1 ~~Spatially~~ A spatially hybrid hydrological modeling approach

2 based on spatial heterogeneity of watershed characteristics

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Abstract:

~~Hydrological modeling with a uniform~~The model structure of a hydrological model is primarily determined by the spatial discretization scheme and the representation of hydrological processes. Using a spatially consistent model structure is often unreasonable for complex watersheds with significant spatial heterogeneity. ~~For such a situation, a reasonable way is~~ Hydrological modeling framework is a powerful tool to integrate multiple ~~hydrological~~ model structures, each tailored to a specific area ~~in~~of the watershed ~~of interest. While some pioneering hydrological modeling~~. The state-of-the-art frameworks ~~have enabled such integration of different hydrological model structures, they have primarily focused on~~only support lumped ~~and~~ conceptual ~~models. The absence~~model structures and do not support model structures composed of spatially explicit distributed units and physically-based ~~models in such integration limits the capabilities of those frameworks to represent the spatially heterogeneous hydrological processes in detail. This~~simulation algorithms. To fill this gap, this paper ~~proposes~~proposed an innovative spatially hybrid hydrological modeling approach ~~based on a divide-and-conquer idea. In this approach,~~where compatible spatial units and simulation algorithms can be combined to construct different model structures for each subbasin within the watershed ~~is initially divided into model structure allocation units (MSAUs) at the subbasin level. Individual model structure can be flexibly composed of conventional~~such as lumped conceptual and distributed physically-based ~~models, and then allocated to MSAU deemed suitable. Finally, these~~ model structures ~~at MSAU level are~~. Model structures in each subbasin can be integrated ~~into a spatially hybrid~~to perform the entire watershed ~~model~~simulation. The proposed approach is implemented ~~through~~by extending the Spatially Explicit Integrated Modeling System (SEIMS~~). A~~) and evaluated by a case study ~~was conducted~~ in a medium-sized ~~natural watershed in~~headwater of the Heihe River Basin, China~~, where two~~. Two distinct model structures~~, containing the components from both lumped conceptual model and distributed physically-based model,~~ were ~~integrated into a~~

~~spatially hybrid model, so~~designed to ~~evaluate~~ construct the spatially hybrid hydrological model of the ~~effectiveness of the proposed approach.~~study area: a lumped conceptual model structure for gently sloping subbasins and a distributed physically-based model structure for mountainous subbasins. The two model structures were also separately used to build two spatially consistent hydrological models for comparison. Experiment results ~~demonstrate~~showed that the spatially hybrid ~~hydrological~~ model ~~integrated using the proposed approach~~structure could harness the strengths of both model structures on the simulation performance. This approach holds promise for improving the rationality of hydrological modeling in watersheds with significant spatial heterogeneity~~ thus benefiting watershed research and decision supporting~~.

Highlight

- We proposed ~~a~~ an approach for spatially hybrid ~~structure approach for~~ hydrological ~~modeling~~model structure.

- Model structures ~~are spatially varied and~~ can be flexibly constructed in ~~the~~ ~~approach~~subbasins and then integrated.

- ~~The approach is~~We implemented ~~based on extensions to~~the approach by extending SEIMS as an example.

- The spatially hybrid model structure outperformed two ~~conventional uniform~~ ~~models~~spatially consistent ones.

1 Introduction

Hydrological models provide an effective way to simulate and understand complex hydrological processes in real-world watersheds. ~~A variety of~~Various hydrological models ~~exist~~have been developed, with each suitable for different ~~modeling requirements dictated by the unique~~ application contexts according to watershed characteristics ~~of a watershed and~~, available data, and other factors (Beven, 2000; Gharari et al., 2021; Wagener et al., 2001). ~~This suitability is fundamentally shaped by~~ Hydrological models can be classified from two perspectives that define the model ~~structures they adopt. The structure of most hydrological models encompasses two aspects:~~ structure: the spatial discretization, scheme (i.e., lumped and semi- or fully-distributed models) and the representation of hydrological processes ~~representation.~~(i.e., conceptual and physically-based models) (Chow, 1988; Milad et al., 2012; Dingman, 2015; Hrachowitz and Clark, 2017). The determination of an application-specific model structure, which involves deciding the suitable spatial discretization scheme and hydrological process representations, stands as the primary and critical step in hydrological modeling (Butts et al., 2004; David et al., 2022; Pilz et al., 2020; van Esse et al., 2013).

The spatial discretization scheme refers to the organization of one or several types of spatial units within the watershed for hydrological modeling deriving from spatial data including terrain, land use, soil, and others (Dehotin and Braud, 2008). Spatial units for lumped hydrological models typically ignore or broadly describe the spatial heterogeneity of watershed characteristics using dominant geographic attribute space, such as the dominant hydrological response unit (HRU) (DominantHRU for short, i.e., HRUs defined by dominant soil types, land use types, and slope classes within each subbasin; Arnold et al., 2010). In this regard, the entire watershed or subbasins could also be defined as DominantHRU for lumped hydrological models. In contrast, spatial units of semi- or fully-distributed hydrological models can fully cover the entire geographic spatial space of the watershed with different detailed levels,

98   such as HRU defined by unique combinations of selected geographic attributes

99   (FullHRU for short and one HRU may consist of several spatially separated areas;

100   Dile et al., 2016), spatially explicit HRUs (ExplicitHRU for short and each HRU is a

101   spatially independent and continuously area; Teshager et al., 2016), fields or patches

102   (Tague and Band, 2004), and grid cells (Wigmosta et al., 1994). ~~involves simulating~~

103   ~~hydrological~~It is noted that the HRU is actually a broad term that can be specifically

104   defined as lumped units (DominatHRUs), semi-distributed units (FullHRUs), and

105   fully-distributed units (ExplicitHRUs). From this perspective, the widely used SWAT

106   (Soil and Water Assessment Tool; Arnold et al., 1998) model can be used as a lumped

107   or semi-distributed hydrological model according to different HRU definitions.

108   However, it cannot be a fully-distributed model since it does not consider lateral flow

109   processes between HRUs.

110   The representation of hydrological processes denotes the simulation algorithms

111   abstracting the real-world hydrological processes (e.g., evaporation, infiltration, and

112   ~~channel~~surface and subsurface flow routing) ~~on specific spatial units (e.g., the entire~~

113   ~~watershed, subbasin, channel lines, and grid cells). Meanwhile, the hydrological~~

114   ~~process representations, which encapsulates the translation of real-world hydrological~~

115   ~~processes into simulation algorithms, involves the selection of~~using different

116   mathematical equations, numerical solutions, ~~and the temporal scale (e.g., annual,~~

117   ~~monthly, daily, and hourly) of simulation.~~temporal scales, and spatial units. A

118   conceptual representation would simplify the hydrological processes within a

119   watershed as three basic processes, which are water storage, water loss, and flow

120   routing processes, based on conceptual reservoirs (also called buckets), such as the

121   linear method or two-reservoir method for runoff prediction. The parameters of such

122   conceptual representations often lack explicit physical meanings (Fenicia et al., 2011;

123   Knoben et al., 2019). In contrast, a physically-based representation uses known

124   scientific principles to model water movements in vertical or lateral directions by the

125   partial differential equation representing the mass, momentum, and energy balance

126 that solved by finite difference approximations or empirical equations (Abbott et al.,

127 1986), such as the Richards' equation or kinematic wave method for infiltration

128 (Graham and Butts, 2005). The rigorous physically-based models with partial

129 differential equations for water movement such as the MIKE SHE (Systeme

130 Hydrologique Europeen; Graham and Butts, 2005) often faces challenges of data

131 requirements and computational complexity. Most physically-based models today,

132 such as the SWAT (Arnold et al., 1998), TOPMODEL (TOPography based

133 hydrological MODEL; Beven and Kirkby, 1979), and WetSpa (Water and Energy

134 Transfer between Soil, Plants and Atmosphere; Wang et al., 1996), also use empirical

135 formulations based on simplified representations of physical principles and adhere to

136 mass and energy balance. Parameters (especially terrain and soil attributes) used in

137 such physically-based models primarily have clear physical meanings and may be

138 derived from field measurements. Therefore, ~~the selection of an application-specific~~

139 ~~model structure stands as the primary and critical step in hydrological modeling, as~~

140 ~~implied in many model structure evaluation researches (Butts et al.,~~ we regarded

141 "physically-based" as a broad term in this study. ~~2004; David et al., 2022; Pilz et al.,~~

142 ~~2020; van Esse et al., 2013).~~

143   ~~The~~Existing methods of determining model ~~structure determined for a~~

144 ~~watershed~~structures can be categorized ~~into two types, i.e., the uniform model~~

145 ~~structure, and the~~ as spatially consistent method and spatially varying method. The

146 spatially consistent model structure~~, according~~ means the types of spatial units (also

147 referred to ~~whether they~~as simulation units) and simulation algorithms of hydrological

148 processes are ~~spatially varying within~~ the same for the whole watershed ~~of interest~~.

