Geosci. Model Dev. Discuss.,
https://doi.org/10.5194/gmd-2019-354-AC2, 2020

Geoscientific Model Development Discussions

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Interactive comment on "Solver for Hydrologic Unstructured Domain (SHUD): Numerical modeling of watershed hydrology with the finite volume method" *by* Lele Shu et al.

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Received and published: 12 March 2020

Thank the reviewer for these helpful comments concerning my manuscript entitled "Solver for Hydrologic Unstructured Domain (SHUD): Numerical modeling of watershed hydrology with the finite volume method". These comments are all valuable and very helpful for revising and improving my paper, as well as the important guiding significance to my research. We have studied comments carefully and have made corrections, which we hope to meet with approval.

Comments by the anonymous reviewer are pasted here in bold font; our answers are given in normal font.

Comment 1: It is not until well into the paper (section 4.1) that we learn what distinguishes SHUD from PIHM. Barring this information, this paper would be merely a "reference manual" for a model developed many years ago. It might be a good idea to convey from the outset that SHUD has many improvements and added features relative to PIHM.

I added a brief history of PIHM and relation to the SHUD model, and then explain the differences of the new model with the original PIHM in the last section.

The conceptual structure of the two-state integral-balance model for soil moisture and groundwater dynamics was devised by (Duffy, 1996), in which the partial volumes occupied by unsaturated and saturated moisture storage were integrated directly upon local conservation equation. This two-state integral-balance structure simplified the hydrological dynamics while preserving the natural spatial and temporal scales contributing to runoff response. Brandes et al. (1998) use FEMWATER to realize the numeric experiments of inflow/outflow behavior within a hillslope-stream scheme. In 2004, Qu (2004) embedded the evapotranspiration and river network, and released Penn State Integrated Hydrologic Model (PIHM) v1.0, which was an important milestone integrating the two-state soil moisture-groundwater process with 2-D surface overland and channel flow. Since PIHM v1.0 (Qu, 2004), the PIHM code became a generic, fully-integrated hydrological model applicable to watersheds and river basins. After that, PIHM v2.0 (Kumar et al., 2009; Kumar and Duffy, 2009) enhanced the land surface modeling and adapted the input/output to accept national geospatial soils data. A GIS-tool, PIHMgis(Bhatt et al., 2014) and the Essential Terrestrial Variables Data Server (HydroTerre Leonard and Duffy (2013)) dramatically facilitated rapid the model deployment and applications with PIHM. Because of the sophisticated hydrological modeling and efficient spatial representative of PIHM, various model coupling project initialized. For example, Flux-PIHM coupled the NOAH Land Surface Model into PIHM to calculate more details in energy balance and evapotranspiration (Shi et al., 2015, 2014). Zhang et al. (2016) coupled a landscape evolution model with PIHM

(LE-PIHM). Bao (Bao, 2016; Bao et al., 2017) coupled a reactive transport module with PIHM (RT-PIHM, RT-Flux-PIHM). Flux-PIHM-BGC (Shi et al., 2018) coupled an ecological biogeochemistry code into Flux-PIHM. The Multi-Module PIHM (MM-PIHM) project (https://github.com/PSUmodeling/MM-PIHM) planned to build a uniform repository for all coupled modules. Still, more PIHM coupling projects are ongoing, such as sediments, lakes, crops, etc.. In addition, a finite volume-based integrated hydrologic modeling (FIHM) was developed (Kumar et al., 2009), which used second-order accuracy and solved 2D unsteady overland flow and 3D subsurface flow. Figure 1 shows the family tree of PIHM and SHUD. Every revision/branch received cross-pollination from others. Although PIHM and SHUD share the same fundamental conceptual model for process integration, the input/output and internal algorithms for each process have been completely re-designed to improve the efficiency of the code execution and allowing improved solution speedup and much larger domains at high resolution. Details of differences between them are summarized in the last section of this paper.

Figure 1 The family tree of PIHM and SHUD. PIHM and SHUD share the same fundamental conceptual model but use different realization. The PIHMgis and SHUTtoolbox are GIS-tools for pre- and post-processing.

Comment 2: To help the reader appreciate the evolution of the model from PIHM towards SHUD (there was a FIHM model at some point as well, I believe), it would be useful to cite some of the papers that represent key development stages of the modeling framework and significant applications.

Thank you for integral-balance the suggestion. I added a paragraph in the first section, briefly describing the history of PIHM and the coupled modules of the PIHM model. That explains the development of PIHM and why I name the new model as SHUD.

Comment 3: The paper is also lacking in citations (and accompanying contextualization with respect to PIHM/SHUD) of physics-based, distributed, integrated, surface-subsurface hydrologic models (ISSHMs) that are perhaps in many ways

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Discussion paper

more similar (relevant) to PIHM than some of the models that are cited in the paper (VIC, HEC, HBV, SWAT, ...).

You are right that some of the models (VIC, SWAT, HBV) are different from PIHM-like integrated hydrological models. I cited the inHM, tRIBs, and PAWS are similar integrated hydrological models with coupled numeric methods. PAWS uses the Finite Difference Method. The rRIBS and inHM also use triangular mesh, and they both utilize the Finite Element Method. I plan to make a model comparison of various modeling scenarios to see the differences among them.

