of flow accumulation was considered for each time interval. The excess rainfall intensity was calculated for every cell, the cumulative inflow for all cells (overland and channel cells) was carried out by using the GIS flow accumulation function which is amenable for the discharge and flow calculation equations.

5. \( Q \) represents the cumulative runoff at time step \( t \), the runoff at the time step being the difference between cumulative runoff at time step \( t \) and that at time step \( t - 1 \) as is shown in Eq. (23) of Du et al. (2009).

6. The calibration process was performed as follows: five cells were selected as the first channel threshold. Then 10 cells as the second; 1, 50 and 100 were selected based on an analysis of the results of the first two calculations to establish the tendency. The value 5 was determined to be the channel threshold by calibration on the basis of multiobjective analysis results. We think this is reasonable for this small watershed located in a mountain region where channel flow is a dominating phenomenon and that it is not appropriate to compare this with values found in the literature because the calculation methods used and topography of the watersheds are different.

7. The surface runoff routing was not considered in the way Saghafian and Noroozpour appear to have assumed. If done in that way, the travel time based runoff routing would be overly complicated for an operational model calculation and a full physically based distributed model may be more suitable than using the travel time based method. Therefore, in our model, the excess rainfall at each cell for every time interval was routed to the watershed outlet separately, in accordance with the procedure described above.

8. We calibrated the first storm (which happened to be the earliest), and validated the model using the other storms. As the results were satisfactory, we did not make any amendments to them. The SCS curve number procedure was developed at the watershed scale to calculate the streamflow from a storm (total storm volume minus baseflow). A storm usually occurs in fits and starts and is hardly continuous. It has never been established (to our knowledge) that the storm has to be a continuous process.

9. Saghafian and Noroozpour have raised an important and interesting issue; however, we do not share their opinion that the SCS is unable to deal with the saturation excess phenomenon. Such an opinion is a misinterpretation of what runoff from curve number procedure is. In this context, the authors refer to the excellent paper of Garen and Moore (2005), where details of the SCS method, i.e., its concept, procedure, uses and abuses, are discussed. It is a common misunderstanding that SCS can only be used to calculate infiltration excess runoff. According to USDA-SCS (1972), the curve number procedure was designed to predict direct (surface) runoff which is composed of streamflow arising from different mechanisms in unknown proportions and where it is unknown whether this flow is generated from all or part of the land area of the watershed. Garen and Moore (2005) also noted that Victor Mochus, the developer of the curve number method, expressed the view that saturation overland flow was the most likely runoff mechanism to be simulated by the method and not necessarily Hortonian overland flow or crusting. Other researches have shown that the basis of the SCS method can be described in ways that are nominally consistent with both the infiltration-excess concept (Hjelmfelt, 1980) and saturation-excess hydrology (Steenhuis et al., 1995). In its most elementary form, the traditional SCS-CN method is conceptually consistent with the saturation-excess hydrology (Lyon et al., 2004).

10. We claimed it as a new storm runoff approach because our procedure (or framework) for routing runoff is different from SDDH, which holds the travel time field to be static, and it also differs from other time-area based methods which need to establish the unit hydrograph or isochrones (even time variant isochrones such as proposed by Saghafian et al. (2002)). With our method, once the cumulative travel time for all cells has been computed, the discharge process at the outlet can be generated without relying on the unit hydrograph or isochrones. What is deserving of further study, however, is to apply different travel time computation methods to our studied watershed and to compare the results.

Acknowledgment

The authors would like to express their sincere thanks to Prof. V.P. Singh of Texas A&M University for proofreading our reply.

References


USDA-SCS (US Department of Agriculture-Soil Conservation Service), 1972. SCS National Engineering Handbook, Section 4, Hydrology. Chapter 10, Estimation...


Jinkang Du
Hua Xie
Yujun Hu
Youpeng Xu
School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, PR China

Chong-Yu Xu
Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, N-0316 Oslo, Norway
Department of Earth Sciences, Uppsala University, Villavgen 16, 75236 Uppsala, Sweden
Tel.: +47 22 855825; fax: +47 22 854215.
E-mail address: chongyu.xu@geo.uio.no