149 Most research on directly ~~choose an~~choosing a single existing hydrological model

150 with a fixed or near-fixed model structure ~~which is uniform for the whole study~~

151 ~~area.~~fall into this category. Such ~~a~~model ~~as well as its model structure~~structures are

152 often developed with specific assumptions and ~~intended~~suitable for ~~application in~~

153 constrained ~~catchment characteristics. Examples of such single models~~

includeapplication contexts. They vary from lumped to distributed spatial discretization schemes, and from conceptual to physically-based representation of hydrological process, such as HBV (Hydrologiska Byråns Vattenbalansavdelning; Lindström et al., 1997), GR4J (modèle du Génie Rural à 4 paramètres Journalier; Perrin et al., 2003), SWAT (Arnold et al., 1998), TOPMODEL (Beven and Kirkby, 1979),, SWAT, RHESSys (Regional Hydro-Ecologic Simulation System; Tague and Band, 2004), and DHSVM (Distributed Hydrology Soil Vegetation Model; Wigmosta et al., 1994). Adopting a spatially consistent model structure assumes that the spatial variability of watershed characteristics can be sufficiently represented by input data and model parameters required by the determined model structure. Wigmosta et al., 1994). Nevertheless, it is recognized that the uniformfixed or near-fixed model structure lacks flexibility in changing simulation units or customizing alternative simulation algorithms of considered hydrological processes and thus. Thus, it cannot accommodate watershed applications under diverse circumstancesand complex application contexts (Ley et al., 2016; Savenije, 2009).

To accommodate complex application contextcontexts with flexibility in controllingdetermining the model structure compositions, researchers have increasingly turned to modular hydrological modeling frameworks, such as SUMMA (Structure for Unifying Multiple Modeling Alternatives; Clark et al., 2015), ECHSE (ECo-Hydrological Simulation Environment; Kneis, 2015), SUMMA (Clark et al., 2015), MARRMoT (Modular Assessment of Rainfall–Runoff Models Toolbox; Knoben et al., 2019), SEIMS (Spatially Explicit Integrated Modeling System; Liu et al., 2016; Zhu et al., 2019), and RAVENRaven (Craig, 2020). These frameworks have been developed to integrate the compositions of multiple existing models, allowing for easilyfocus on different perspectives of flexibility in customizing application-specific model structures. It is typical that each of the interdependent modules within a hydrological modeling framework simulates a specific, such as extensible types of simulation units and associated simulation algorithms (Kneis,

2015), alternatives of simulation algorithms of each specific hydrological process

(Zhu et al., 2019), and alternatives of simulation algorithms of each conceptual part of

~~the~~ hydrological processes~~, and there are often multiple alternative algorithms for~~

~~simulating one hydrological process.~~ (Craig, 2020). These ~~modeling~~ frameworks ~~well~~

~~support~~ provide supports for the concept of "multiple working hypotheses"~~, as~~

~~advocated by Clark et al. (2011). However, it is important to note that~~ (Clark et al.,

2011), facilitating studies including the suitability and uncertainty of different model

structures (David et al., 2022; Kiraz et al., 2013; Knoben et al., 2020). The focus of

these ~~modeling~~ frameworks is primarily ~~emphasize the application of~~ customizing and

applying a ~~uniform~~ consistent model structure across the ~~entire application area, with~~

~~spatial variability confined to input data and model parameters. This way assumes that~~

~~spatially heterogeneous data and parameters are sufficient to capture the behavior of~~

~~hydrologic processes, while the model structure remains spatially uniform. While~~

~~such a modeling way with spatially uniform model structure yields satisfactory results~~

~~in many applications, the uniform~~ whole watershed. However, the spatially consistent

model structure may be unreasonable and inaccurate to capture the characteristics of

the dominant hydrological processes when the application context ~~(i.e., the watershed~~

~~characteristic or data availability) exhibit~~ exhibits significant spatial heterogeneity~~.~~

(Gao et al., 2018; Sui and Turner, 2021).

Recognizing the limitation of ~~the uniform-structure modeling approach, some~~

~~approaches~~ utilizing spatially consistent model structures, researchers have explored ~~to~~

~~construct~~ constructing spatially varying model ~~structure~~ structures within the watershed

~~under simulation. These approaches are mainly based on one of the~~ in two ~~different~~

~~ideas:~~ ways. The first is externally integrating multiple individual models manually

(Liu et al., 2020; Li et al., 2021; Wang et al., 2021) or through a unified model

interoperable interface~~, and internally integration within a hydrological modeling~~

~~framework. Examples of the external integration are the works of Liu et al. (2020), Li~~

~~et al. (2021), and Wang et al. (2021), as well as those works done through model~~

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~~integration frameworks~~ such as ESMF (Earth System Modeling Framework; Hill et al., 2004) and OpenMI (Open Modeling Interface; Harpham et al., 2019). ~~What they~~However, the flexibility of such model-level integration may be limited because each integrated ~~are commonly individual models that simulates entire~~ hydrological ~~processes, from rainfall to runoff. However, as a great deal of~~model has fixed or near-fixed model structures. Besides, different interoperable interfaces often need to be implemented ~~to integrate a model, the flexibility of the external integration may be~~ ~~limited. The structures constructed in this way are often fixed, and once the integrated~~ ~~model is established, it will require further coding efforts to change the spatial~~ ~~constitution of the model structure, which is difficult and inconvenient for most~~ ~~hydrologists~~for each hydrological model to be integrated, making it challenging for hydrologists without programming skills.

To augment the ~~modeling~~ flexibility of spatially varying model ~~structure, several~~ ~~studies suggested~~structures, the ~~internal integration approach based on the~~other idea was to internally construct and integrate multiple model structures within one modular hydrological modeling framework such as FLEX-Topo (Topography-driven Flux Exchange hydrological model; Gao et al., 2014; Savenije, 2010), SUPERFLEX (SUPER Flux Exchange hydrological model; Fenicia et al., 2011, 2016), and airGR (suite of GR Hydrological Models; Coron et al., 2017; Thébault et al., 2023).~~frameworks.~~ In this ~~approach~~way, model structures can be distributed to different modeling areas in the watershed~~,~~ with only minor ~~change~~changes in configuration or ~~the main functions. This approach has been exemplified by works~~ ~~based on the FLEX-Topo framework (Gao et al., 2014; Savenije, 2010),~~ ~~SUPERFLEX framework (Fenicia et al., 2011, 2016), and airGR framework (Coron et~~ ~~al.,~~ source code. ~~2017; Thébault et al., 2023).~~ Nevertheless, ~~the hydrological~~ modeling frameworks employed in these studies are inherently limited to conceptual ~~hydrological process representations, and their spatial discretization is also confined~~ ~~to subbasins or hydrologic response units (HRUs). Such a constraint on model~~

238 ~~structure poses~~representations of hydrological processes, with the simulation units

239 being only subbasins, DominantHRUs, or FullHRUs. Therefore, these state-of-the-art

240 flexible frameworks only support lumped or semi-distributed conceptual model

241 structures and thus face a substantial challenge when attempting to integrate ~~and~~

242 ~~utilize distributed and~~ physically-based ~~models or~~simulation algorithms ~~based on~~and

243 spatially explicit distributed simulation units, such as grid cells ~~or~~and patches, where

244 the spatial relationship between units are kept to enable the execution of physically-

245 based hydrological process representation.

246 ~~As~~To address the ~~state-of-the-art flexible approach to achieving spatially varying~~

247 ~~model structure,~~ inability of existing ~~internal integration studies based on modular~~

248 hydrological modeling ~~framework only~~ frameworks to support ~~lumped and conceptual~~

249 ~~model structures. This inability of framework in supporting~~ distributed ~~and~~

250 physically-based model structures ~~limits the flexibility and applicability during~~

251 ~~hydrological experimentation, comparative analyses, and applications pertaining to~~

252 ~~diverse model structures. To relieve such an inability~~in a spatially varying manner,

253 this paper ~~proposes~~proposed a novel spatially hybrid ~~hydrological~~ modeling approach

254 ~~by enabling the spatial allocation of various.~~ In this new approach, compatible types

255 of simulation units and simulation algorithms,~~ comprising both~~ can be combined to

256 construct different model structures for each subbasin within the watershed, such as

257 lumped conceptual and distributed physically-based ~~models, to different areas within~~

258 ~~a watershed~~model structures. Model structures in each subbasin can then be integrated

259 to perform the entire-watershed simulation. The remainder of ~~the~~this paper ~~is~~was

260 organized as follows: Section 2 ~~outlines~~outlined the design of the proposed ~~spatially~~

261 ~~hybrid modeling~~ approach and its implementation based on the SEIMS framework.

