We thank the Editor, the Reviewers, and Dr. Martinez for their careful comments, which were very useful to clarify the scope of the study and focus on the main message of the work. In the following pages all comments have been addressed. To facilitate the reading, comments from the Reviewers and the Editor are in BLUE.

Please, notice that during the revision of our manuscript we opted for changing the name of the proposed routing scheme from HydroSCAPE to HYPERstream. Indeed, we received a personal communication from a colleague who had the impression that HydroSCAPE acronym could be confused with a larger package of software originating from his own research. Although we do not quite agree with the colleague, we opted to use the acronym HYPERstream in order to avoid any possible misinterpretation and wrong affiliation of the model.

Editor comments

Dear Authors,

The paper proposes a new routing scheme based on the classical WFIUH approach. The topic has been appreciated by the two referees, and by Dr Martinez who give an additional valuable review. However, the main issues raised by both referees and Dr Martinez is that the authors should make a further effort to highlight the originality of the work and clarify the methods used and the applications, in order to increase the impact of their study.

We agree with the Editor that in the original version of the manuscript the novelty of the work was probably not sufficiently emphasized. From the comments raised by Reviewer 1 (which are partially summarized in the following points of the Editor) we realized that this apparent lack of originality was due to the fact that the objective of the work was not sufficiently clear. We recognize that this caused significant misinterpretations of both the methodology that we adopted and the practical application that we presented. In order to address this concern, we thoroughly and carefully revised the whole manuscript.

I think all reviewers made valuable suggestions in this regard:

i) Extend the literature review, and discuss the originality and the novelty of the approach in comparison to existing methods.

Following Editor's and Reviewers' comments we extended the literature review. For details, please refer to the following specific replies to Reviewers' comments: point 3 of Reviewer 1, point 3 of Reviewer 2, and point 3 of Dr. Martinez. Furthermore, in the revised version of the manuscript we emphasized the originality, value, and importance of the work.

ii) Compare the conceptual representation of the model and the physical processes, especially the effect of grid size when moving from 20 m to few km. What does mean "perfect scaling"?

With the term "perfect upscaling" we mean that "*geomorphological dispersion (Rinaldo et al., 1991) is invariant with respect to the grid size of the land component and the network response is perfectly upscaled to the computational grid*" (see lines 4-6 at page 9060 of the original manuscript; see also lines 18-22 at page 9065, and conclusions).

To further elucidate the term "perfect upscaling" we modified lines 103-111 of the revised manuscript, adding an explicit definition of the term: "*Here we refer to as "perfect upscaling" to indicate that the proposed routing scheme keeps the network contribution inherently invariant with respect to the grid size of meteorological forcing, i.e. geomorphological dispersion (Rinaldo et al., 1991) is preserved as it is derived from the morphological information embedded in the available DEM. […]Here perfect upscaling is presented for the case study of Upper Tiber (central Italy), where we show that our routing scheme does not entail any deterioration in the watershed width functions when considering progressively coarser spatial resolutions.*"

Additionally, in order to clarify the effect of grid size when moving from 20 m to a few km on the construction of the width functions (as suggested by the Editor), we modified Figure 4 adding the complete width function at node Santa Lucia for the three considered grid sizes. We also modified the text improving the description and understanding of the new figure. We acknowledge that these additional graphics where missing in the original version of the manuscript, and that they are necessary to fully support the following sentence "*When all the width functions of the macrocells contributing to the SL node are combined (i.e., 57, 19 and 2 macrocells for 5, 10 and 50 km, respectively), the global width functions are exactly the same, thereby confirming that routing is insensitive to the size of the macrocell as desired*" (see lines 5-9 at page 9069 of the original manuscript). At any rate, we emphasize that the "perfect upscaling" of our model is by design, as explained in the developments of Section 2, and hence Figure 4 is merely illustrative.

iii) Explain how the model runs at the hillslope level before downstream aggregation. If needed, please add additional figures in order to show processes and pathflows.

In the revised version of the manuscript we clarified that what we propose is a routing scheme and not a hydrological model (as was erroneously written in some sentences of the original manuscript). For this reason, the focus of the work is not on the hillslope production model. In the description of the model (Section 2: Model development), the hillslope production function has been intentionally left unspecified in order not to divert the attention of the reader from the core of the methodology, i.e. the routing scheme. In the revised version of the manuscript we further emphasized that HYPERstream can be coupled with any hillslope production model the user may envision. For details, please refer to our reply to comment 6 of Reviewer 1, comment 5 of Reviewer 2, and comment 1 of Dr. Martinez.

In the light of the above considerations and of the clarifications added in the revised version of the manuscript, we do not think that additional figures are required.

iv) Analyse the spatial distribution of rainfall and justify the methods used for the spatial interpolation.

In the revised version of the manuscript we clarified that "*the precipitation data in input can be of any type, the reconstruction by interpolation with the kriging tool being just one of the possible cases.*"

Details about the spatial variability of the precipitation field can be found in E. Volpi, Modello di struttura spaziale del campo di precipitazione, unpublished technical report, available upon request (this reference is cited in the manuscript).

For a more detailed answer to this point see also replies to comments 5 and 7 of Reviewer 1, and comment 7 of Dr. Martinez.

v) Results are only shown on two flood events on only one basin. How these results can be useful for applications on other basins and/or other events? What are the limitations of the method developed function of the basin characteristics (DEM, soil, landuse), the importance of the main hydrological processes, the input data, the spatial distribution of rainfall, the model parameters, etc. Additional applications in various hydro-climatic conditions will help the analysis.

We fully agree with the Editor that more example applications would be valuable to analyze the performances and potential of the model in details. Applications considering a number of hydro-climatic conditions would be particularly attractive too. However, we feel that this would make the whole manuscript too long, not focused on the presentation of the routing scheme, and in general disorganized. Indeed, we see the risk to send the wrong message again: HYPERstream is not a hydrological model but a routing scheme than can be implemented in more complex hydrological models.

We revised the introductory part of section 3.3 Application example to emphasize this aspect (see lines 349 and 382-386 of the revised article). Please, see also our replies to comment 9 of Reviewer 2.

In general this paper offers an interesting contribution for streamflow routing in large-scale hydrological. The paper will be reconsidered after major revision. The authors must give a clear and convincing response to each of the points raised by both reviewers and by Dr Martinez. Please highlight clearly what you changed in the revised manuscript, so the reviewers are able to assess your changes.

We thank the Editor for appreciating the manuscript. All Reviewers' comments have been addressed in the following pages.

Reviewer 1

We thank the Reviewer for her/his comments, which were instrumental to better clarify the main message of the manuscript. Indeed, based on the Reviewer's comments, we realized that in some parts of the manuscript the objective of our work was not adequately described and focused. We have revised the entire manuscript, in particular the abstract and the introduction, to better elucidate the main scopes of the work. In the following pages, all Reviewer's comments are addressed and discussed.

1. This paper proposes some improvements to the WFIUH approach.
   From this and a few other comments (see our replies to the following points) we realized that the main message of the work was not sufficiently clear in the previous version of the manuscript. Indeed, we are not proposing any improvements to the WFIUH approach here, but rather an innovative routing scheme based on the classical WFIUH approach. The scheme aims at upscaling river network dispersion at the scale of the block, which represents the smallest scale resolved by large-scale hydrological models.
   Although we believe that the main scope of the work was rather clear (from the title to the conclusions), we acknowledge that the first sentence of the abstract (in particular) was misleading. Therefore, we modified the manuscript throughout (see e.g., abstract, introduction, lines 127-128, lines 382-386), to better clarify the aims of our work.

2. The first argument of the paper is the emergence of socio-hydrology, which is not in scope of the paper. Then, justification of the paper is based on a literature review of Earth System Models and Large Scale Hydrological Models, which leads to the choice of the WFIUH approach for its parsimony, conceptualization, scalability…
   We agree with the Reviewer that the first sentence of the Introduction was not within the scope of our contribution. In the revised version of the manuscript we removed this sentence and other not focused sentences (please, refer to the attached track-changes file for the details).

3. But finally the literature background of the geomorphology-based approaches, including the WFIUH, is not comprehensive and well displayed forefront, so that several claims of the "innovative", "perfect scaling" etc. proposal are not demonstrated.
   We agree with the Reviewer that a more detailed literature review on geomorphology-based approaches would have been necessary if the manuscript was about the description of an improved WFIUH approach. However, the objective of the work is different (please, see our reply to the first point) and we think that the references we included are sufficient for the scope. We have revised the Introduction in order to clarify the reasons why the proposed routing scheme is innovative. Perfect upscaling is not claimed, but it is rather achieved by "construction" of our routing scheme, as clearly demonstrated in Section 2 and shown in the example of Section 3.2.
   Nonetheless, we agree that some additional references addressing the adoption of distributed versions of the GIUH should be included in our manuscript, since they share the common purpose of delineating a possible application of the classical geomorphological approach in the case of spatially variable rainfall/infiltration patterns. To this end, in the revised manuscript we added the following references (see lines 248-249):
   - Moussa, R., 1997, Geomorphological transfer function calculated from digital elevation models for distributed hydrological modelling, Hydrological Processes

- Hallema, R., Moussa, R., Andrieux, P. and Voltz M., 2013,Parameterization and multi-criteria calibration of a distributed storm flow model applied to a Mediterranean agricultural catchment, Hydrological Processes
- Naden PS, 1992. Spatial variability in flood estimation for large catchments: the exploitation of channel network structure, Hydrological Science Journal

4. The main underlying issue is the dealing with the emergence of dominant hydrological processes and the relevance / improvement of the WFIUH in this regards when applied to mesoscale basins (as exemplified with upper Tiber basin in Italy): between hillslope / channel / drainage network; between grids and basin sizes / scales; between dispersion, space variability and simplifying assumptions (average velocity or not, rainfall spatial variability assessment and accounting...) – which could be made more explicit.
   We agree with the Reviewer that the scope of the work could have been made clearer and more explicit; we fully addressed it in the revised manuscript. Please, see our replies to points 1 and 2, and the Introduction of the revised manuscript (in particular from line 97 to the end of the section).

5. Literature about hillslope/channels (individuals and networks) articulation is acknowledged here and there, but the one about accounting for spatial variability in geomorphology-based IUH is not acknowledged. Papers do address this issue with different rainfall data input (radar, interpolation…), convolution enrichments, notions of effective networks, sub-basins nestings… The approach presented here should be framed in the whole landscape of the corresponding literature.
   We partially addressed this comment in our previous replies. If with "spatial variability in geomorphology-based IUH" the Reviewer refers to the spatial variability of precipitation and its interaction with the WFIUH approach (which works with the mean precipitation over the surface to which it refers) we emphasize that this is only a limitation in the size of the macrocell, which should be of the order, or smaller, of the integral scale of the precipitation field. However, in most cases this is not a significant limitation, given the rather large integral scale of the precipitation field (from a few to tens of km).
   If with "spatial variability in geomorphology-bases IUH" the Reviewer refers to the fact that channel velocity can be assumed as random, or dependent on the cumulated area, we acknowledge that this in principle may be a limitation of the proposed approach. However, including this spatial variability is not *per se* an improvement if proper data are not available. In addition, including nonlinearities has the drawback that contributions from different macrocells cannot be superimposed, therefore losing much of the benefit that the WFIUH approach offers. Furthermore, when dealing with floods stream velocity can be safely assumed as constant through the network, as commonly accepted in the literature (see also our reply to comment 3 of Reviewer 3). In the revised manuscript we discussed this point and provided proper references, at lines 199-201.
   We stress again that the scope of the paper is not to propose an improvement of the WFIUH approach by accounting for spatial variability of rainfall. Rather, we are proposing a new routing scheme based on the classical WFIUH approach. The proposed scheme is designed to be easily coupled with weather forecasting and climate models providing the meteorological forcing. In this sense, we account for spatial variability of rainfall without modifying or improving the WFIUH method. No assumptions are made on spatial variability of meteorological forcing, which is totally inherited from the meteorological, or climatic, model.

Nonetheless, at page 9066 of the original version of the manuscript a few references to the literature that the Reviewer suggested were already included *"… with the latter embedding the spatial variability of rainfall patterns according to the macrocell resolution (a similar approach, but based on a partition of the catchment into sub-basins, can be found in Rinaldo et al., 2006; Rigon et al., 2015; Bellin et al., 2015)."*, and are now expanded (see also our reply to comment 3).