Comment 4: The model is described as multi-scale but the actual physical scale most suited for application of the model, if there is one, is not really made clear.

The model is applicable from microscale (sandbox) to a regional scale (large basin). An ongoing simulation of SHUD is on Sacramento Watershed with an area of $\sim 700,000km^2$. Namely, the applicable area of the SHUD model ranges from the hill-slope scale $\sim 100m^2$ to 10^6km^2. We are currently advancing the model with HPC applications.

Comment 5: I don't think the (very long) nomenclature is needed for this paper. Describing each variable (and its units) when it first appears should be sufficient.

I moved the nomenclature to the appendix. That explains the meaning of symbols and make the paper readable.

Comment 6: The paragraph from lines 164 to 169 seems out of place. It can perhaps be merged with the first paragraph of the Intro?

We rephrased this paragraph and merged it into the first paragraph in the revision.

Comment 7: There is a tendency in the paper to justify some of the key assumptions underlying the model as being perfectly reasonable (e.g., lines 211, 214, and 230-231), whereas of course reality is much more complex and some of

these assumptions may actually represent serious limitations of the model. The authors should maybe try to be a bit more nuanced regarding the key assumptions behind the model.

Thanks for this suggestion. We rephrased the assumptions and gave more practical options upon them. As every model has its own assumptions, we thought it is useful to explicitly explain the assumptions rather than users summarize based on the equations, simulations, or codes.

Comment 8: There is missing information for the Bergstrom reference.

This reference is a technical report. I added the publisher.

Comment 9: The (insanely!) long list of authors for the Bloschl reference is made even longer by repeating the entire list from Duthmann onward.

That is true. That is a very long name list. I change the name list to "Bloschl, Günter and Bierkens, Marc F.P. and et. al.", which makes a shorter list.

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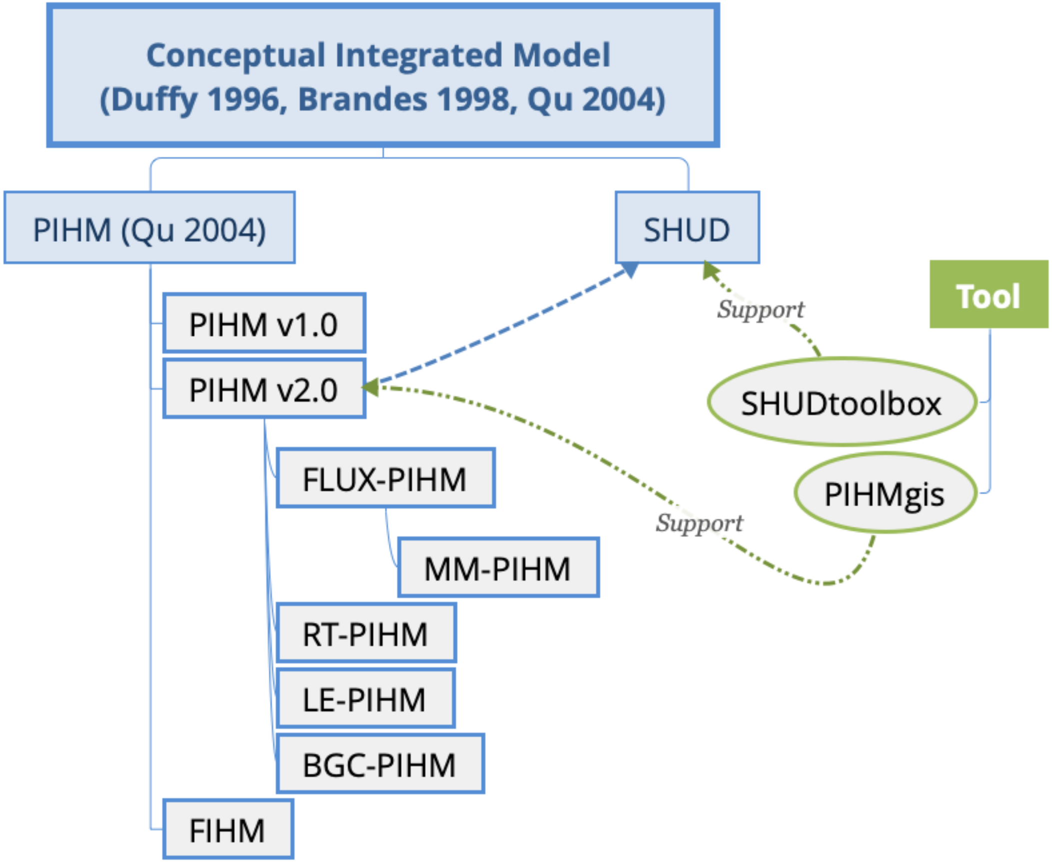

Fig. 1. The family tree of PIHM and SHUD. PIHM and SHUD share the same fundamental conceptual model but use different realization. The PIHMgis and SHUTtoolbox are GIS-tools for pre- and post-processing.