262 Section 3 ~~discusses the~~presented an experimental case study, followed by ~~presentation~~

263 ~~of~~results and discussion in Section 4, and conclusion in Section 5.

2 Method design and implementation

2.1 Basic idea

~~The~~ The basic idea of designing a spatially hybrid hydrological modeling approach is constructing and executing different model structures on relatively independent areas within the watershed in a divide-and-conquer way. Subbasins are relatively closed catchment areas connected by the watershed drainage network and thus can be regarded as the modeling unit to be configured with an individual model structure. Therefore, the core design of the ~~spatially hybrid modeling~~ proposed approach involves two aspects: ~~the first is~~ 1) the flexibility for model structure construction, which enables the combination of different spatial discretization ~~methods~~ schemes and hydrological process representations ~~across the watershed of interest; the second is~~, and 2) the ability to distribute individual model structures to ~~different areas within~~ subbasins of the watershed~~,~~ and integrate them to be executed under the same time loop.

The basic idea of designing the flexibly constructed model structure is to decouple the hydrological process representations (~~or~~ specifically, the simulation algorithms) from being bound to ~~particular~~ specific spatial discretization ~~methods~~ scheme (specifically, the simulation units). For instance, the physically ~~and process~~-based algorithms are typically applied to fine-scale simulation units such as grid cells for both are assumed to describe the hydrological process in detail. Similarly, conceptual algorithms are typically applied to lumped or coarse-scale units such as ~~HRUs~~ DominantHRUs, hillslopes, or subbasins.

Such a binding is not necessary, and conversely, the combination of ~~these~~ model structure components have been acknowledged as effective. ~~Hydrological modeling can be approached through two main paradigms: the bottom-up way, based on physical theories, and the top-down way, founded on empirical and conceptual deductions. Each of these approaches has its own set of advantages and~~

291 ~~disadvantages, depending on the circumstances (Clark et al., 2011; Hrachowitz and~~
292 ~~Clark, 2017). The fusion and compromise between the two ways could often yield~~
293 ~~advantages such as the ease of implementing, computational efficiency, and the data~~
294 ~~requirements~~, as demonstrated by various studies (Gunduz and Aral, 2005; Liu et al.,
295 2020; Sidle, 2021) and popular models such as the SWAT ~~and TOPMODEL.~~. The
296 simulation algorithms can be categorized as computationally dependent and
297 independent according to their computational characteristics between simulation
298 units. The simulation of a computationally dependent algorithm on one simulation
299 unit often relies on the water flows or state variables of its adjacent or upstream units,
300 while the simulation of computationally independent algorithm on each simulation
301 unit is independent with others (Figure 1b). Similarly, existing simulation units can be
302 categorized as spatially connected and disconnected depending on whether spatially
303 explicit relationships exist between units (Figure 1a).
304 ~~The combination of distinct simulation units and algorithms is possible when the~~
305 ~~simulation algorithms are categorized as computational independent or dependent,~~
306 ~~according to whether the interaction among adjacent or upstream-downstream~~
307 ~~simulation units is required or not. An essential constraint on the applicability of~~
308 ~~simulation algorithms is that their computational dependencies must be satisfied by~~
309 ~~the spatial relationship of simulation units provided by chosen spatial discretization~~
310 ~~method.~~Therefore, three combinations of compatible simulation algorithms and
311 simulation units can be summarized: computationally dependent algorithm with
312 spatially connected units, computationally independent algorithm with spatially
313 connected units, and computationally independent algorithm with spatially
314 disconnected units (Figure 1b). For example, the conceptual reservoir-based surface
315 runoff generation algorithm with the physically-based kinematic wave-based surface
316 routing can be integrated to be applied to grid cells, where computational dependency
317 is satisfied by the flow directions between grid cells; the physically-based ~~Richards~~
318 ~~equation-based~~Green-Ampt surface runoff generation algorithm and the conceptual

319   unit hydrograph-based surface routing algorithm can be integrated to applied on

320   HRUs, (Craig, 2020), where no computational dependency is required. Note that the

321   computational dependency is only a basic constraint, the rationality of the model

322   structure is to be determined by the modeler's knowledge and requirements. Thus,

323   diverse model structures could be formed and customized through combinations of

324   compatible simulation units and simulation algorithms under the same hydrological

325   modeling framework (Fig. 1a and Fig. 1b).
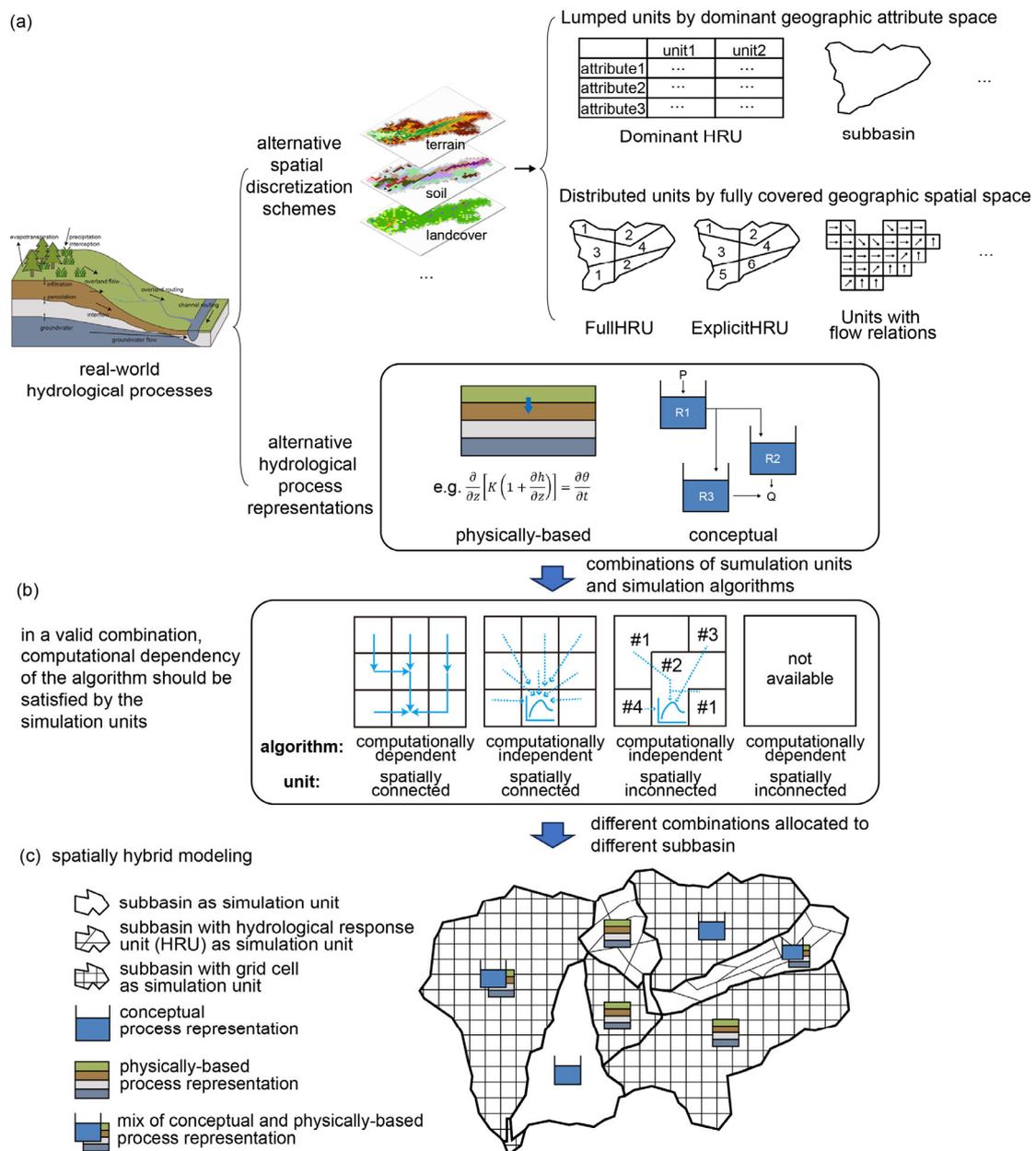
327   Figure 1. Design of the proposed spatially hybrid hydrological modeling approach,

328   which involves. a) incorporating diverse decoupling the simulation of hydrological

processes into spatial discretization ~~methods~~schemes and hydrological process
representations ~~and~~; b) supporting ~~their flexible~~ combinations ~~into model structure on
the MSAU level;~~ of compatible simulation algorithms and simulation units; and c)
enabling the spatial ~~varied~~ varying allocation of ~~these MSAU models~~different model
structures at the subbasin level.