6. Further, even if the griding and nodes rationale presented here allows in theory to account for spatial variability of runoff, it is not clear how calculations are operationalized. Hillslope runoff relies on classical models such as the SCS one, but how is this run at the hillslope level before downstream aggregation? How are soils and land covers described and conceptualized at the elementary level of this rationale? Runoff is in fact closer to net rainfall than to gross rainfall. This "hillslope production function" is very contingent across hillslopes and along time non linearities and is a major epistemological obstacle in the geomorphology-based literature which this paper somehow overlooks.
When we introduced the "hillslope production function" η (at line 20 of page 9062 of the original manuscript) we intentionally left it unspecified in order to describe the routing scheme in the most general possible form. We emphasize that the proposed routing model is independent from the choice of the hillslope production model. Indeed, the routing scheme has been designed with a flexible structure, which makes possible to implement any rainfall-runoff model, according to specific user needs and preferences. A comment on these model's peculiarities was already included in the previous version of the manuscript and further emphasized in the abstract (lines 18-20), the introduction (lines 117-119), and in the main text (lines 131-132) of the revised version.
In the revised version of the manuscript, we also emphasized that in order to focus on routing we deliberately kept the rainfall-runoff model (which again is not the focus of our work) as simple as possible. Thus we opted to use the widely known, and applied, SCS-CN model. We are aware of the limitations affecting this model, but again the hillslope model is not the focus of our contribution and our routing scheme can be coupled with any conceivable hillslope model. We have revised also section 3.3, where the application example is described, making clearer how soil and land covers are described within the macrocell (see lines 365-366 of the revised manuscript).

7. Spatial explicitation / Interpolation of rainfall (ideally net rainfall before the convolution with the transfer function) is also a major issue which is here solved by kriging with external drift from the network of available raingauges (changing from one event to the other). The influence of this interpolation approach on the rainfall-runoff modelling is not neglectable compared to the geomorphometric side. Is kriging relevant at the used modelling time step? Is'nt the geostatistical structure changing for changing rainfall fields under convective, advective and orographic influences? Further the griding scheme could be more linked/discussed in conjunction with the raingauge geometry and resolution.
We understand the worries of the Reviewer concerning rainfall interpolation. However, as we already mentioned in the previous points, the application example has been intentionally kept as simple as possible in order to focus on the routing scheme, which is the objective of the work. Indeed, the example application should be seen as an ancillary part of the work, whose core is Section 2 (where the routing scheme is described) and section 3.2, where we demonstrate that our routing scheme enjoys perfect upscaling, irrespective to the size of the overlying blocks, whose size depends on the model providing

the meteorological forcing and on the objectives of the simulation. For this reason, we decided to use a simple method, as SCS for runoff production and kriging for rainfall interpolation with a semivariogram structure tailored to the case at hand. However, we remark again that the precipitation model can be any, the kriging tool employed here being just an application example, though often used in applications. This is clarified at line 401-402 of the revised manuscript.

The precipitation pattern that we had in mind when developing our scheme is the one deriving from the climatic models, i.e. cell-based, since applications combining meteorological models, such as WRF for example, with hydrological models are becoming more and more frequent. See also our reply to the previous point.

8. A full WFIUH approach is developed for nodes corresponding to macro grid cells, and then “rigidly translated” to downstream nodes. The relevance and interest of this nesting approach with a jump in simplifying assumptions are not discussed whereas it is at the origin of the high calculation cost (and so parallelization challenge) and whereas the classical WFIUH is parsimonious in calculation as based on a simple convolution.

   We have read this comment several times and we are unsure to have correctly understood what the Reviewer wanted to say. If he/she is wondering about the correctness of rigidly translating streamflow between nodes, we remark that the assumption is conceptually fully compatible with the WFIUH approach, which, in the case hydrodynamic dispersion is neglected (as e.g. in Botter and Rinaldo, 2003), allows a rigid and time-invariant translation in time of water parcels injected in the system. Hence, there is no jump of assumptions. Concerning the hypothesis of a constant stream velocity, in addition to the references already cited in the original version of the manuscript, we added lines 199-201.

   Finally, we note that there is not any parallelization challenge in the routing scheme we presented. On the contrary, what we claimed is that the scheme is well suited for parallelization, which can be easily implemented thanks to the linearity of routing and independency of the runoff generation module adopted at the cell scale (see abstract, introduction, model description, and conclusions). Certainly, the computational cost increases with increasing number of macrocells, but this also allows for a more detailed description of hydrological processes compared to the case when a single convolution is done for the whole basin. This is discussed in Section 3.3, where we compared results obtained considering macrocells of increasing size, from 5 km to 150 km.

9. The proposed approach is exemplified with two historical events of the upper Tiber basin. Results obtained do not allow to conclude 1) if the proposal performs better than “classical WFIUH”, including options which already account for spatially-variable rainfall; and 2) about relative errors, uncertainties and improvements of the rainfall space-time variability accounting, the hillslope production and transfer modelling, and the “innovative” network transfer modelling.

   At the risk of being redundant, we wish to point out again that the scope of the manuscript is not to propose a new WFIUH method accounting for spatially variable rainfall. Rather, we want to present a simple and fast routing scheme based on the classical WFIUH approach to be easily coupled with weather forecasting or climate models that use a gridded computational domain. Therefore, the Reviewer is right in saying that the results presented in the manuscript do not allow to draw the conclusion written in her/his comment. Indeed, these considerations are beyond the scope of the paper and are not the message that we want to convey.

Reviewer 2

We thank the Reviewer for her/his comments, which were very helpful in clarifying and focusing a few aspects of our work.

Dear Dr. Moussa,
This is an evaluation of the paper entitled “HydroSCAPE: A multi-scale framework for streamflow routing in large-scale hydrological models” (HESS-2015-371) submitted to Hydrology and Earth System Sciences by Dr. Piccolroaz et al. on August 24 of this year. In it, the authors present a hydrologic model that they named HydroSCAPE, and which uses the Width Function Instantaneous Unit Hydrograph (WFIUH) for flow routing in medium-sized watersheds and larger.

The study is both original and scientifically relevant as far as I can judge based on my knowledge of the topic, and provides a relatively new perspective that we have already seen applied in other fields of science, but now applied to watershed modeling. Given the importance of this contribution and the quality of the presentation, I recommend the paper for publication provided the authors apply a series of minor corrections to clarify some matters.
Hoping that this review may prove helpful in your decision, I remain yours faithfully.
We thank the Reviewer for her/his appreciation of our work.

Suggestions for improvement:

1. p. 9058 l. 2: Please rephrase. Rather than being two separate equations, the kinematic wave equation is itself an approximation (simplification) of the Saint-Venant equation assuming uniform flow and a friction slope equal to the slope of the channel bed.
   The Reviewer is right. We have modified the text removing the explicit reference to the kinematic wave equation.

2. 2. p. 9058 l. 10: “0.1 to 0.5 degrees” Please indicate the corresponding ground-projected area in km x km.
   Accepted. We have added the distance in km corresponding to 0.1° and 0.5° of latitude.

3. p. 9059 l. 23-26: I mentioned above that this paper provides a relatively new perspective. That being said, this paper appears to be very much an extension of last year’s paper by Hallema and Moussa (2014) with regard to the application of the WFIUH and spatial subdivision of the watershed. Instead of describing the flow nodes, that paper refers to the flow vectors connecting these nodes, which they call land surface components and channel components, but represent essentially the same substance. The main differences I think are the size of the watershed used in the case study and the use of macrocells. Please cite and elaborate.
   We carefully considered the analogies and differences of our method with the distributed GIUH proposed by Hallema and Moussa, 2014. Both have in common the derivation from the Geomorphologic Theory of the hydrologic response, the underlying idea of further exploring the capabilities of the GIUH approach, and the idea of watershed subdivision; we referenced this paper in the revised manuscript as it has some points in common. However, we also remark that the two models show relevant differences for purposes, scales of possible applications, but also for their inherent structure. The main idea of Hallema and Moussa, 2014 is the representation of anthropogenic hillslopes, and their “representative unit” is a planar, rectangular element which embeds both hillslope “slow”

response and channel flow routing within the REH; the scale of application proposed is 1 hectar as order of magnitude. This stems from the objective of representing in detail the specific configuration of anthropogenic terrain features, such as terrace cultivations typically found in agricultural regions. Small scale also explains why in the real-world application of this model rainfall and infiltration are uniform in space. As we explain in the Introduction and Model development sections, we aim instead at (i) providing an effective and accurate routing scheme for large scale flood modelling, such that the geomorphological dispersion at the scale of the macrocell is explicitly accounted for, similar to the concept of block-scale dispersivity adopted in groundwater models (Rubin et al., 1999); this is indeed the major contribution of our work; (ii) explicitly embedding the variability of rainfall and infiltration, though studying their impact on modeling is beyond the scope of this work (and literature is available on this specific issue), (iii) coupling different scales of representation for geomorphology-based components and meteorological forcing (this motivated the adoption of the "macrocells"), and (iv) clearly separating the different contributions from hillslope component (which could be treated with different case-dependent sub-models) and drainage network.
Nonetheless, we consider the citation of Hallema and Moussa a worth addition to our manuscript and thus we included a reference at line 249 of the revised manuscript.

4. p. 9062 l. 4 "where streamflow is desired" Suggest: "where we want/need to calculate streamflow"
   We have modified this sentence as follows "*where streamflow is simulated*", and one in the Abstract in a similar manner.

5. p. 9062 l. 25 "depends on the partitioning of hydrological fluxes" Explain which processes this refers to, i.e. the Hortonian mechanism, subsurface flow, etc.
   In principle, the routing scheme presented here does not impose any restrictions on the hillslope processes to be simulated. Therefore, here we are not referring to any particular process, and the sentence should be considered with its most general meaning. To make this more explicit, we have modified the sentence as follows "*The resulting water flow is triggered by rainfall or snowmelt and depends on the partitioning of hydrological fluxes at the hillslope scale, according to the selected hillslope model and the hydrological processes that are simulated*".

6. p. 9063 l. 18 "In agreement with the WFIUH theory, stream hydrodynamic dispersion is neglected" Not sure if that requirement was explicitly defined for the WFIUH theory, suffice it to state that WFIUH simply does not account for hydrodynamic dispersion.
   Indeed, neglecting stream hydrodynamic dispersion is not required in the application of the WFIUH, while many works adopted this simplification after the role of Geomorphological Dispersion was recognized (Rinaldo et al., 1991). We agree with this Reviewer's comment and we have modified the sentence accordingly.

7. p. 9067 l. 4 "Relevant flood events" Suggest: "Substantial flood events"
   Acceepted, we have modified the sentence as suggested by the Reviewer.

8. p. 9067 l. 16 "multi-site model calibration" I gather from section 3.3 that the model is calibrated with regard to the Ponte Nuovo station alone, which would make this a monosite calibration. Multi-site calibration implies that the model parameters have been

calibrated to optimize performance at multiple sites at once, for example by optimizing average NS for all stations. This does not seem to be the case here

The Reviewer is right. We have corrected the sentence by replacing “calibration” with “validation”. Indeed, in Section 3.3 we presented both multi-site and multi-site/multi-event validation of the model, which has been previously calibrated at the control section of Ponte Nuovo.

9. p. 9075 l. 20-25 and Table 2. As stated in this paragraph, the watershed model inherits parameters (and values of corresponding state variables) from the ‘sub’ models so to speak, but would the authors consider that consequentially, errors inherited from these underlying models can accumulate rapidly? The authors show this already given the near optimal Nash-Sutcliffe coefficient at Ponte Nuovo and lower performance for other flow stations. I think that Table 2 can list more criteria than the Nash-Sutcliffe coefficient alone, such as the (relative) peak flow and volume errors. This will help identify the strengths and points of improvement for this approach.

   We thank the Reviewer for this comment. Certainly, computing and including additional metrics in Table 2 would help to better quantify modeling errors and uncertainty. However, our focus here is not on identifying the best possible model, but rather to show how our approach is able to take into account in a proper manner the effect of routing along the river network, irrespective of the scale at which meteorological and hillslope processes are represented. Of course the results depend on how the spatial variability of soil properties and meteorological forcing are reproduced (both are constant within the cell), but this is not, by any means, a limitation of our approach. We believe the NS coefficient suffices to illustrate this point. In validation, the average of the NS values at the nodes where simulated streamflow is confronted with observations is insensitive to the macrocell size, up to the largest scale ensuring a good reproduction of the spatial variability of precipitations (in our case about 10 km, which is about 1/3 of the integral scale, estimated in 36 km). As the macrocell size grows larger than this upper limit, the average of NS values deteriorates significantly, as an effect of the inaccurate spatial representation of the precipitation, which cannot anymore considered uniform within the macrocell. This cannot be attributed to our routing scheme, which represents accurately the unmodeled river network irrespective to the macrocell size, but rather to an inaccurate representation of precipitation. Notice that at the larger macrocell dimensions calibration is partially able to compensate for the inaccurate representation of precipitation at PN (i.e., high NS values, larger than 0.9), where the model is calibrated, but not in the other gauging stations, which are used to validate the model. This is the classic situation in which calibration produces good results for the wrong reason, an inadequate spatial variability of precipitation, as widely discussed in the literature. Considering this aspect of hydrological modeling is beyond the scope of our work, but following the suggestion by the Reviewer we computed additional metrics (see the Table below). The inspection of the Table shows that the new metrics confirm what was already evident from the analysis of NS, and therefore we do not include them in the revised manuscript.