Based on the above idea of flexible model structure construction, ~~different areas
within the watershed should then be assigned distinct application-specific model
structures and executed after integration (Fig. 1c). In~~ approach, in this study, ~~the
minimal~~ considering the spatial heterogeneity of watershed characteristics, each
subbasin unit ~~for~~ is regarded as the modeling unit to be configured with an individual
model structure (namely a subbasin model structure ~~allocation is named as a model
structure allocation unit (MSAU), which is currently defined to be coincident with the
subbasin unit. In other words, each subbasin adopts a~~) to simulate hillslope processes,
and then integrated as a watershed model through channel routing processes (Figure
1c). A subbasin model structure ~~and~~can take all ~~subbasin-level~~ hydrologic process as a
whole, or more commonly, separately consider hillslope processes and channel
routing processes. Therefore, different subbasin model structures can be constructed,
such as conceptual algorithms with subbasin as simulation unit, physically-based
algorithms with grid cells as simulation units, and a mix of conceptual and physically-
based algorithms with HRU as simulation units for hillslope process and conceptual
algorithms for channel routing processes (Figure 1c). All subbasin model structures
will collectively constitute the watershed model structure. ~~These subbasin models are
interconnected~~ by interconnecting through the ~~stream~~drainage network with upstream-
downstream relationships. The execution ~~sequence of subbasin models can be
determined accordingly. When the input requirements of all~~of a downstream ~~MSAUs
are satisfied with~~subbasin relies on the output of its upstream ~~MSAUs, the models on
each MSAUs can be integrated. Models on MSAUs~~subbasins. Thus, executions of

subbasins without ~~the~~ upstream-downstream ~~relationship~~relationships could be ~~parallelly executed,~~parallelized; otherwise~~, they must be executed~~ sequentially.

2.2 Design of the spatially hybrid hydrological modeling approach based on the hydrological modeling framework SEIMS

Following the above basic idea, the proposed spatially hybrid hydrological modeling approach ~~is~~was designed based on the ~~modular~~ hydrological modeling framework SEIMS ~~(Liu et al., 2016; Zhu et al., 2019),~~ for its flexible modular design and ~~"subbasin-simulation unit"~~ two-level parallelization strategy. ~~The detailed design of the proposed approach based on SEIMS includes two aspects (Fig. 2): (1) Enabling the construction of model structures with diverse simulation units and algorithms, which serves as the basis of the flexibility and diversity of the watershed model constructed. This requires SEIMS to be extended on the spatial discretization methods and upgrading the simulation modules to accommodate to different simulation units. (2) Enabling the spatial-varied allocation of individual model structures and their integrated execution.~~

~~Figure 2. Overall design of the spatially hybrid hydrological modeling approach based on extension to the Spatially Explicit Integrated Modeling System (SEIMS), which includes a) supporting various spatial discretization methods; b) supporting flexible application of the simulation unit to compatible simulation units; and c) supporting spatial-varied model structure allocation~~ (Liu et al., 2016; Zhu et al., 2019).~~.~~

381 ~~2.2.1 Brief introduction to~~ the modular design and parallelization strategy of

382 ~~Spatially Explicit Integrated Modeling System (SEIMS)~~

383 ~~SEIMS provides standard and concise interfaces to implement the simulation~~

384 ~~algorithms into modules, which involves hillslope process simulation modules on grid~~

385 ~~cells and channel routing process simulation modules on channel segments or channel~~

386 ~~grid cells. Each module exposes input and output information via metadata for the~~

387 ~~integration with other modules. Therefore, a list of user-configured modules~~

388 ~~comprises a SEIMS-based model in a loosely coupled manner.~~ To support the flexible

389 model structure ~~configuration required in~~construction of the proposed approach, the

390 spatial discretization ~~methods as well as the module library~~schemes of SEIMS should

391 be expanded (~~Fig.~~Figure 2a ~~and 2b; detailed in~~; Section 2.2.2~~)~~.

392 ~~The two-level parallelization strategy of SEIMS treated subbasin as relative~~

393 ~~independent spatial units for hydrological modeling dispatched to dedicated~~

394 ~~computing~~), the simulation modules of hillslope processes ~~through the Message~~

395 ~~Passing Interface (MPI). The simulation tasks on grid cells within a subbasin are~~

396 ~~dispatched among computing threads via the Open Multi-Processing (OpenMP).~~

397 ~~Although the parallelization strategy underpins the relative independence of~~

398 ~~computations within each subbasin, thereby providing the potential to apply different~~

399 ~~model structures to distinct subbasins, the simulation modules and simulation units~~

400 ~~are predefined to be uniform for the whole watershed. These modules are loaded~~

401 ~~based on a configuration text file that sequentially records the modules involved.~~

402 ~~Therefore,~~should be upgraded to accommodate compatible simulation units (Figure

403 2b; Section 2.2.2), and the execution of SEIMS-based model should be upgraded to

404 allocate different model structures to subbasins and executed ~~independently (Fig. 2c;~~

405 ~~detailed in~~in an integrated way (Figure 2c; Section 2.2.3).
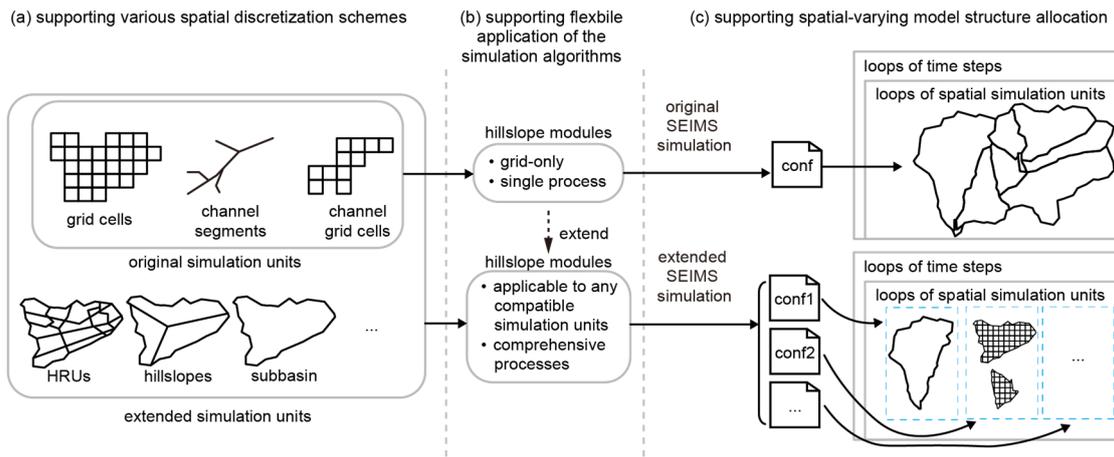
Figure 2. Overall design of extending the SEIMS (Spatially Explicit Integrated Modeling System) to implement the proposed spatially hybrid hydrological modeling approach: a) supporting various spatial discretization schemes; b) supporting applying simulation algorithms of hillslope processes to compatible simulation units; and c) supporting spatial varying model structure allocation on the subbasin level to construct a watershed model.

2.2.1 Brief introduction to SEIMS

As a hydrological modeling framework, SEIMS provides users with the complete toolchain to preprocess modeling data, construct and execute the SEIMS-based model, analyze the parameter sensitivity, and so on (Liu et al., 2021; Zhu et al., 2019). More importantly, SEIMS supports developers in adding simulation modules of hydrologic processes following the developing principles. The principles are briefly introduced in three aspects: the spatial discretization scheme, the modular modeling design, and the parallelization strategy.

(1) Spatial discretization scheme

SEIMS adopts a two-level spatial discretization scheme, i.e., the "subbasin-basic simulation unit." In the stage of preprocessing modeling data, SEIMS delineates the watershed into subbasins, each with one channel. Within each subbasin, the basic simulation units (i.e., grid cells in the original implementation) are delineated and

organized as a one-dimension array with their actual positions recorded. Most

simulation modules of hillslope processes use grid cells as simulation units, while a

few modules use subbasin units such the linear reservoir algorithm for the

groundwater process. Modules of channel routing processes use channel lines or grid

cells as simulation units. All parameters required by the modules on these simulation

units are prepared using the preprocessing scripts of SEIMS. The grid cells are

layered within each subbasin based on the flow direction of each cell (i.e., the single

flow direction in the original implementation; Liu et al., 2014). The layers are used in

modules of hillslope surface or subsurface flow routing processes to determine the

simulation sequences of grid cells. The same idea is used for layering subbasins (i.e.,

channels).

(2) Modular modeling design

A SEIMS-based hydrological model is constructed by the SEIMS main program

and several user-configured modules of hydrologic processes in a text-based format

rather than hard-coded. The main program controls the time loop of the simulation

and repeatedly invokes the modules in sequence. Each module is responsible for the

simulation of one or several hydrologic processes on corresponding simulation units

in different orders. For example, the potential evapotranspiration module executes on

every grid cell in an arbitrary order, the subsurface flow (also referred to as interflow)

routing module executes on every grid cell by layering orders (Liu et al., 2014), and

the channel routing module executes on each channel by upstream-downstream

orders.

In SEIMS, each module should handle its required simulation conditions. Users

should decide the feasibility of the module combinations to meet the requirements of

each module, including the boundary conditions when calculating vertical and lateral

water movements. For example, to implement a physically-based interflow module

based on the Darcy's Law, the boundary condition could be set either with the

hydraulic gradient equal to the slope at each cell, or with the output of other

455 cooperating modules.

456   Each module inherits from a standard module interface, including the definitions

457 of input data, parameters, and output data. The input data and parameters of one

458 module can be either read from the database created during the preprocessing stage or

459 referred from other modules during the runtime. Each module itself initializes its

460 output data. In this way, during the execution of the SEIMS-based model, the same

461 variable is shared among modules.

462 **(3) Two-level parallelization strategy**

463   Since SEIMS treated subbasins as relatively independent modeling units for

464 hydrological modeling, the first level of the two-level parallelization strategy

465 dispatches the simulation of subbasins to different computing processes (or nodes)

466 through the Message Passing Interface (MPI) (Liu et al., 2016). The second level is

467 achieved within each subbasin by dispatching the simulations of grid cells without

468 mutual dependencies to computing threads via Open Multi-Processing (OpenMP)

469 (Liu et al., 2014). Based on the design of the modular structure, variables required to

470 be communicated among subbasins only need to be defined in the metadata of each

471 module and will be handled by the SEIMS main program (Zhu et al., 2019). That

472 means the complicated MPI programming details are hidden from module developers.

473 Besides, the implementation of OpenMP-based parallelization only needs one line of

474 preprocessor directive code before the loop of computationally independent code.

475 Therefore, module developers can easily develop modules and build high-

476 performance hydrological models in a nearly serial programming way (Zhu et al.,

477 2019). The two-level parallelization strategy provides the potential to implement the

478 proposed approach in this study that applies different model structures to distinct

479 subbasins.

2.2.2 Constructing model structures with diverse simulation units and algorithms ~~based on extension to SEIMS~~

To enable the flexible ~~customization for a hybrid structure~~construction of model structures based on SEIMS, the diversity of both spatial discretization ~~methods~~schemes and hydrological process representations should be guaranteed. For spatial discretization, the idea of constructing hydrological response ~~unit (HRU~~units (HRUs) could be added as ~~a~~simulation ~~unit type~~units of hillslope processes in SEIMS, ~~thus enabling~~including DominantHRU, FullHRU, and ExplicitHRU (see the ~~simulation based on not only grid cells but also HRUs. The HRUs, generated using soil and land-use maps, could follow~~Introduction section for details) (Figure 2a). In terms of parameters, the ~~parameterization methodology of semi-distributed models and support both conceptual and~~physically-based parameters. ~~Physically-based parameters~~ can be derived from ~~the~~actual properties of the soil ~~or land-use~~, landuse/landcover, and other spatial data, while conceptual parameters are directly specified ~~within the~~by lookup tables of soil and land-use ~~lookup tables~~. For instance, the reservoir capacity ~~within~~of an HRU can be represented by the soil depth associated with that specific HRU area~~.~~, while some experimental coefficients could be specified in the lookup tables.

Under such ~~a~~an HRU discretization ~~method~~scheme, the hillslope unit and subbasin ~~simulation~~unit can be ~~supported with SEIMS, as specialized cases of HRUs. For example, subbasin simulation is achieved when all HRUs within a subbasin share identical parameter values. With the above extension for spatial discretization method,~~ regarded as specific DominantHRU to be used as simulation units. Therefore, the extended SEIMS will offer the flexibility of utilizing ~~subbasin~~subbasins, hillslopes, HRUs, and grid cells as ~~spatial discretization options, allowing modelers to choose the most appropriate option for specific~~simulation units of hillslope processes for various modeling needs.

507 ~~The expansion of diverse discretization methods within SEIMS necessitates a~~

508 ~~corresponding extension of the hydrological process library to support the flexible~~

509 ~~combination of conceptual and physically-based processes across different~~

510 ~~discretization methods.~~For hydrological process representations, SEIMS was initially

511 designed to primarily integrate simulation algorithms ~~simulating~~of one ~~specific~~

512 ~~processes~~hydrological process into each single module, while it ~~previously~~ lacked a

513 conceptual model capable of considering multiple hydrological processes

514 comprehensively~~.~~ (Figure 2b). To bridge this gap, the lumped conceptual models

515 could be integrated as two separate process-based hillslope modules~~:~~, i.e., the surface

516 runoff ~~modules~~module that generate runoff at each simulation unit~~,~~ and the surface

517 routing module that directly convey water to the subbasin outlet. ~~Such modules could~~

518 ~~be applied to any simulation unit in SEIMS, including grid cells, HRUs, hillslopes,~~

519 ~~and subbasins. Following this schema, a~~ For example, the representative ~~of~~ widely

520 used conceptual models, GR4J (Perrin et al., 2003), ~~was~~is suitable to be incorporated

521 ~~into the~~as SEIMS ~~module library~~modules. Such modules could be applied to any

522 simulation unit types stated above.

523   To ensure the combination compatibility of ~~module combinations with the spatial~~

524 ~~discretization method~~simulation algorithms with simulation units applied to

525 subbasins, the SEIMS module interface ~~of SEIMS is~~should be extended to mark its

526 computational dependency requirement as ~~one of the following two types.~~

527   - ~~computational~~computationally dependent~~:~~ or independent. A

528 computationally dependent simulation module is exclusively applicable to grid cells,

529 ~~where water is routed based on flow directions derived from digital terrain~~

530 ~~analysis.~~and a computationally independent module is applicable to any types of

531 simulation unit. A model structure containing any ~~computational~~computationally

532 dependent module can only be applied to the ~~MSAU with~~subbasin using grid cells as

533 the basic simulation ~~unit of grid cell~~units.

534   ~~- computational independent: applicable to any simulation unit, including grid~~

535   cells, HRUs, subbasins, and the entire watershed within SEIMS.

536

537   **2.2.3 Allocating individual model structures to ~~MSAUs based on~~**

538   **~~SEIMS~~subbasins and integrating as a hybrid watershed model structure**

539   An essential ~~aspect~~part of ~~implementing~~ the spatially hybrid hydrological

540   modeling ~~method~~approach is to enable the separate allocation and execution of

541   individual model structures to different ~~MSAUs~~subbasins (referred to as the subbasin

542   models) within the watershed. ~~This entails allowing the separate construction and~~

543   ~~execution of individual models on each MSAU, referred to as MSAU~~All subbasin

544   models ~~(or subbasin models in this study), which~~ are subsequently integrated ~~into~~as a

545   watershed model. ~~This requires the MSAUs to be treated individually in an objective~~

546   ~~oriented manner. To achieve~~The requirements of flexible ~~and swift~~ model ~~construction~~

547   ~~and modification, the structure~~ configuration ~~should be text-based rather than hard~~

548   ~~coded.~~

549   ~~Among the above-mentioned requirements, the~~and subbasin-separate simulation

550   ~~and flexible model configuration~~ are compatible ~~to~~with the ~~two-level parallelization~~

551   ~~strategy and~~ text-based module configuration ~~of SEIMS, as illustrated in section 2.2.1.~~

552   ~~While extension should still be implemented on its module~~method and two-level

553   parallelization strategy of SEIMS (see section 2.2.1) but still need improvement. The

554   module configuration file of SEIMS should be extended to designate a model

555   structure to the specific subbasin, and the adopted type of basic simulation units

556   (Figure 3). In this way, the SEIMS main program can read the configuration ~~method~~

557   ~~to support spatial-varying model structure allocation. To facilitate such an ability, the~~

558   ~~configuration files should be extended to include the subbasin number it is assigned~~

559   ~~to, and the discretization method the subbasin adopts, given that the MSAU is defined~~

560   ~~to be subbasins in this study. This allows an individual configuration when the~~

561   ~~computing processes of~~ file for each subbasin dynamically ~~read the configuration~~

~~files~~, load ~~each module~~simulation modules, and retrieve the ~~spatial~~modeling parameters ~~of each subbasin with~~according to the specified ~~discretization method~~basic simulation units.