	5 km		10 km		50 km		150 km	
	Feb 1999	Dec 1992	Feb 1999	Dec 1992	Feb 1999	Dec 1992	Feb 1999	Dec 1992
NS (PN) [-]	0.99	0.57	0.99	0.60	0.97	0.61	0.94	0.28
NS (all nodes) [-]	0.64	0.27	0.69	0.31	0.56	0.38	-0.69	-0.65
Volume error (PN)	0.80%	27.60%	0.46%	26.26%	1.48%	20.95%	0.21%	22.93%
Volume error (all nodes)	7.83%	35.27%	8.94%	33.37%	10.01%	27.53%	11.63%	32.74%
Peak flow error (PN)	1.83%	3.90%	0.60%	1.36%	0.06%	2.49%	1.49%	8.41%
Peak flow error (all nodes)	16.76%	17.31%	14.02%	16.70%	13.88%	10.94%	16.51%	29.58%
Peak time error (PN) [h]	0.00	0.50	0.50	0.50	0.50	1.00	1.00	2.00
Peak time error (all nodes) [h]	1.80	0.88	1.90	0.75	1.30	1.25	3.10	2.13

Table 1. Nash Sutcliffe Efficiency index, Volume error, Peak flow error, and Peak time error at Ponte Nuovo and the other nodes where streamflow measurements are available for different spatial scale resolutions. Errors are shown in absolute value. When referred to all nodes, errors are evaluated as the average of errors at each node. Note that for the case of a single macrocell of 150 km, the significantly lower values of NS in validation (both multi-site and multi-site/multi-event) are primarily due to larger errors in simulating the timing of the peak flow rather than the volume or the maximum streamflow, compared to the other spatial scales.

10. p. 9075 l. 25-27 "Parsimony is important for a meaningful and reliable parameter estimation procedure and uncertainty analysis, especially when dealing with largescale and complex basins." If anything, basin models are often more accurate than models of smaller headwater catchments because of more and better quality data. Generally speaking however, it is more correct to assume that parsimony is equally important at all scales, whether for a hillslope runoff model or a soil infiltration model.

    We agree with the Reviewer. We only meant that uncertainty estimation can be very difficult as the size of the basin gets larger, due to the natural variability of the processes involved. We have removed the second part of the sentence from the revised manuscript.

Short comment

Introduction

This document corresponds to a peer review process of the article titled HydroSCAPE: a multi-scale framework for streamflow routing in large-scale hydrological models. The objective is to revise and make comments about findings of the model and its obtained results. This peer review is summarized in the following comments.

We thank Fabian Martinez for his interesting comments.
Below we reply to the comments.

Comment 1

The paper states that most of available models inherit the grid approach from the Large Scale Surface Models (LSMs) which works fine for vertical fluxes but provides grid dependency to the surface routing. In most cases routing is performed by solving either the kinematic wave or the de Saint-Venant equation by using the same discretization adopted for resolving the vertical fluxes, thereby leading to scale-dependent inaccuracies in the representation of horizontal fluxes.

- How horizontal and vertical fluxes are defined?
- Are both flow components (vertical and horizontal) considered in the model?
- Are subsurface flows taken into account?

Following a standard definition, horizontal fluxes can be defined as the movements of water within the landscape through streams, rivers, and aquifers, while vertical fluxes can be defined as the exchanges of water between atmosphere, land surface, soil, and groundwater (e.g., precipitation, evapotranspiration, infiltration, percolation etc.).

In principle, both horizontal and vertical flows can be considered, depending on the hillslope sub-module that the user decides to adopt. Indeed, the routing scheme that we present here offers the possibility to be easily coupled with any rainfall-runoff model, thereby accounting for different hydrological processes (e.g., surface and sub-surface flows, groundwater etc.). This has been emphasized and clarified in the revised version of the manuscript (see lines e.g., 18-20, 117-119, 131-132).

Comment 2

The model emphasizes on the importance of defining proper hillslope-channel within the macro cell that contributes to a certain node. However, it is not explained what is a hillslope-channel area and how they are defined. For example, in Figure 1 several hill-slope areas are colored; but it is not understood under which geomorphological considerations they were defined (slope, elevation, etc.).

We assume in the paper a classical hillslope-channel topological separation of the entire watershed; however, as we did for other model features, we emphasize that the choice of the hillslope-channel separation methodology may be suitably chosen when the model is applied to a real study case, depending on the accuracy needed and the DEM available. For example it can be achieved through the application of some of the standard schemes listed in the references (lines 14-20 at pg. 9061 of the previous version, also included in the revised manuscript).

Please note that the sketch in Figure 1 does not refer to a real-world case, but it is a scheme created and used as an example made with the purpose of visualizing the different possible operational cases.

In the application example provided in section 3, the geomorphological hillslope-channel separation criteria adopted are adequately described and supported by appropriate references (see lines 9-16 at page 9068 of the original manuscript).

Comment 3

Based on the kinematic conceptual scheme of the model, water flow produced by the hillslope enters the network system through the hillslope-channel transition site and is subsequently routed through it. The streamflow contribution of the hillslope `, belonging to the macrocell i, to node k is defined in a way that considers a constant stream velocity Vc and it states that this assumption is crucial for the linearity of the process.

- Since stream velocity depends on stream geometry, does this imply that the model considers a constant geometry of the stream network over time?
- How does the model account for seasonal variations of stream velocities associated to variations on channel Manning's n values?
- How does a non constant velocity makes the system non linear?

- We don't explore the variability of velocity associated with temporal variation of local hydraulic characteristics and their effects on the shape of the response function. We rather assume a constant velocity, which is a common assumption in representing flood events (see the following point for a brief discussion and references). Notice that in case of flood the velocity we are considering here is the celerity of propagation of the perturbation caused by the rainfall input, not the local mean stream velocity. Therefore, the assumption is that the celerity is constant across the river network.
- We do not account for seasonal or spatial variations of velocity, although that is a possible extension. Using a constant channel velocity for channel routing is a common assumption in rainfall-runoff models adopted in several geomorphological studies. Some of them are already cited in the original manuscript (see lines 16-17 at page 9063: (Gupta et al., 1986; Mesa and Mifflin, 1986; Gupta and Mesa, 1988; Rodríguez-Iturbe and Rinaldo, 1997). Furthermore, this assumption is supported by experimental measurements, especially for high flows (see Pilgrim, D.H., 1976 and 1977 DOI: 10.1029/WR012i003p00487 and 10.1029/WR013i003p00587; the latter references have been added to the revised version of the manuscript, at lines 199-201). In developing a model it should be considered also that the detailed geometry of the streams, needed to safely evaluate the local mean velocity, are at best available in the main stem, while morphological studies showed that the mean velocity averaged along a reach (the portion of the stream between two successive junctions) changes slightly with the contributing area, making the local variation of the velocity irrelevant for the objective of computing network-scale streamflow.
- Regarding the last comment we note that a temporally varying channel velocity would imply that the response function depends on the shape and intensity of the meteorological forcing, thus making the model non-linear; this assumption is sometimes used in rainfall-runoff models (compare Robinson and Sivapalan, 1996, DOI: 10.1002/(SICI)1099-1085(199606)10:6<845::AID-HYP375>3.0.CO;2-7), but it is not coherent with the simple, linear and parallelizable routing scheme we are presenting.

Comment 4

The article states that if the DEM resolution is high and the total domain A where the model is applied is large, the preprocessing step can be time consuming; the effort is however compensated in the application of the model, particularly if the modeling activity is performed in a multiple run framework.

- What does consist the preprocessing step?
- Why the preprocessing depend on the size of the DEM?
- Is there any other input to the model that needs to be preprocessed?

Please, see lines 9-12 at page 9060 of the original manuscript: pre-processing is needed in order to compute the geomorphological width functions, thereby identifying and separating the river network from the hillslopes. The larger the area A and/or the finer the resolution of the DEM, the higher the number of pixel considered in the pre-processing step, thus the larger the time required to perform these operations.

Following the suggestion of the Reviewer, we remarked that the only pre-processing analysis is the calculation of the geomorphological width function by adding a sentence at lines 254-257 of the revised version of the manuscript.

Besides calculating the geomorphological width functions no additional pre-processing operations are required, with the exception of creating the input files (observed streamflow and precipitation) according to the format used in the code.

Comment 5

The DEM used for the case study in the Upper Tiber Basin corresponds to a high resolution 20 m grid size DEM. If it has been established that the model is non dependent on the grid size, why such a high resolution DEM is used? On the other hand, how was associated a CN II number to each DEM cell? A spatially distributed 20m resolution soil classification was available for the site?

In that context, “grid size” refers to the size of macrocells used to subdivide the computational domain, not to the DEM discretization. Using a high resolution DEM allows for a better description of the width function at the scale of the macrocell, thus of the geomorphologic response of the watershed. Please, refer to Figure 5, where we show the comparison between the width function derived by the 20 m resolution DEM and the analogous width functions after DEM aggregation at 5, 10 and 50 km. A significant deterioration of the width function is clearly detectable when the DEM is aggregated over cells of increasing size. Therefore, computations are performed at km- or larger scale macrocells, while WFIUH is obtained at the DEM scale, such as to represent geomorphological dispersion at scales smaller than the macrocell size.

Notice that the values of CN II were associated to the macrocells, not to the single DEM cells. The map of CN II was derived from the digital maps of land use and lithological characterization supplied by the European Environmental Agency (Corine Land Cover project) and by Italian Agency for Environmental Protection and Research (ISPRA), respectively (see page 9067 of the original version of the manuscript); both of them are vector maps. Those features were automatically processed though standard procedures in order to obtain the homogeneous CN II zones; the final value of the CN for each macrocell was obtained by performing a spatial averaging over the macrocell area.

Comment 6

An application of HydroSCAPE flood prediction is presented for the Upper Tiber basin. In order to focus in routing, a simple runoff model was coupled. Hence, subsurface contribution to streamflow is not explicitly considered in the model. In some basins, subsurface flows can be determinant and add an important contribution to the flood. What parameters of the model can be affected if a subsurface flow model is coupled?

Including sub-surface flow means adopting a different hillslope sub-model, thus a different set of parameters. This can be easily done, but it is beyond the scope of the present work.

Comment 7

In the same application example, the superficial runoff at a hillslope is calculated using a classic SCS-CN approach. The procedure assumes that the cumulative rainfall remains constant within a macrocell. This is a very strong assumption depending on the size of the macrocell.

- How valid is this assumption considering the strong spatial variation of rainfall, specially in basins with high orographic influences like the one studied in the application example?
- Based on the previous point, wouldn't be more appropriate to create a macrocell that matches areas with more or less the same accumulated rainfall? It is believed that this would help to not create excessive differences between observed spatial variation of the rainfall and the assumption of a constant value

The smaller the macrocell, the better the description of rainfall spatial variability and patterns, but to a certain point. For example, from basic principles of geostatistics it is known that using macrocells smaller than $I/4$ (i.e., one fourth of the integral scale I) does not provide any improvement in the reproduction of the random field, the precipitation in our case. This is already acknowledged in the text, please refer to lines 24-29 at page 9072 of the original manuscript. "*Notice that all cases with the average NSE>0.5 are with a macrocell dimension equal or smaller than the integral scale of the precipitation, which is about 36 km (E. Volpi, Modello di struttura spaziale del campo di precipitazione, unpublished technical report). It is therefore clear that the inaccuracies encountered with large macrocells are due to the inaccurate spatial description of the precipitation*." In other words, it is true that the macrocell's size should be suitable to reproduce accurately the precipitation field, but this is not by any means a limitation of our scheme, rather a modeling choice. However, given the large correlation scale of precipitation, macrocells with size of a few km (i.e. from 5 to 10 km, depending on the computational domain) suffice to reproduce accurately the spatial distribution of precipitation, while geomorphological dispersion is captured by routing rainfall excess through the WFIUH model.

Concerning the second point: the routing scheme presented here has been designed to share the same computational grid of the meteorological model (we better stress this point in the revised manuscript at lines 97-100, 159-160, and 241-245). The geometry of macrocells is therefore controlled by the meteoclimatic model. Notice that all the meteorological variables, and in particular precipitation, that could be provided by Regional Climate Models or weather forecasting models are assumed constant within their computational cells.

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~~HydroSCAPE~~HYPERstream: A multi-scale framework for streamflow routing in large-scale hydrological models.