~~Extension should also be made on the design of the two-level parallel computing strategy to enable the execution of the individual subbasin models in SEIMS. In the original strategy, the simulation unit within a subbasin particularly refers to the grid cells, while simulation at the HRU level was not fully considered and implemented. To extend this strategy, the HRUs could be designed in a manner similar to grid cells but without topological orders, and are directly distributed to different computing threads using OpenMP. the subbasin-level parallelization could remain unchanged, with subbasins hierarchically sorted based on their flow relationships and subsequently assigned to different computing processes using MPI.~~

~~This enhanced strategy allows subbasin models to operate within the same time loop, enabling the parallel execution of hillslope processes among subbasins, with the output at each subbasin's outlet exchanged with its downstream subbasin using the configured channel routing module. The routing modules of SEIMS are retained and not extended to allow for spatial variation, as the hillslope processes with spatial variability are considered sufficient to represent the heterogeneity of hydrological processes.~~

2.3 Current implementation

~~The~~The two-level parallelization strategy should be improved in two aspects. The first is task scheduling of the subbasin-level parallelization for load balancing handled by the SEIMS main program. The domain decomposition of subbasins should be determined by upstream-downstream relationships between subbasins and the number of basic simulation units of each subbasin in the runtime, rather than using the numbers of grid cells of each subbasin in the preprocessing stage in the original implementation of SEIMS (Liu et al., 2016). The second aspect concerns the basic

simulation unit-level parallelization handled in computationally independent modules, which could be easily extended to support newly added simulation units such as HRUs since the OpenMP for-loop code structure does not need to be changed.

2.3 Implementation

Based on the above method design, the implementation of the proposed approach with SEIMS involves modifications to both the preprocessing and the main modeling programs of SEIMS. In the original Python-based the data preprocessing program, spatial parameters of a watershed, including terrain, land-use, soil, and meteorological data, are distributed to grid cells organized by subbasins. The new implementation introduces support for HRU-based delineations, such as tools, SEIMS main programs, and SEIMS module library. The data preprocessing tools mainly include a collection of Python scripts and C++ programs to delineate spatial units at different scales (e.g., subbasins and hillslopes. This entails calculations of), extract spatial parameters of spatial units, and create watershed modeling database (Zhu et al., 2019). In this study, a configurable tool was implemented to support the delineation and parameterization of HRU-based spatial units. This tool allows users to specify environmental variables (e.g., the default land-use and soil types) to delineate HRU-based units. This tool also allows specifying base spatial units and delineation strategy to generate different types of HRU such as taking subbasins or hillslopes as base units to generate DominantHRU or FullHRU. Therefore, the data preprocessing tools could prepare various types of spatial unit and associated spatial parameters for multiple times for every each subbasin and every type of simulation unit specified in according to the user-defined configuration file. The main to meet various hydrological modeling program and the module library scenarios. The procedures of the spatially hybrid modeling with SEIMS are based on the is depicted in Figure 3.

25

614
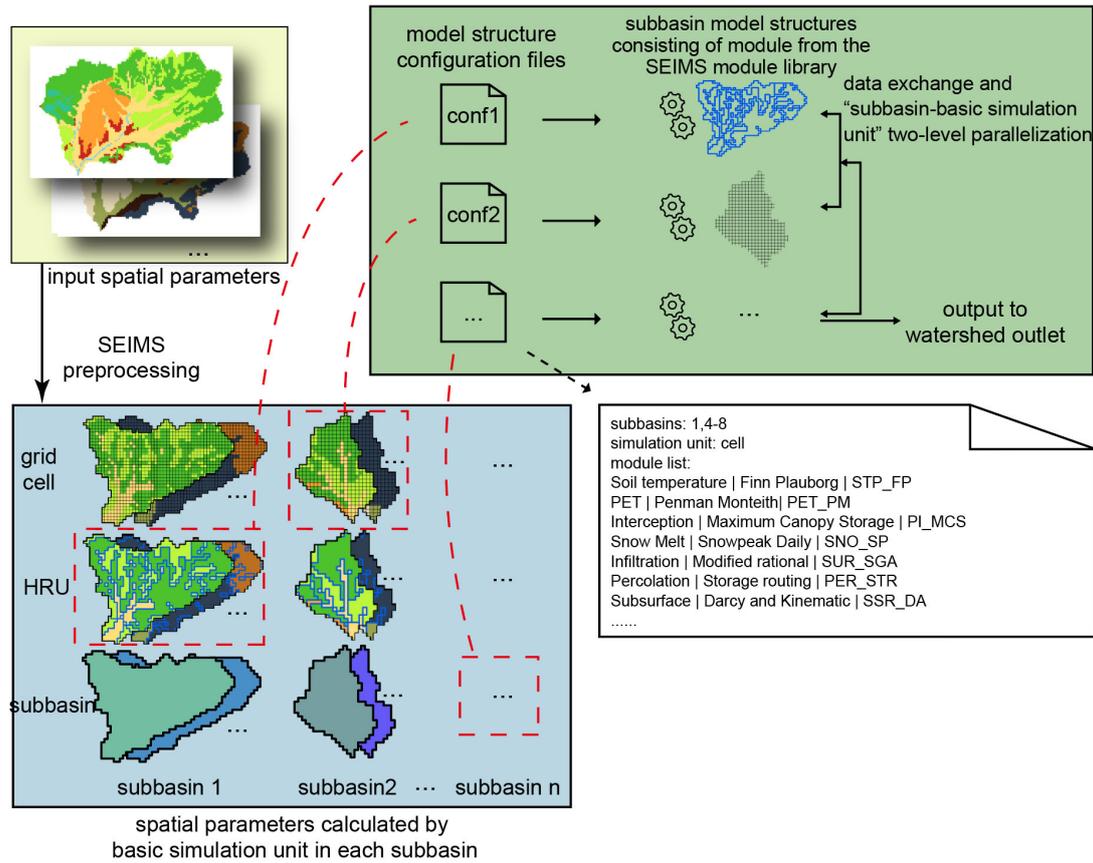
Figure 3. Procedures of spatially hybrid modeling with the SEIMS (Spatially Explicit Integrated Modeling System)

The SEIMS main program, written in C++ language. They have been++, was extended to distinguishread the configuration file for each subbasin, load simulation modules and retrieve the spatialmodeling parameters, which are stored in MongoDB, corresponding according to the simulation unitspecified simulation units. Simulation modules of the SEIMS module library were updated to declare the type of subbasin. The declaration of computational dependency is also added to every module in the module library. . New conceptual simulation modules were added such as GR4J for simulating hillslope runoff generation. With the above briefly introduced implementation of the proposed approach, SEIMS can now support users in constructing spatially hybrid model structures for considering spatial heterogeneity of the watershed, where each subbasin may be simulated with different combinations of

conceptual or physically-based simulation modules and spatial units. Consequently, 42 modules are available after the implementation of this study (detailed in Table S1 of the supplementary material), supporting simulation of processes including snowfall, atmospheric deposition, snow balance, interception, soil temperature, glacier, surface runoff, evapotranspiration, infiltration, percolation, interflow, groundwater, channel routing, plant growth, and soil erosion.

With the SEIMS extensions introduced in this study, users can now construct diverse model structures by selecting alternative simulation modules, and assign these structures to any subbasin within a watershed all through text-based configuration editing. The SEIMS is open-source on GitHub (https://github.com/lreis2415/SEIMS) and is under continuous development, such as adding conceptual and physical-based simulation modules for various geographic environments.

3 Case study

3.1 Study area and data

In this study, we selected the Babao River watershed at Qilian, Qinghai Province, China, in the upper reaches of the Heihe River Basin (Figure 4) as the case study area to verify the proposed approach through daily-scale runoff simulation. The Babao River watershed Figure 3 is one of the headwaters of the Heihe River Basin. It is located in a high-altitude, cold and mountainous region with an area of approximately 25112,511 km^2. The average elevation is 35653,565 m, and the region features glacier, snow cover and frozen soil.

ThisThe data for hydrological modeling in this study extensively relies onare all publicly available data. We used. The MERIT DEM with the 3"resolution (approximately of 90 m) MERIT DEM sourced from (Yamazaki et al. (., 2017) was selected for watershed delineation and calculation of terrain attributes. Meteorological input data for the model werewas obtained from the China Meteorological

27

Assimilation Driving Datasets for the SWAT model (CMADS) version 1.2, provided

in the form of approximately 0.125-° resolution gridded station data (Meng et al.,

2019). Land cover data ~~for the model were~~was derived from GLOBELAND30 with a

resolution of 30 m (http://www.globallandcover.com). Soil attribute ~~input~~ data ~~for the~~

~~model were~~was sourced from the Harmonized World Soil Database (HWSD~~; Wieder,~~