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Abstract. We present ~~HydroSCAPE, a large scale hydrological model with~~ HYPERstream, an innovative streamflow routing scheme based on the Width Function Instantaneous Unit Hydrograph (WFIUH) theory, which is specifically designed to facilitate coupling with weather forecasting and climate models. ~~HydroSCAPE~~ The proposed routing scheme preserves geomorphological dispersion of the river network when dealing with horizontal hydrological fluxes, irrespective of the ~~adopted grid size , which is typically~~ computational grid size inherited from the overlaying ~~weather forecast or climate model~~ climate model providing the input meteorological forcing. This is achieved ~~through a separate treatment of hillslope processes and~~ by simulating the routing within the river network ~~, with the latter simulated by~~ through suitable transfer functions ~~constructed~~ obtained by applying the WFIUH theory to ~~the desired~~ a chosen level of detail. The underlying principle is similar to the block-effective dispersion employed in groundwater hydrology, with the transfer functions used to represent the effect on streamflow of morphological heterogeneity at scales smaller than the computational grid. Transfer functions are constructed for each grid cell ~~and~~ with respect to the nodes of the network where ~~water discharge is desired~~ streamflow is simulated, by taking advantage of the detailed morphological information contained in the Digital Elevation Model (DEM) of the zone of interest. These characteristics ~~render HydroSCAPE~~ make HYPERstream well suited for multi-scale applications, ranging from catchment up to continental scale, and to investigate extreme events (e.g., floods) that require an accurate description of routing through the river network. The ~~model enjoys reliability and robustness, united to~~ routing scheme enjoys parsimony in the adopted parametrization and computational efficiency, leading to a dramatic reduction of the computational effort with respect to full-gridded models at comparable level of accuracy~~of routing~~. Additionally, ~~HydroSCAPE~~ HYPERstream is designed with a simple and flexible modular structure ~~, which makes it~~ that allows for the selection of any rainfall-runoff model to be coupled with the routing scheme and the choice of different hillslope processes to be represented, and makes the framework par-

ticularly suitable to massive parallelization, customization according to the specific user needs and preferences~~(e.g., choice of rainfall-runoff model), ~~, and continuous development and improvements.

1 Introduction

~~The emerging of socio-hydrology as a research area of hydrological sciences, addressing multiple scale feedbacks between human activities and hydrological processes, ~~The increasing pressures on freshwater resources originating from a multitude of complex and interacting factors led in recent years to a growing need of tools able to provide water resources information at regional to global scales (see e.g., Archfield et al. (2015) for a commentary). Overall, this fostered new developments in large-scale hydrological models as a component of more comprehensive, and complex, Earth System Models (ESMs). Manabe (1969) was the first to add a land component in a climate model. His work prompted the development of a first generation of Global Circulation Models and a parallel development of Land Surface Models (LSMs) for hydrological applications (see Haddeland et al. (2011) and Prentice et al. (2015) for a comprehensive review). Land Surface Models are developed with the intent of providing a realistic and detailed representation of vertical water, energy and CO_2 fluxes, with the perspective to facilitate coupling with atmospheric models. On the other hand, Large-scale Hydrological Models (LHMs) have been developed with the perspective of a realistic representation of water resources and horizontal water transfer (Haddeland et al., 2011). VIC (Liang et al., 1994), LaD (Milly and Shmakin, 2002), H08 (Hanasaki et al., 2008a, b), Noah-MP (Niu et al., 2011), WEHY-HCM (Kavvas et al., 2013), and CLM (Oleson et al., 2013), are examples of LSMs, while MacPDM (Arnell, 1999), WBM (Vörösmarty et al., 1998), WGHM (Döll et al., 2003), WASMOD-M (Widén-Nilsson et al., 2007), PCR-GLOBWB (Van Beek et al., 2011), LISFLOOD (van der Knijff et al., 2010)), and mHM (Samaniego et al., 2010) can be classified as belonging to the category of ~~hydrological models~~LHMs. This classification notwithstanding, the boundary between these two categories is blurred since in their recent developments most of these models are converging to a comprehensive representation of the terrestrial processes, in an attempt to increase realism, though this is often achieved at the expense of reliability and robustness (Prentice et al., 2015). However, at the current stage of ~~the developments~~development, both category of models suffer from a discretization which is often too coarse to represent routing in the river network with enough detail to capture geomorphological dispersion (Rinaldo et al., 1991).

The hydrological component of both categories of models, which for simplicity we indicate here as LHMs, rely on simplified conceptualizations and empirical upscaling procedures (Nazemi and Wheater, 2015), when dealing with heterogeneities that characterize hydrological fluxes across a hierarchy of scales, ranging from the hillslope to the catchment and the continent. In addition, most of the available hydrological models inherit the grid approach from LSMs, which works fine for the vertical fluxes, but ~~renders grid dependentthe surface routing. In most cases routing~~

~~is performed by solving either the kinematic wave or the de Saint-Venant equation (or one of its simplifications) by using the same discretization adopted for resolving the vertical fluxes, thereby leading to scale-dependent~~ makes streamflow routing grid dependent. The obvious consequence is the presence of inaccuracies in the representation of horizontal fluxes, unless a very fine discretization is used, which however is untenable at large scales also for the currently available high performance computational resources. ~~The introduction of improved routing schemes to adequately resolve horizontal fluxes with an acceptable computational effort is therefore indicated as one of the priorities in ESMs, and in LHMs as well, (Clark et al., 2015). In fact,~~ Indeed, grid-based ~~models~~ LHMs are typically applied with a spatial resolution ranging from 0.1^o (ca. 11 km) to 0.5^o ~~. This resolution~~ (ca. 55 km), which has been proven to be insufficient to capture geomorphological dispersion and travel time distribution at the level of accuracy needed to model horizontal fluxes~~, in particular~~. This is particularly significant at intermediate scales, i.e., scales of the order of thousand or tens of thousand km^2 (Gong et al., 2009; Verzano et al., 2012), which are relevant in modeling flood events. The introduction of improved routing schemes to adequately resolve horizontal fluxes with an acceptable computational effort is therefore indicated as one of the priorities in ESMs, and in LHMs as well, (Clark et al., 2015).

Hyper-resolution LHMs relying on global digital drainage networks at fine scales, such as HydroSHEDS at 90 m resolution (Lehner et al., 2008), represent a possible strategy to overcome the above limitations and obtain reliable estimates of horizontal fluxes (Wood et al., 2011). However, applying a LHM at a such fine discretization is ~~untenable~~ difficult for the large computational cost associated to it, which becomes unbearable when inversion is applied to infer model parameters from observational data. This burden is currently too high for LHMs adopting explicit hydrodynamic routing through the numerical solution of the mass and momentum conservation equations (i.e., the de Saint-Venant equations), but also for models adopting cell-by-cell routing algorithms based on mass conservation and relationships between river-channel storage and streamflows (Yamazaki et al., 2011; De Paiva et al., 2013). If modeling high flow events is the objective of the analysis a hourly, or smaller, time scale should be adopted, thereby further increasing the computational burden, ~~for the same spatial discretization,~~ with respect to the daily or monthly time scale typically adopted in large-scale simulations of water resources.

Mixed schemes in which routing is separated from runoff have also been employed (see e.g., Gong et al., 2009, 2011; Wen et al., 2012; Lehner and Grill, 2013). HydroROUT is a vector-based routing scheme fully integrated with ArcGIS (ESRI, 2011) developed by Lehner and Grill (2013), in which streamflow is obtained by routing to the catchment outlet the surface runoff (as provided by an external runoff simulator to be coupled with the routing scheme) accumulated at the nodes of the network. Routing is performed by using a 'plug-flow' routing scheme similar to that implemented by Whiteaker et al. (2006) and applied to the HydroSHEDS river network (Lehner et al., 2006).

Wen et al. (2012) proposed a multi-scale routing framework employing a pdf distribution for the overland flow path lengths lumping the effect of unmodeled sub-grid variability in the parameters describing the pdf. The kinematic wave routing method is then employed for both overland and channel flow simulations, thereby resulting in a highly computational demand, as already discussed above. In addition, the routing scheme generates streamflow only at the outlet of the catchment without the possibility to simulate streamflows at internal nodes, such as lakes, reservoirs or other infrastructures, while the use of response functions aggregated at the daily time scale limits the applicability to flood events occurring in large river basins, with the approach proposed by Gong et al. (2009, 2011).

To overcome the above limitations without resorting to hyper resolution hydrological models (when not needed to better reproduce spatial variability of soil water storage and transmission), we propose a multi-scale approach for streamflow routing based on the travel time approach. More specifically, we propose a scheme based on the Width-Function Instantaneous Unit Hydrograph (WFIUH) theory (see e.g., Rodríguez-Iturbe and Rinaldo, 1997), applied to a hybrid raster-vector data structure, according to the definition proposed by Lehner and Grill (2013). ~~To emphasize that the model~~ The proposed scheme is designed to ~~reproduce the effect of landscape on horizontal water transfer, we coined the name "HydroSCAPE", where "SCAPE" also recalls that the model is inherently SCAlable and highly ParallelizablE. In fact, by design, routing is independent from the grid size adopted to simulate~~ work at large, up to the continental, spatial scales with the resolution of the computational grid inherited directly from the climate or weather forecasting models used to simulate the input meteorological forcing. Similarly to LHMs water storage and runoff generation processes (we call this part the land component of the model) ~~, which as in all LHMs depends on the resolution of the climate or weather forecasting model used to simulate the meteorological forcing. In particular, geomorphological dispersion (Rinaldo et al., 1991) is~~ are simulated according to this relatively coarse grid, whilst streamflow routing is performed through a scheme that is irrespective of this spatial resolution thus allowing for an improved reproduction of horizontal water transfers. Here we refer to as "perfect upscaling" to indicate that the proposed routing scheme keeps the network contribution inherently invariant with respect to the grid size of ~~the land component and the network response is perfectly upscaled to the computational grid~~meteorological forcing, i.e. geomorphological dispersion (Rinaldo et al., 1991) is preserved as it is derived from the morphological information embedded in the available DEM. Scale-invariance is an important feature characterizing our modeling approach not enjoyed by grid-based LHMs, which rely on empirical upscaling procedures in order to represent unmodeled geomorphological dispersion. Here perfect upscaling is presented for the case study of Upper Tiber (central Italy), where we show that our routing scheme does not entail any deterioration in the watershed width functions when considering progressively coarser spatial resolutions. An additional crucial aspect is the computational time efficiency, which stems from the fact that the most demanding step of the procedure is the computation of the geomorphological width functions, which is performed only once as an offline pre-processing procedure. This characteristic, coupled with easiness ~~to~~ of parallelization and parsimony ~~, makes HydroSCAPE~~ in parameterization, inspired us to coin the name HYPERstream, where "HYPER" recalls that the proposed model is based on a HighlY Parallelizable and scalablE Routing scheme. Finally, HYPERstream is designed with a flexible and modular structure which allows the coupling with any lumped or process-based formulation for infiltration and subsurface flow processes, while the simplicity and computational efficiency makes it an appealing tool for uncertainty assessment of the predictions, and in general for simulations conducted in a Monte Carlo framework.

This paper is organized as follows: Section 2 describes the multi-scale hydrological conceptual model, details of the pre-processing module and derivations of node specific width functions are provided in Section 3, with reference to the Upper Tiber case study. An example of application for two flood events is discussed in Section 3.3, and finally concluding remarks are drawn in Section 4.

2 Model development

As stated in the Introduction, our aim is to develop a simple, parsimonious and computationally efficient method for ~~modeling streamflow (and particularly~~ streamflow routing (with particular attention to floods) in large river basins. To this aim, we adopt different modeling strategies for the river network and the associated hillslopes ~~: a lumped non-linear formulation for the latter and a~~ (the land component introduced in Section 1): a linear, geomorphologically-based approach for the former~~.~~, and a lumped formulation for the latter. We note that the land component can be decided without particular restrictions, depending only on the user's needs and preferences. The proposed modeling framework reflects the current understanding of hydrological processes at the hillslope and watershed scales (see e.g., Sivapalan, 2003).

The sketch of Fig. 1 displays the conceptual model adopted here. The modeled domain A, which can be of any size and may include any number of disconnected river networks (for example, the sketch of Fig. 1 contains two river networks), is subdivided into N macrocells, each one characterized by a contributing area $A^{(i)}$, such that $\sum_{i=1}^{N} A^{(i)} = A$. We emphasize that the generic $A^{(i)}$ does not need to coincide with the macrocell area, for instance this happens when the macrocell contains parts of neighbor watersheds (see the macrocells at the boundary of Fig. 1). There are no constraints on A, except that it must cover all the watersheds of interest. For easiness of representation, in Fig. 1 macrocells are represented as squares, but this is not by any means a ~~constraint~~ limitation of the model and irregular macrocells can be used if convenient in the application of the model. ~~However~~Indeed, size and geometry of the macrocells can be set to coincide with the gridding of the weather or climate model used to provide the input meteorological forcing.

Drainage characteristics of the basins are obtained from the ~~Digital Elevation Model (DEM)~~ DEM of the area of interest. The spatial resolution of the DEM should be fine enough to adequately

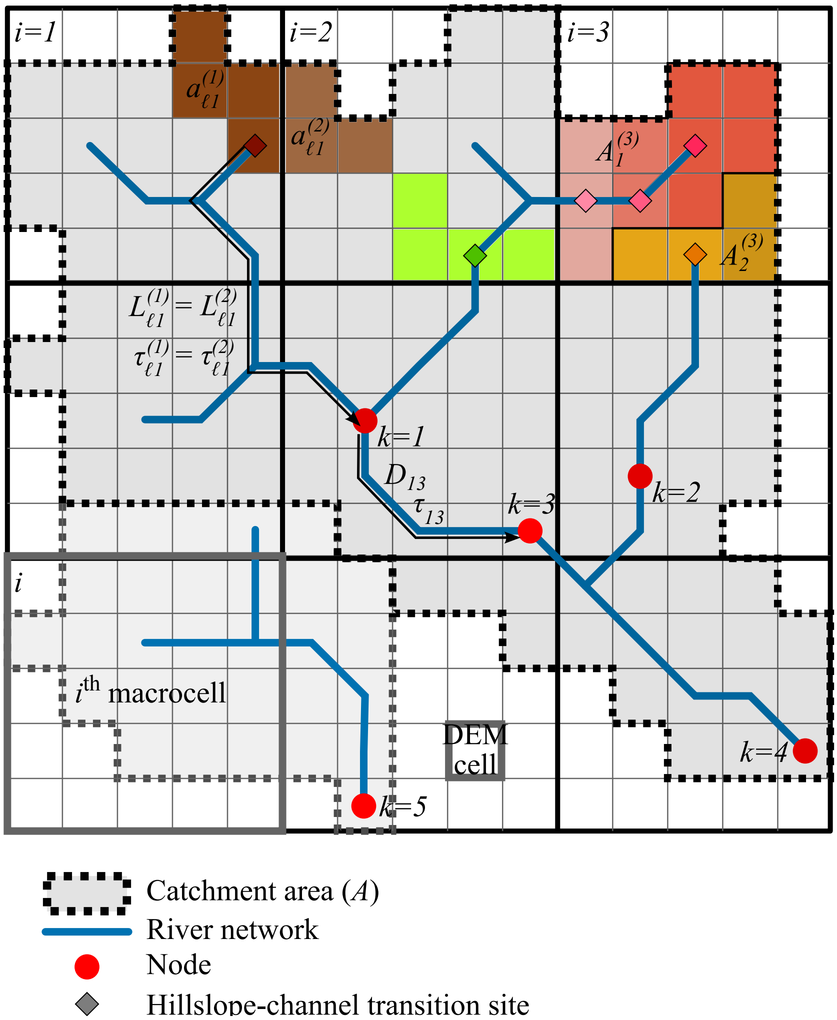

Figure 1. Sketch of basin conceptualization: subdivision of the study area into macrocells and nodes (red dots). River network is subdivided into hillslope-channel transition sites (colored squared symbols) each associated to a pertaining hillslope area $a_{\ell k}^{(i)}$ (colored areas). For this simple case we consider $N = 9$ macrocells and $k = 5$ nodes. An example of two pathways characterized by the same length $L_{\ell k}^{(i)}$ and travel time $\tau_{\ell k}^{(i)}$ is also sketched.

capture the spatial structure of the drainage basins and the embedded river networks. Following procedures widely adopted for the identification of drainage direction and hillslope-channel separation (Tarboton et al., 1991; Montgomery and Foufoula-Georgiou, 1992) (see Sect. 3.2), the river networks are extracted and the hillslopes identified.

The area of the hillslopes changes through the domain, unless identification of the river networks is performed by using a constant threshold area. The link between the hillslope and the channel is denoted as hillslope-channel transition site. As an example, a synthetic DEM grid is shown in Fig. 1 (25 DEM cells per macrocell) together with the identified river ~~networks~~network. The figure shows also a few hillslopes (colored areas), each of them associated to the corresponding hillslope-channel transition site (colored squared symbols). Notice that in the example the brown hillslope is divided between two macrocells ($i = 1, 2$), a common situation in our approach since the discretization of the domain into macrocells may be arbitrary (i.e., it does not necessarily use topographic information, as is generally the case in weather forecasting or climate models).

The next step in the construction of the model is the identification of the N_k nodes where streamflow is ~~desired~~simulated. In the example of Fig. 1, $N_k = 5$ nodes, identified by red bullets, are distributed within two networks. No limitations are imposed to the number and position of these nodes, which represent locations were streamflow is computed either to compare it with observational data, as part of the inversion procedure, or for other purposes, such as to verify flood protection structures (or the need to build them). Each macrocell i may feed one or more nodes; for instance, the macrocell $i = 3$ in Fig. 1 includes contributing areas to nodes $k = 1$ and $k = 2$, with different routes. It may also occur that a macrocell contributes to the same node k with different routes, as for the case of macrocell $i = 2$ which contributes to node $k = 1$, through both hillslopes highlighted in green and brown.

We denote with $A_k^{(i)}$ the area of macrocell i contributing to node k, such that $\sum_{k=1}^{N_k} A_k^{(i)} = A^{(i)}$. Notice that $A_k^{(i)} = 0$ if the macrocell i does not contribute to node k. The ~~streamflow~~ runoff generation processes occurring at the hillslope scale can be modeled by using schemes of different level of complexity, from the simple SCS-CN method (U.S. Soil Conservation Service, 1964) to methods based on the solution of the Richards equation, or one of its simplification (Clark et al., 2015), depending on the objectives of the analysis. Whatever the hillslope model, for the sake of generality hereafter we indicate with $\eta_{\ell k}^{(i)}$ $[L/T]$ the water discharge per unit area produced by the hillslope ℓ of area $a_{\ell k}^{(i)}$ $[L^2]$, which belongs to the macrocell i and contributes to the streamflow at the closest downstream node k along the river network (for instance, the hillslope highlighted in green in Fig. 1 contributes to node $k = 1$, which is the first node encountered moving downstream). The resulting water flow is triggered by rainfall or snowmelt and depends on the partitioning of hydrological fluxes ~~, triggered by rainfall or snowmelt,~~ at the hillslope scale~~and may include the contribution of groundwater~~, according to the selected hillslope model and the hydrological processes that are simulated. According to the above conceptual scheme, water flow produced by the hillslope enters the network system through the hillslope-channel transition site, and is subsequently routed through it.

From this kinematic scheme, it follows that the streamflow contribution of the hillslope ℓ, belonging to the macrocell i, to node k can be written as follows

$$q_{\ell k}^{(i)}(t) = A_k^{(i)} \tilde{a}_{\ell k}^{(i)} \int_0^t \eta_{\ell k}^{(i)}(t-\tau)\, \delta\left[\tau - \tau_{lk}^{(i)}\right] d\tau = A_k^{(i)} \tilde{a}_{\ell k}^{(i)} \eta_{\ell k}^{(i)}(t - \tau_{\ell k}^{(i)}), \qquad (1)$$

where $\tilde{a}_{\ell k}^{(i)} = a_{\ell k}^{(i)} / A_k^{(i)}$ $[-]$ is the relative hillslope area, δ $[1/T]$ is the Dirac delta function, $\tau_{\ell k}^{(i)}$ $[T]$ is the travel time from the hillslope-channel transition site of the hillslope ℓ to node k, and t $[T]$ is the current time.

Under the hypothesis that the stream velocity V_c $[L/T]$ is constant through the network, the travel time assumes the following expression: $\tau_{\ell k}^{(i)} = L_{\ell k}^{(i)} / V_c$, where $L_{\ell k}^{(i)}$ is the distance, measured along the network, from the hillslope-channel transition site of the hillslope ℓ to the first downstream node k. The assumption of constant V_c is crucial for the linearity of the processes at the watershed scale, as stated at the beginning of this section. Eq. (1) is consistent with the general conceptual framework used to derive the Width Function Instantaneous Unitary Hydrograph by rescaling the geomorphological width function through a suitable constant velocity (Gupta et al., 1986; Mesa and Mifflin, 1986; Gupta and Mesa, 1988; Rodríguez-Iturbe and Rinaldo, 1997). ~~In agreement with the WFIUH theory,~~ We note that the assumption of constant channel velocity is supported by experimental measurements, especially for high flow conditions (see e.g., Pilgrim, 1976, 1977). Additionally, stream hydrodynamic dispersion is neglected, owing to its small to negligible effect on the hydrological response, which has been demonstrated to be dominated by geomorphological dispersion already embedded into the rescaled width function (Rinaldo et al., 1991, 1995; Rodríguez-Iturbe and Rinaldo, 1997).

The streamflow $q_k^{(i)}$ $[L^3/T]$ generated by macrocell i and contributing to the node k is then obtained by summing up all the contributions stemming from the hillslopes of the macrocell draining to the node k:

$$q_k^{(i)}(t) = A_k^{(i)} \sum_{\ell} \tilde{a}_{\ell k}^{(i)} \int_0^t \eta_{\ell k}^{(i)}(t-\tau)\, \delta\left[\tau - \tau_{lk}^{(i)}\right] d\tau \,. \tag{2}$$

Under the hypothesis that the hillslope water discharge per unit area is constant through the cell i, i.e. by assuming that $\eta_{\ell k}^{(i)} = \eta^{(i)}$, Eq. (2) simplifies to:

$$q_k^{(i)}(t) = A_k^{(i)} \int_0^t \eta^{(i)}(t-\tau)\, f_k^{(i)}(\tau)\, d\tau = A_k^{(i)} \eta^{(i)} * f_k^{(i)}(t) \,, \tag{3}$$

where $f_k^{(i)}(\tau) = \sum_{\ell} \tilde{a}_{\ell k}^{(i)}\, \delta\left[\tau - L_{\ell k}^{(i)}/V_c\right]$ is the probability density function (pdf) of the travel time $\tau_{\ell k}^{(i)}$ weighted by the relative hillslope area $\tilde{a}_{\ell k}^{(i)}$. In Eq. (3) the asterisk denotes convolution.

Finally, water discharge $Q_k(t)$ $[L^3/T]$ at the node k is given by the sum of the direct contribution of each macrocell i to the node plus the contribution of the nodes upstream of k:

$$Q_k(t) = \sum_{i=1}^{N} q_k^{(i)}(t) + \sum_{i=1}^{N} \sum_{j=1}^{N_k^{up}} q_j^{(i)}(t - \tau_{jk}) \,, \tag{4}$$

where $\tau_{jk} = D_{jk}/V_c$ is the travel time from the node j, located upstream to the node k, to the node k, D_{jk} is the distance between the two nodes, and N_k^{up} is the number of nodes upstream of k. In the first right hand term of Eq. (4) summations are extended over all the macrocells, with the convention that $q_k^{(i)} = 0$, because $A_k^{(i)} = 0$, for all macrocells not contributing, i.e. not connected through the network, to the node k (the same applies for index j). Notice that, in the second right hand term of (4) the streamflow computed at the node j is rigidly translated to the node k with the delay τ_{jk} depending on the distance between the two nodes, thereby neglecting again the effect of stream hydrodynamic dispersion, as typically done in the WFIUH approach (see e.g., Gupta et al., 1986; Van Der Tak and Bras, 1990; Botter and Rinaldo, 2003; Giannoni et al., 2005).

The above method is simple and computationally effective. The underlying principle is similar to the block-effective dispersion employed in groundwater hydrology (see e.g., Rubin et al., 1999; De Barros and Rubin, 2011), with the travel time pdf used to represent the effect on streamflow of morphological heterogeneity at scales smaller than the macrocell, with a lower cutoff given by the ~~DEM's~~ DEM scale. The linearity of the transfer processes at the scale of the network makes the algorithm easy to parallelize~~.~~, making it promising for large-scale applications at small time scales (i.e., with hourly or sub-hourly time step). In principle, streamflow generated by a macrocell can be elaborated by a single processor (with the convolution of Eq. (3) being the most demanding step), for the whole duration of the simulations, independently from the other processors. Then, the streamflow $Q_k(t)$ at the nodes of interest is further processed with Eq. (4) when all processors terminated the elaboration of their macrocell. For the same reasons, this model is particularly suited to multiple Monte Carlo runs (e.g., for parameter estimation, uncertainty analysis~~or~~, multi-model or multi-scenario analysis). The main advantage of the method is that, by design, it preserves the global geomorphological dispersion of the basin, as calculated by the fine grid DEM, no matter the size of the macrocells. Consequently, the upscaling of river network dispersion is perfectly resolved, without resorting to hyper-resolution numerical grids. This point shall be illustrated in the ensuing ~~Section. In addition, with the proposed approach we address one of the main limitation of the WFIUH formulation: the inadequacy of the original method (generally based on a single WFIUH for the whole river basin) to properly account for spatial~~ section. Spatial variability of precipitation~~. It is in fact recognized that at intermediate spatial scale (typically beyond a few thousands of km^2) the spatial distribution of rainfall~~, which indeed plays a fundamental role in shaping the hydrological response of river basins ~~(see e.g., Nicótina et al., 2008; Volpi et al., 2012; Sapriza-Azuri et al., 2015).With our approach this limitation is overcome by assembling in the right hand term of Eq.(4) the convolution of Eq. (3)between the macrocell-specific rescaled width functions $f_k^{(i)}$ and the discharges per unit area $\eta^{(i)}$, with the latter embedding the spatial variability of rainfall patterns~~ at intermediate spatial scale (i.e., beyond a few thousands of km^2, see Nicótina et al. 2008; Volpi et al. 2012; Sapriza-Azuri et al. 2015), is in our scheme inherited from the companion climatic model and it is embedded in the hillslope production function η according to the macrocell resolution~~(a similar approach, but~~. Similar approaches relying on distributed versions of geomorphological response, but generally based on a partition of the ~~catchment into~~ watershed into natural or anthropogenic sub-basins and not focused on large scales applications, can be found in ~~Rinaldo et al. (2006),~~ Naden (1992), Moussa (1997), Rinaldo et al. (2006), Hallema et al. (2013),Hallema and Moussa (2014), Rigon et al. (2015), and ~~in ?)~~Bellin et al. (2016).