~~2014~~) Version 2.0 (Nachtergaele, 2023).
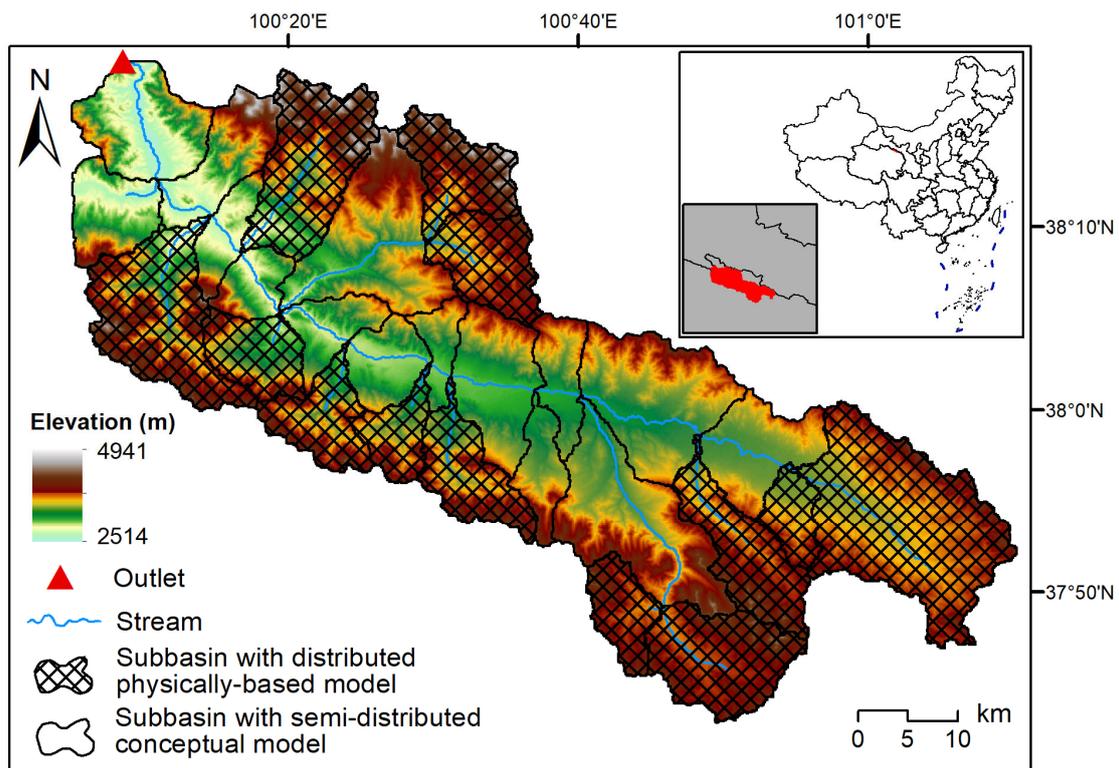
Figure ~~3~~4. The Babao River watershed ~~in the upper reaches of the Heihe River Basin~~

and the spatial constitution of the spatially hybrid watershed model.

3.2 Experimental ~~setting~~design

~~Two individual model structures were adopted to construct the spatially hybrid~~

~~model. One is a physically-based model structure using grid cells as the simulation~~

~~unit, providing a more detailed representation of spatial and hydrological processes.~~

~~This structure holds promise for simulating regions with significant elevation~~

28

variations, such as mountainous areas within the watershed. The other was a conceptual model structure with HRUs as the simulation units, which offers simplicity and can generalize multiple hydrological processes. The HRU are derived from the land-use and soil maps. This structure was assumed to be well-suited for large, gently sloping terrain within the watershed, compared to the physically-based structure. The algorithms for hydrological process description of the two model structures are listed in Table 1. Note that the physically-based structure includes both physically-based modules (such as the interflow module that calculates the flow cell by cell) and conceptual modules (such as the surface routing module based on unit hydrograph), which reflects the flexibility of the supported model structures.

Table 1. The modules adopted for the physically-based model and the conceptual model.

However, since the lack of modules for permafrost and glaciers in SEIMS, a purely physically-based model, if applied, may be confronted with inaccuracies in representing certain processes. Therefore, a spatially hybrid model structure combining both physically-based and conceptual models can be considered in this watershed to achieve more accurate runoff simulations. Under this assumption, a combination of conceptual and physically-based model structures was allocated to different subbasins in the Babao River watershed, resulting in a spatially hybrid model, as depicted in Figure 3. Another two model structures were established for comparison. The first model exclusively utilized the physically-based model for all subbasins, referred to as the physically-based model. The second model employed the conceptual model structure for all subbasins, referred to as the conceptual model.

The three model structures described above were utilizedTo verify the feasibility and effectiveness of the proposed spatially hybrid hydrological modeling approach and its implementation based on SEIMS, we constructed one distributed physically-

based model structure (section 3.2.1) and one lumped conceptual model structure (section 3.2.2) to build spatially consistent and spatially hybrid watershed models (section 3.2.3) for comparison after parameter calibration (section 3.2.4). It is worth noting that the watershed models constructed in this comparative experiment are not intended to model the hydrological processes in the study precisely nor to enumerate the possible model structures applicable as illustrated in Figure 1.

3.2.1 The distributed physically-based model structure

The distributed physically-based model structure uses grid cells as the basic simulation units and encompasses simulation algorithms based on physical laws. For example, the algorithms of percolation and interflow are based on Darcy's law. The percolation is calculated as the product of hydraulic conductivity and the gradient of the hydraulic potential, and the interflow is calculated from the kinematic approximation of Darcy's Law and, with the hydraulic gradient equal to the slope at each grid cell. These two methods are the same as those used in WetSpa [please refer to Liu and Smedt (2004) and Safari et al. (2012) for more details]. Table 1 listed the considered hydrological processes and their simulation algorithm associated with key parameters for model calibration. The physically-based simulation algorithms primarily utilize spatial parameters with clear physical meaning, such as soil hydraulic conductivity and leaf area index. The geomorphology-based unit hydrograph is derived from terrain data. Besides, this model structure also includes conceptual simulation algorithms such as the surface routing module based on unit hydrograph (Table 1). A model structure combined physically-based and conceptual hydrological process representations is often regarded as a physically-based model, as stated by existing hydrological model with a fixed or near-fixed model structure such as SWAT, WetSpa, and RHESSys.

30

724 Table 1. Simulation algorithms adopted for the distributed physically-based model

725 structure and the parameters involved in model calibration

Hydrological process	Simulation algorithm	Parameters involved in calibration
Potential evapotranspiration	Penman-Monteith	K_pet (correction factor)
Interception	Maximum canopy storage	Interc_max (maximum interception storage), Interc_min (minimum interception storage), Pi_b (interception storage capacity exponent)
Glacier	HBV method	-
Snow melt	HBV method	T_rain_snow_delta (rain/snow mixture temperature range)
Infiltration and surface runoff	Modified coefficient method	K_run (runoff exponent), P_max (maximum precipitation corresponding to potential runoff coefficient), Runoff_co (potential runoff coefficient)
Depression	Linsley	Depression (depression storage capacity)
Percolation	Storage routing	-
Interflow	One-dimension kinematic wave	Ki (interflow scale factor)
Actual evaporation	Thornthwaite and Mather method	-
Plant growth	Simplified EPIC	-
Groundwater	Linear reservoir	Base_ex (baseflow recession exponent), df_coef (deep percolation coefficient), gwmax (maximum ground water storage), Kg (baseflow recession coefficient)
Surface routing	Geomorphology-based unit hydrograph	-
Channel routing	Muskingum	MSK_X, MSK_K

726 **3.2.2 The lumped conceptual model structure**

727 The lumped conceptual model structure has DominantHRUs as the simulation

728 units and has GR4J as the main simulation algorithm, which offers simplicity and can

729 generalize multiple hydrological processes (Table 2). The DominantHRUs are derived

730 from the overlay of the categorized land cover and soil maps, with the HRU with

731 occupying the largest area being the DominantHRU. The Hargreaves method is used

732 to provide the potential evapotranspiration for the GR4J. And the GR4J receives the

31

733   potential evapotranspiration and precipitation as input to generate the hillslope runoff

734   at subbasin outlets, which are then aggregated by the Muskingum method.

735

736   Table 2. Simulation algorithms adopted for the lumped conceptual model structure

737   and the parameters involved in model calibration

Hydrological process	Simulation algorithm	Parameters involved in calibration
Potential evapotranspiration	Hargreaves	-
Conceptual and comprehensive hillslope runoff	GR4J	SOILTHICK (X1), X2, X3, X4
Channel routing	Muskingum	MSK_X, MSK_K

738

3.2.3 One spatially hybrid watershed model structure and two spatially

consistent model structures for comparison

741   Ideally, a physically-based model could better simulate hydrological processes

742   with explicit physical meaning. While limited to the insufficiency of the cognization

743   of hydrological processes and difficulty of implementing complicated simulation

744   algorithms, a conceptual model could be a valuable complementary, which is often

745   come up with mathematical fitting under some degree of generalization. Therefore, a

746   spatially hybrid model structure (referred to as the HybM) combining both physically-

747   based and conceptual models were constructed in a fourthis case study. Most

748   parameters of the distributed physically-based model structure were derived from

749   actual terrain, landuse, and soil data, which would vary more significantly in spatial.

750   Thus, the distributed physically-based model structure is considered more suitable for

751   mountainous areas than the lumped conceptual model structure. Under this

752   assumption, the HybM in the Babao River watershed was constructed, as depicted in

753   Figure 4. In the HybM, 16 subbasins were assigned with the lumped conceptual

754   model structure, and the other 13 subbasins with the distributed physically-based

model structure.