Routing requires the definition of only a parameter, the channel velocity V_c, which is a very parsimonious, yet effective, parametrization with respect to grid-based routing schemes. If the DEM resolution is high and the total domain A where the model is applied is large, the preprocessing step can be time consuming; the effort is however compensated in the application of the model, particularly if the modeling activity is performed in a multiple run framework. We note that the only pre-processing operation required is the analysis of the DEM aimed at identifying the river network and the drainage characteristics of the river basin, and at computing the geomorphological width functions.

3 Description of the model features, with application to the Upper Tiber Basin

3.1 Study area

In this section we describe an application of ~~HydroSCAPE~~ HYPERstream to the Upper Tiber river basin, providing a practical example of model characteristics and performances. The study area covers the upper portion of the Tiber river basin, located along the Apennine ridge (central Italy) between $42^o\,36'$ and $43^o\,51'$ latitude North and $11^o\,48'$ and $12^o\,55'\,12''$ longitude East (see Fig. 2a). The basin drains an area of approximately $4000\,km^2$ which represents about 25% of the entire Tiber basin at the river mouth in the Tyrrhenian sea. The basin is predominantly mountainous, with elevation ranging from 145 to $1560\,m\,a.s.l.$ (see Fig 2b) and it is aligned to the North-West South-East direction, with the Apennine ridge-line representing an important physical boundary at East that causes variability in precipitation and temperature. From a geological point of view most of the catchment is underlined by low-permeability formations, chiefly flysch, sandstone clay, and limestone clay. However, high-permeability formations (calcareous lithology) are found in the upper part of the basin and on the eastern divide.

Intense precipitation events are typically associated with humid frontal advection from the Mediterranean sea and condensation due to the orographic uplift. Because of strong topographic gradients, headwaters experience intense rainfall events, mostly occurring from autumn to spring, associated with frequent flood events. ~~Relevant~~ Substantial flood events have been also observed in the floodplain of the river (southern part) where most of population and economical activities are clustered (Manfreda et al., 2014). Topography is represented through a $20\,m$ resolution DEM provided by the Istituto Geografico Militare (IGM, available online at http://www.igmi.org/). Digital maps of land use and lithological characterization were supplied by the European Environmental Agency (Corine Land Cover project) and by Italian Agency for Environmental Protection and Research (ISPRA),

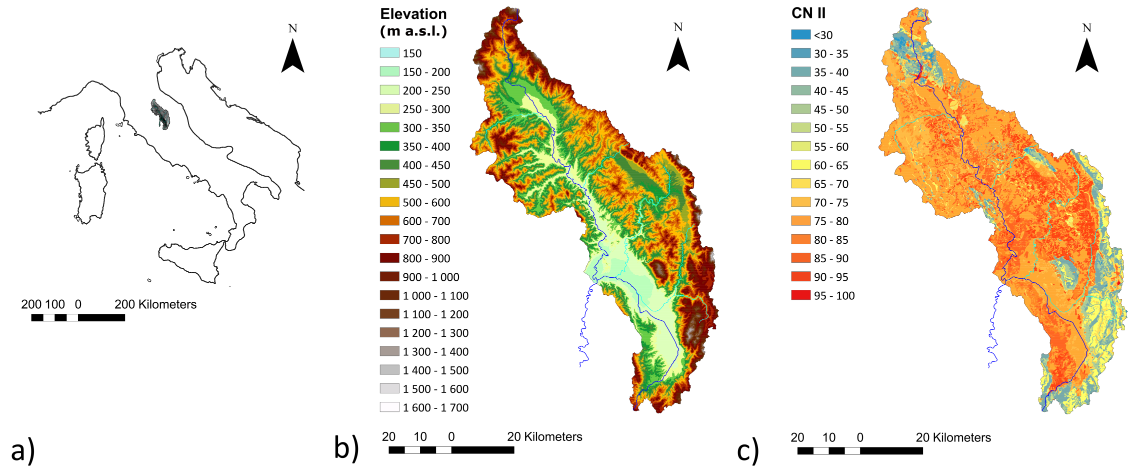

Figure 2. Maps showing: a) the location of the Upper Tiber river basin within the Italian Peninsula, b) DEM of the watershed and c) fine scale land classification according to the CN II parameter.

respectively (maps not shown). Furthermore, land use classes from Corine classification and infiltration capacity estimates were used to associate at each DEM cell a value of the Curve Number parameter (CNII, see Fig. 2c), which shall be used in the SCS-CN runoff model as described in Sect. 3.3.

3.2 Macrocell discretization, width functions derivation and perfect upscaling

The control sections adopted for multi-site model ~~calibration~~ validation (see Sect. 3.3) are located at 5 stream-gauge stations: Santa Lucia (SL), Ponte Felcino (PF), Ponte Bettona (PB), Ponte Rosciano (PR) and Ponte Nuovo (PN), with the latter being the outlet of the river basin (see Fig. 3). Drainage area (ranging between 1000 and 4000 km^2), longest flow path, and other geomorphic characteristics of the sub-catchments identified by the 5 control nodes are reported in Table 1. The control nodes are located along the main course of the Tiber river and its two major tributaries (Chiascio and Topino rivers), and they are equipped with gauges registering water levels at 30 minutes time step. Stage measurements in the period 1990-2000 together with validated stage-discharge relationships have been provided by the Hydrographic Service of Umbria Region (http://www.idrografico.regione.umbria.it). The meteorological forcing is described with half-hourly precipitation at 32 meteorological stations managed by the same institution. Fig. 3 shows a map with the locations of the meteorological and stream gauging stations together with the subdivision of the watershed into the 5 inter-basin areas.

In the following the effect of spatial discretization on the hydrologic response is analyzed with reference to macrocells of different dimensions. In particular, the study area was overlaid with macrocells of increasing size, from 1 to 150 km (the latter including the whole Upper Tiber river basin

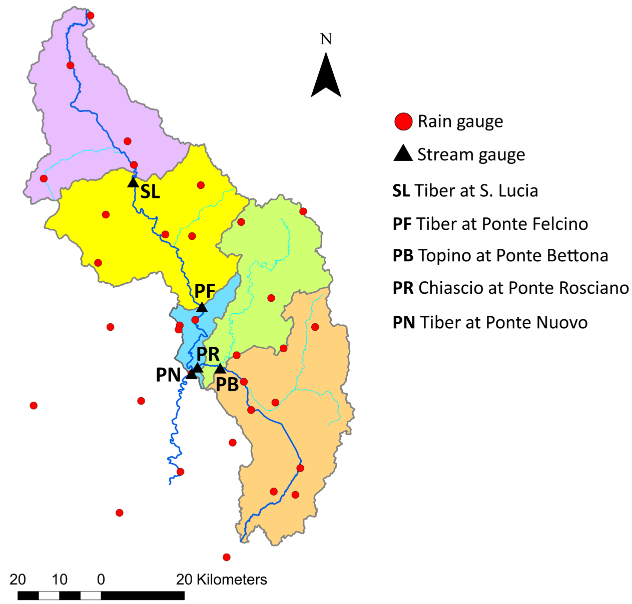

Figure 3. Map showing the subdivision of the watershed into 5 inter-basins, each one identified by a node where water discharge is computed (black triangles). The location of the meteorological stations are also shown as colored dots.

within a single macrocell), and corresponding to about $37''$ and $1^o 36'$, respectively. Domain discretization with macrocells of 5, 10 and 50 km are shown as an example in Fig. 4.

~~Identification~~ The identification of the drainage network and associated geomorphic metrics was performed by adopting standard DEM pre-processing techniques. In particular, the identification of the flow path lengths involved the following steps: (i) pit and flat area removal following the procedure of Tarboton et al. (1991); (ii) determination of the drainage directions by using the standard single direction D8 algorithm (O'Callaghan and Mark, 1984); (iii) ~~identification~~ calculation of the space filling tree network, which connects each site to the outlet; (iv) definition of channel initiation, by adopting a combination of the threshold-slope area and the threshold-support area criteria (Di Lazzaro, 2009).

For a given resolution of the macrocell grid, it is thus possible to derive the frequency distribution $\cancel{f^{(i)}_{\ell k}}$ $f^{(i)}_{k}$ of the flow path lengths $L^{(i)}_{\ell k}$ pertaining to macrocell i and connecting the hillslope-channel transition site of the hillslope ℓ to the control node k (i.e., the macrocell-node specific width functions introduced in Section 2), which is the best possible approximation of the width function, given the scale of the DEM.

Fig. 4 shows as an example width functions constructed at the Santa Lucia node (upstream node on the main river-course, see Fig. 3), for ~~macrocell size of~~ a few macrocells of size 5 km~~(panel a)~~, 10 km~~(panel b)~~ , and 50 km~~(panel c)~~, respectively. ~~We observe that the distribution of path lengths is wider for larger macrocells, because more hillslopes contributing to the node are included into~~

~~the same macrocell, such that a larger portion of available path lengths is sampled. When a single macrocell is used, containing the entire catchment, all the hillslopes are included and the macrocell width function coincides with~~ When the macrocell is small with respect to the sub-catchment, its width function is narrow, since it includes a reduced number of hillslopes. Conversely, when the macrocell is large enough to cover the entire sub-catchment, its width function tends towards that of the ~~catchment.~~ sub-catchment. The first case is approached by the discretization with macrocells of 5 km (left panels in Fig. 4). The width functions of three selected macrocells, identified with different colors, are all narrow and centered around a varying median value. On the other hand, when the ~~macrocell coincides with the cell of the DEM the distribution of the lengths reduces to a Dirac delta~~size of the macrocell grows to 50 km (right panels in Fig. 4), most of the hillslopes are contained into the macrocell colored in yellow, whose width function is close to that of the entire sub-catchment (see the grey line in the bottom panel). The intermediate 10 km discretization produces consistent results, showing wider width functions, with less variable median values with respect to the 5 km discretization. This is consistent with the underlying rationale of the model, which is intended to keep the geomorphologic component of dispersion as it is derived from the finest scale description of topography at hand (i.e., the DEM scale), even when runoff generation processes are represented at a larger scale (e.g., to comply with the output of climate models). When all the width functions of the macrocells contributing to the SL node are combined (i.e., 57, 19 and 2 macrocells for 5, 10 and 50 km, respectively), the global width functions are exactly the same for the three discretizations (compare the three graphics in the lower panel of Fig. 4), thereby confirming that routing is insensitive to the size of the macrocell, as desired. Hence, upscaling of geomorphological dispersion is by construction free of errors or scale effects, in our approach. This is not the case for models in which the geomorphological description of the drainage network is performed at the same scale of the macrocells grid (see the discussion in the Introduction). To show this, in Fig. 5 we compare the width function calculated at Ponte Nuovo, the outlet of the catchment, derived from the original 20 m DEM (grey line), which in our formulation is perfectly preserved for any choice of the macrocell size, with the ~~analogous width functions derived~~ corresponding width functions obtained after DEM aggregation at 5 km (blue), 10 km (orange), and 50 km (red), respectively. The figure shows, in particular, how aggregating digital topographic information over ~~macrocells~~ areas of progressively increasing size (as inevitably occurs when routing is performed by using any cell-based scheme) results in a deterioration of the width function, and, as a consequence, of the geomorphologic response of the watershed. This is not the case in our formulation in which the width function ~~maintains all~~ preserves the information derived from the spatial resolution of the DEM, irrespective of the resolution of the adopted runoff generation model.

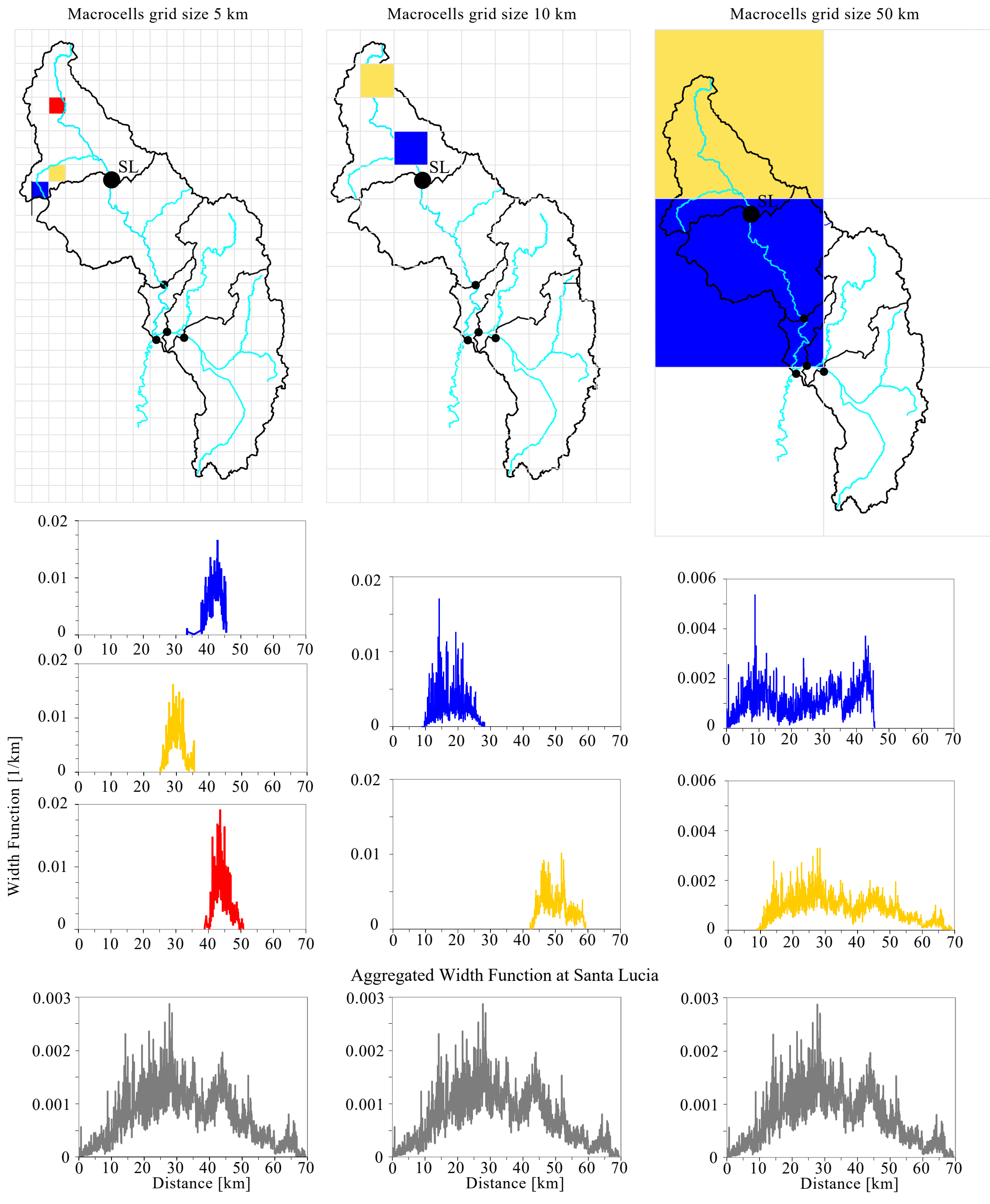

Figure 4. ~~Macrocell width~~ Width functions computed at the Santa Lucia (SL) control section for selected macrocells (colored lines) and for the whole sub-catchment (grey lines, panels at the bottom), considering grid sizes of 5 km, 10 km and 50 km. ~~Colors indicates different macrocell-node combinations~~The width function of the whole sub-catchment is by design the same for the three spatial resolutions.

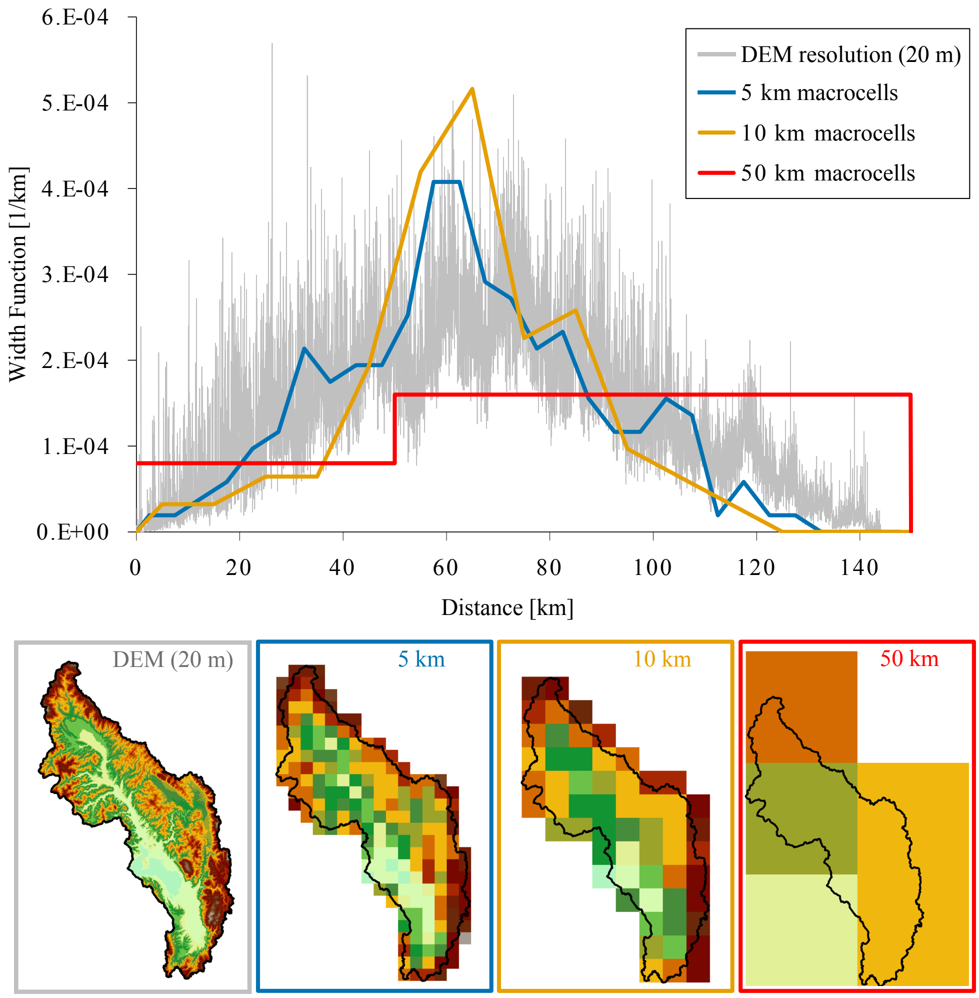

Figure 5. Width functions of the Upper Tiber river basin at Ponte Nuovo (PN) outlet (4116 km^2) obtained aggregating the original 20 m DEM to 5 (blue), 10 (orange), and 50 (red) km. The width function derived from the original 20 m DEM is also shown (grey). Aggregated DEMs with grid size of 5, 10, and 50 km are shown in the lower part of the figure.

3.3 Application example

In this section we present an example of application of ~~HydroSCAPE~~ HYPERstream for flood prediction in the Upper Tiber basin, with the purpose to illustrate its major computational and functional features. To focus on ~~routing, the rainfall-runoff model was~~ the routing scheme, the exercise has been intentionally kept as simple as possible. In particular, ~~we combined the~~ the hillslope production function has been defined by combining the widely used SCS-CN method (U.S. Soil Conservation Service, 1964) for runoff simulation with a linear reservoir model describing the travel time distribution within the hillslope (Rodríguez-Iturbe and Rinaldo, 1997, ch. 7.3). This is consistent with the notion that travel times in hillslopes are important in shaping the hydrologic response of a watershed and cannot be neglected even for large river basins, where the channeled lengths are usually much larger than the mean hillslope size (Botter and Rinaldo, 2003; D'Odorico and Rigon, 2003; Di Lazzaro and Volpi, 2011). Subsurface contribution to streamflow was not explicitly considered for this specific model configuration, which is focused on floods. As ~~an~~ a possible alternative to the linear reservoir model, a ~~hillslope scale rescaled width function can~~ rescaled hillslope width function could be used to represent the travel time distribution at the hillslope scale. In this case, rescaling may be obtained by using a hillslope specific velocity $V_\ell << V_c$.

At the hillslope scale runoff is computed by using the classic SCS-CN scheme:

$$R_i(t) = \frac{(P_i(t) - I_{a,i})^2}{P_i(t) + c_S\, S_i - I_{a,i}}\,, \tag{5}$$

where $P_i(t)$ [L] and $R_i(t)$ [L] are the cumulative rainfall and the cumulative runoff, respectively, at time t, both assumed uniform within the macrocell i. In addition, S_i [L] is the soil potential maximum infiltration (~~identified~~ defined constant within each macrocell and estimated on the basis of the map of CNII shown in Fig. 2c), $I_a = \alpha c_S S$ [L] is the initial abstraction, with $\alpha < 1$ [-] introduced to represent the initial abstraction as a fraction of the maximum infiltration, and c_S [-] is a multiplicative factor accounting for uncertainty in the identification of S.

Therefore, the effective rainfall intensity p_i [L/T] at time t can be computed as follows:

$$p_i(t) = \frac{R_i(t) - R_i(t-\Delta t)}{\Delta t}\,, \tag{6}$$

and Eq. (5) is applied at discrete times, according to the time step Δt.

The specific water flux produced by the hillslopes of the macrocell i can be obtained by applying mass conservation at the hillslope scale by considering the effective precipitation as inflow and runoff η as the only outflow (evapotranspiration can be neglected since the model is applied at the flood event temporal scale):

$$\frac{\eta^{(i)}(t) - \eta^{(i)}(t-\Delta t)}{\Delta t} = \frac{1}{\lambda}\left[p_i(t) - \eta^{(i)}(t-\Delta t)\right]\,, \tag{7}$$

where λ [T] is the mean residence time of the linear reservoir and the left hand term is the first order approximation of the time derivative of runoff $\eta^{(i)}$. Parameters α, c_S and λ were assumed uniform through the river basin, i.e., all the macrocells share the same coefficients. On the basis of preliminary analysis α was found not to be a sensitive parameter and was set to 0.08 (which is in agreement with the values found by D'Asaro and Grillone (2012)), while c_S and λ are calibration parameters, together with the channel velocity V_c. We emphasize that this simplified ~~version of HydroSCAPE~~ hydrological model obtained as the combination of HYPERstream routing scheme and the SCS rainfall excess model is event-based since it does not include a continuous soil-moisture

~~budget~~accounting module; however, this is enough for the purpose of this example application, mainly focused on flood events, which aim is to show how ~~HydroSCAPE~~ HYPERstream implements routing. As explained in Sect. 2, ~~HydroSCAPE~~ HYPERstream is not limited to this simplified implementation, yet effective for the purpose of flood forecasting, and can work with more sophisticated runoff generation schemes, offering a wide range of possibilities.

In order to illustrate model performance we selected two major rainfall events within the decade 1990-2000, that generated significant, yet not extreme, floods. The streamflow triggered by these rainfall events was compared with observational data at the 5 nodes described in section 3.1. The two events occurred in December 1992 and February 1999, respectively. In both cases precipitation was caused by humid frontal advection from the Mediterranean Sea followed by condensation due to orographic uplift (Calenda et al., 2005). ~~The~~ For the sake of simplicity, the spatial distribution of the precipitation was not retrieved from a climatic model, but was obtained by interpolation of the measurements at the available rain gauges (18 and 32 for the events of December 1992 and February 1999, respectively) by means of Kriging with External Drift (see e.g., Goovaerts, 1997). The precipitation was interpolated separately at each time step by using the same exponential semivariogram which has been obtained by analyzing offline the available data. In particular, precipitation was first calculated over a $1\,km$ resolution grid and successively aggregated at the macrocell scale, according to the resolution adopted in the simulations. We remark here that the precipitation data in input can be of any type, the reconstruction by interpolation with the kriging tool being just a simple example.

In order to test the computational efficiency of ~~HydroSCAPE~~HYPERstream, model calibration was performed generating a large number (i.e., $100,000$) of model parameter sets using the Latin Hypercube Sampling technique (McKay et al., 1979) with the following boundaries: $V_c \in [0.5, 4]$ m/s, $c_S \in [0.3, 3]$, and $\lambda \in [0.01, 1]$ d. The optimization procedure was based on the maximization of the Nash-Sutcliffe Efficiency (NSE) index (Nash and Sutcliffe, 1970) for streamflow evaluated at the outlet of the basin (i.e., Ponte Nuovo, see Fig. 3). The model was run with four spatial resolutions (i.e., 5 km, 10 km, 50 km and 150 km, see Section 3.2) with a computational time step of $\Delta t = 0.5\,h$, and calibrated on the event occurred in the period 6-12 February 1999 at Ponte Nuovo (PN) station. Results in terms of optimized parameter sets, NSE index, and computational time for the entire set of $100,000$ runs are summarized in Table 2.

In all cases, the NSE index at the calibration section (PN) assumes high values, close to one, indicating a very good model fit to the observed streamflow data. Optimal parameter sets assume similar values at all the scales, suggesting that the model is able to preserve geomorphological dispersion when the domain is discretized with macrocells of increasing dimension. This is verified also when a single macrocell of $150\ km$ resolution is used, though in this case the impossibility to reproduce the spatial variability of the rainfall (given that only a single macrocell is used the precipitation is considered uniform over the entire basin) resulted in an inaccurate description of inter-basin propagation of fluxes, as emphasized by the negative values of the NSE index averaged over all nodes. Conversely, for all the other spatial resolutions, overall NSE values between 0.56 and 0.69 was obtained. Notice that all cases with the average NSE> 0.5 are with a macrocell dimension equal or smaller than the integral scale of the precipitation, which is about 36 km (E. Volpi, Modello di struttura spaziale del campo di precipitazione, unpublished technical report, available upon request). It is therefore clear that the inaccuracies encountered with large macrocells are due to the inaccurate spatial description of the precipitation. Finally, the computational cost for 100,000 runs and for a single processor (Intel(R) Xeon(R) W5580 @ 3.20 GHz core), the code being written in Fortran 90, is shown to increase from a few seconds in the case of one single macrocell to about 10 minutes for the finer resolution (1 km, corresponding to 476 macrocells). We emphasize that the computational efforts can be reduced considerably by implementing parallel computing techniques, to which ~~HydroSCAPE~~ HYPERstream is particularly suited thanks to its inherently parallel formulation (see also Section 2).

Model validation was carried out by means of a combined multi-site, multi-event approach, and was coupled with a Monte Carlo based uncertainty analysis performed on a subset of parameter combinations sampled during calibration at PN with the 1999 flood event as observational data. This subset was identified according to a model efficiency rejection criterion that classifies as behavioral all sets of parameters with a NSE index greater than zero, resulting in $14\,958$ parameters sets and model realizations. Successively, the 95% uncertainty bands associated with the retained simulations were evaluated using the standard likelihood weighted procedure proposed by Freer et al. (1996). Results obtained for the 10 km spatial resolution configuration are presented in Fig. 6, which shows 95% prediction uncertainty bands and observed streamflow at the 5 nodes shown in Fig. 3. Simulated hydrographs obtained adopting the optimal parameter set reported in Table 2 are also shown with a continuous black line. Subplots 6a-e show uncertainty bands for the February 1999 event (the calibration event) considering all the gauging stations including PN, which was the only used in calibration. Other indicators of goodness are P- and R-factors (see e.g., Abbaspour et al., 2009), which are defined as the percentage of data bracketed by the confidence band, and the ratio between the average width of the band and the standard deviation of observations, respectively. Computed water discharge at all nodes provided high P-factor values (80% for SL and 100% for all the others), and moderate R-factor values (1.99, 2.56, 1.62, 2.87, and 3.21 for PN, PF, SL, PR, and PB, respectively). The somewhat suboptimal performance with respect to the R-factor is in part due to the decision of considering behavioral all the models with NSE> 0, instead of the typical choice of setting the threshold at NSE$= 0.5$, with the consequent reduction of the uncertainty band thus of the R-factor. Visual inspection of Fig. 6 and the above performance factors indicate that the model is able to encompass most of the observed discharges, while retaining reasonable uncertainty band amplitudes. The same analysis was performed also for the event occurred between 4 and 7 December 1992 (multi-site, multi-event validation). Results are presented in subplots 6f-i, which suggest reasonable model prediction capability (P-factor equal to 100%, 39%, 17%, 100%, and R-factor equal to 1.63, 1.47, 1.06, and 2.28, for PN, PF, SL, and PR, respectively; we note that no water discharge data were available at PB during this event), although a general tendency to underestimate the flood volume is evident. This is likely due to inherent differences between precipitation conditions (e.g., intensity, spatial distribution) during the two events and in the preceding days, which reflect into different initial soil moisture conditions that cannot be fully captured with the simple event-based SCS-CN model used here.

4 Conclusions

This work presents an innovative, multi-scale streamflow routing method based on the travel time approach. The principal aim is to develop a simple, parsimonious and computationally efficient method for modeling streamflow (and particularly floods) in large basins. The model, coined as ~~HydroSCAPE~~HYPERstream, aims at correctly reproduce the relevant horizontal hydrological fluxes across the scales of interest, from a single catchment to the whole continent. The method is based on the WFIUH theory applied to a hybrid raster-vector data structure, that allows to derive localized information on travel times and flow characteristics without the need of narrowing the resolution of the computational grid adopted for the study area. The relevant features of the model are illustrated through the modeling of two flood events in the Upper Tiber river basin (~~Central~~ central Italy), with 4 different domain discretizations, i.e., different dimensions of macrocells.

The main results of the present work can be summarized as follows.

- ~~HydroSCAPE~~ HYPERstream employs a strategy for modeling cell-scale runoff dispersivity such that the ~~catchment response~~ simulation of horizontal hydrological fluxes is independent from the grid size, which in turn is function of the resolution of the atmospheric model or the integral scale of observed precipitation ~~,~~ (in case ground-based rainfall measurements are used as in the example application provided here). In particular, the contribution of the geomorphological dispersion is ~~invariant with respect to the grid size, and the upscaling of the~~ kept invariant at all spatial scales, since in our scheme river network response ~~at the cell scale is automatically taken into account~~is derived from the morphological information embedded in the available DEM. This "perfect upscaling" characteristic of ~~HydroSCAPE~~ HYPERstream is particularly important in all cases when the catchment response needs to be accurately represented, e.g. when dealing with extreme events like floods and inundations.

- The above "perfect upscaling" characteristic allows adopting large cells, making the model suitable to large-scale models, up to the continental scale. The overall response function of the river networks will anyway be preserved, no matter the discretization.

– Computational efficiency is another relevant feature of the proposed approach. Efficiency stems from the fact that the demanding calculation of the width functions is a pre-processing, one-time effort. Furthermore, the model is prone to parallelization, stemming from the linearity of routing and independency of the ~~streamflow generation modules~~ runoff generation module adopted at the cell scale. These features make ~~HydroSCAPE~~ HYPERstream an appealing tool for uncertainty assessment of the predictions, and for simulations conducted in a Monte Carlo framework.

– The routing component of the model (including hillslope routing) depends on two parameters, ~~while the model inherits the parameters introduced in~~ with the additional parameters inherited from the conceptual model of runoff generation adopted at the hillslope scale. While in principle no limitations are posed to the latter conceptualization, we are in favor of a pragmatic “downward‘” approach, which limits the total number of parameters, to reduce uncertainty and ~~overparametrization~~overparameterization. Parsimony is important for a meaningful and reliable parameter estimation procedure and uncertainty analysis~~, especially when dealing with large-scale and complex basins~~.

We believe that all of the above characteristics make of ~~HydroSCAPE~~ HYPERstream an appealing routing tool to be implemented in LHMs, particularly suitable for climate change impact studies where the accuracy of the streamflow routing may be significantly affected by the spatial resolution adopted.

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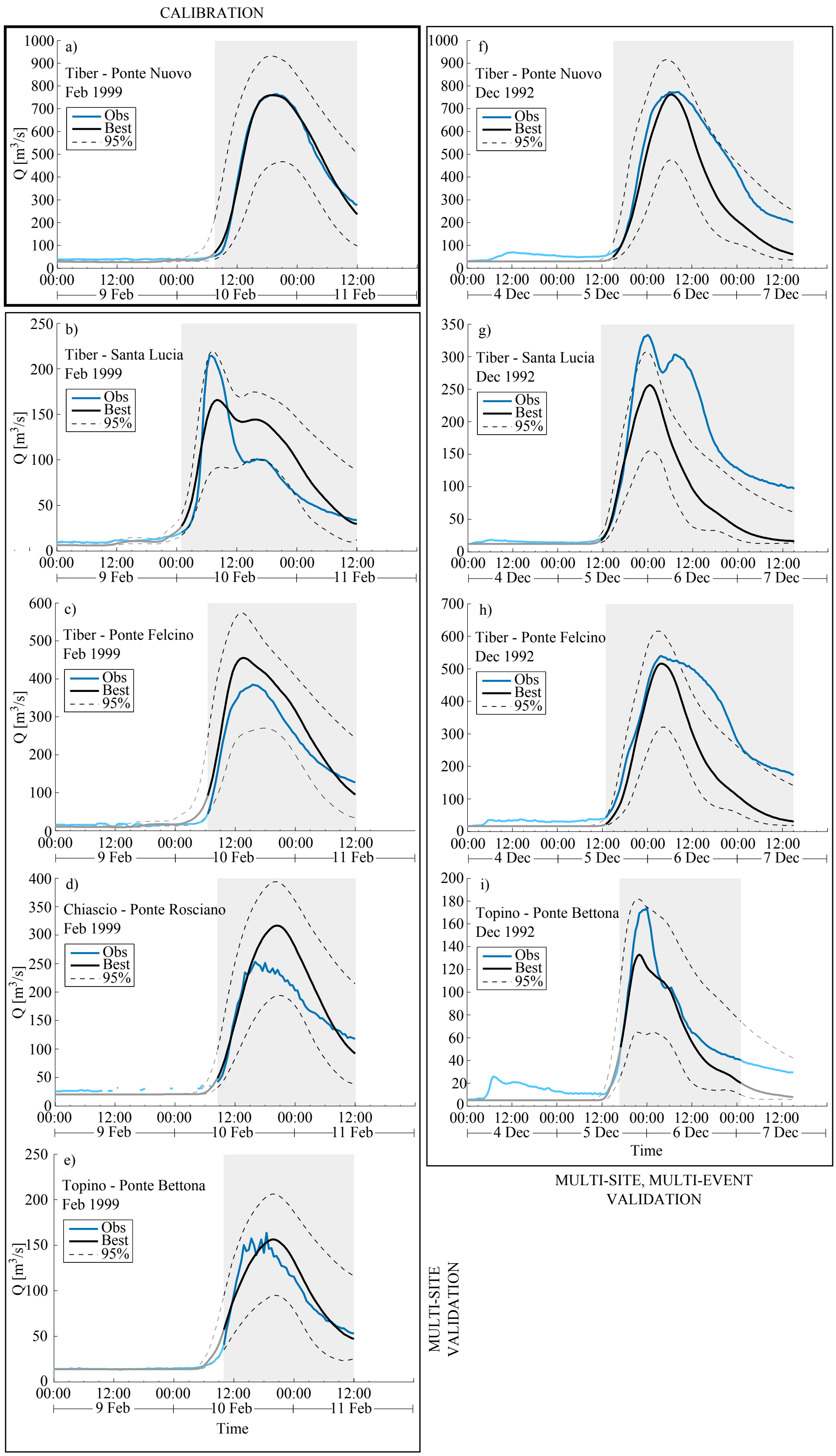

Figure 6. Comparison between 95% confidence band, water discharge simulated with the optimal parameter set and observed at all the gauging stations and events: subplots a-e 6-12 February 1999, and subplots e-i 4-7 December 1992. Shaded areas identify the period considered in the evaluation of P- and R-factors. Model

Table 1. Main geomorphic characteristics of the inter-basin drainage areas within the Upper Tiber river basin (CV: Coefficient of Variation).

Basin	ID	Area	Slope	Channel Length Statistics			
		[km^2]	[m/m]	Max [km]	Mean [m]	Variance [m^2]	CV [m/m]
Tiber at Santa Lucia	SL	932	0.009	66.1	32482	2.03E+08	0.44
Tiber at Ponte Felcino	PF	2032	0.005	112.6	60201	6.97E+08	0.44
Topino at Ponte Bettona	PB	1180	0.009	65.1	37495	2.41E+08	0.41
Chiascio at Ponte Rosciano	PR	1909	0.007	92.9	48477	4.74E+08	0.45
Tiber at Ponte Nuovo	PN	4116	0.005	139.6	67410	8.84E+08	0.44

Table 2. Optimal model parameters, calibrated at Ponte Nuovo station (event February 1999), Nash-Sutcliffe efficiency indexes for Ponte Nuovo and all nodes, and computational time cost (for 100,000 runs) resulting from the calibration procedure, for different spatial scale resolutions (size of the macrocell).

Spatial scale	n. macrocells	V_c [m/s]	c_s [-]	λ [d]	NSE [-] (PN)	NSE [-] (all nodes)	comp. time $[min]$
5 km	476	2.18	1.23	0.30	0.99	0.64	10.2
10 km	126	2.19	1.17	0.29	0.99	0.69	3.00
50 km	6	2.43	1.05	~~0.30~~ 0.29	0.97	0.56	0.44
150 km	1	2.26	0.83	0.22	0.94	-0.69	0.22