The two model structures were then used to build spatially consistent model structures to be compared with the HybM. The model utilizing only the distributed physically-based model structure was referred to as PhyM, and the model utilizing only the lumped conceptual model structure was referred to as ConM.

3.2.4 Comparative experiments of parameter calibration

The parameters involved in model calibration that listed in Table 1 and Table 2 were selected by parameters sensitivity analysis. In the calibration of the HybM, parameters in subbasins with the same model structure (the distributed physically-based or the lumped conceptual) were changed together (i.e., add or multiply). That is, parameters in the mountainous subbasins share the same change, and those in gently sloping subbasins share the same change (Figure 4). For comparison to the HybM, two calibration strategies are used for both the PhyM and ConM: 1) universal calibration, where parameters in all subbasins were changed together. 2) regional calibration, where parameters in the mountainous subbasins were changed together, and those in gently sloping subbasins were changed together, i.e., the same calibration strategy as the HybM.

The three models were executed in a six-year simulation, spanning from January 1, 2013, to December 30, ~~2016~~2018. The first year (2013) served as a warm-up period, followed by ~~two~~three years (2014 ~~and 2015~~–2016) designated for calibration, and ~~the final year (2016~~two years (2017–2018) for validation. ~~Various~~Four model performance indices, including the Nash-Sutcliffe coefficient (NSE; Eq. 1), root mean square error-standard deviation ratio (RSR; Eq. 2), percent bias (PBIAS; Eq. 3), and ~~R-square,~~R^2(Eq. 4), were selected to evaluate the ~~modeling~~model performance. ~~Parameter~~

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

(1)

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}}$$

(2)

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i) \times 100}{\sum_{i=1}^{n} O_i}$$

(3)

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

(4)

780 where O_i and P_i are i-th observed value and predicted value, respectively. $\bar{O}$ is the

781 averaged observed value, and n is the size of simulated time series.

782   The parameter calibration was conducted using the NSGA-II (non-dominated

783 sorting genetic algorithm-II; Deb et al., 2002) integrated in the SEIMS framework,

784 (Zhu et al., 2019), with a population size of 200 and each experiment having an

785 optimization for 15 generations. The calibration objectives are of 360 population and

786 25 generation. The calibration experiments were conducted on a personal computer

787 with a 2.70 GHz Intel Xeon Gold 6150 dual CPU (36 cores). Under the NSGA-II

788 algorithm, the Pareto front of each generation would be kept and compared with the

789 next generation. The objective function for parameter calibration is maximum NSE,

790 minimum absolute values of RSR and PBIAS. The P-factor and R-factor were used as

791 additional indicators on the prediction uncertainty, where P-factor is the percentage of

792 observations fall within the 95% prediction uncertainty (PPU) interval, and R-factor is

793 the average width of the 95% PPU interval, normalized by the standard deviation of

794 the observed data. The two factors are utilized to evaluate the final generations of the

795 experimental model structures., with each component having the same weight.

796 Comparative analysis was carried out to assess the simulation performance of the

797 three model setsmodels based on theselected optimal parameters obtained during

798 calibrationfrom the Pareto front.

799   Table 3. Experiments of parameter calibration with different calibration strategies for

800   different model structures

Calibration strategy	Name of experimental cases		
	ConM	PhyM	HybM
Universal	ConM1	PhyM1	-
Regional	ConM2	PhyM2	HybM

801

4 Results and discussion

4.1 Quantitative performance of the spatially hybrid model structure constructed by the proposed approach

Figure 4 illustrates the calibration results of the three model structures, revealing that the spatially hybrid model (Figure 4c), established using the proposed approach, outperforms the others in terms of the best-fit simulations. The NSE of the best-fit spatially hybrid model is the highest (0.63 / 0.81 for calibration / validation period, the same below), compared to the physically-based model (0.34 / 0.73) and conceptual model (0.45 / 0.61). The lowest RSR (0.61 / 0.43), lowest PBIAS (3.66% / -4.62%) and highest R-square (0.64 / 0.83) are also seen in the spatially hybrid model, which indicates a best fit among the experimental model structures.

Figure 4. The The successful execution of the constructed spatially hybrid watershed model structure proved the feasibility of integrating lumped conceptual model structure and distributed physically-based model structure in a spatially varying manner. According to the comparative experiments in this case study, the effectiveness of the proposed approach and its implementation based on SEIMS can be discussed from three aspects: 1) the performance of different model structures after automatic parameter calibration under different calibration strategies; 2) the rationality of the spatially hybrid model structure; and 3) the advantage of SEIMS in implementing the proposed approach.

4.1 The model performance of different model structures under different calibration strategies

The model performances of the selected optimal individuals of all calibration strategies of the three model structures are listed in Table 4. According to the performance metrics of both calibration and validation periods, the spatially consistent distributed physically-based model (i.e., PhyM) exhibits similar performance under both the universal and the regional calibration strategies (i.e., PhyM1 versus PhyM2). In contrast, for the spatially consistent lumped conceptual model, the ConM2 that utilized the regional calibration strategy outperformed the ConM1. The difference may attribute to the characteristics of modeling parameters. The parameters of the PhyM are derived from spatially distributed input data, implying a low dependency on regional calibration. In contrast, the initial parameters of the ConM were the same across the watershed since their lack of clear physical meaning, resulting in the dependency on distributed calibration.

838 Table 4. Performance metrics of selected optimal calibrated individuals with different
839   model structures under different calibration strategies (PhyM1 and PhyM2:
840 physically-based model structure with universal and regional calibration; ConM1 and
841   ConM2: conceptual model structure with universal and regional calibration,
842 respectively; HybM: the spatially hybrid model structure with regional calibration)

Experimental case	Best Representative individual performance selected from the Pareto front (calibration / validation periods)			
	NSE	RSR	PBIAS (%)	R^2
PhyM1	0.58/0.60	0.64/0.63	10.63/2.58	0.66/0.67
PhyM2	0.59/0.60	0.64/0.63	17.34/13.90	0.67/0.66
ConM1	0.41/0.32	0.77/0.82	2.89/-42.87	0.42/0.61
ConM2	0.45/0.50	0.74/0.71	10.96/-21.03	0.48/0.60
HybM	0.72/0.60	0.53/0.63	10.02/-18.28	0.73/0.71

843

844   The HybM demonstrated an overall better performance over the PhyM and

845 ConM. In terms of NSE, the HybM showed the highest performance in the calibration

846 period (0.72), and one of the highest performances in the validation period (0.6). The

847 HybM also had lower RSR (0.53/0.63) and higher R^2 (0.73/0.71) than the PhyMs and

848 ConMs, while its PBIAS (10.02%/-18.28%) did not show advantage. This

849 demonstrated that the proposed approach could achieve higher performance compared

850 to the spatially consistent model structures.

851 **4.2 The rationality of the spatially hybrid model structure**

852   Figure 4 showed the hydrographs of simulation results of the final generation in

853   calibration of the (a) physically-based model, (b) conceptual model, and (c) the

854   spatially hybrid model from the proposed approach.

855

In terms of P-factor and R-factor, the spatially hybrid model shows a medium P-factor (0.42 / 0.30) and the lowest R-factor (0.60 / 0.49). In comparison, the physically-based models show the lowest P-factor (0.26 / 0.37) with a medium R-factor (0.65 / 0.57), which indicates a lower prediction uncertainty among the populationConM2, PhyM1, and HybM, compared to the conceptual models, while the accuracy is also low. The conceptual models, while having the highest P-factor (0.57 / 0.51), show a wide prediction interval with the highest R-factor (1.36 / 1.03). This indicates that althoughwith the observed discharge values are more within the prediction interval of conceptual models, the uncertainty is also high. The result shows the spatially hybrid model structure has a more concentrated prediction with the lowest uncertainty in the last generation during optimization. While uncertainty may originate from multiple sources including parameters and model structure, this result also implies a potential advantage in achieving more possibly accurate results through parameter optimization.

4.2 Discussion on the simulation results in terms of the hydrographs from the proposed approach

The strength of the spatially hybrid model becomes more evident when examining the visual interpretation of the simulation results (Figure 5). To elucidate this, we begin by discussing the disparities between the physically-based model and the conceptual model (Figure 4a and 4b(Figure 4). In dry seasons, typically from November to the following April when baseflow is the primary contributor to discharge, the physically-based modelPhyM1 exhibits a noticeable underestimationan accurate estimation of baseflow during. In contrast, the dry season between 2015 and 2016. This discrepancy suggests potential inaccuracies in representing groundwater processes. Conversely, the conceptual modelConM2 provides an overall reasonableoverestimation of the baseflow simulation but at. In the cost of

882 ~~overestimating baseflow. This overestimation can serve as compensation for low~~

883 ~~flows in~~ wet seasons, ~~which typically occur from May to October. In~~ the ~~wet seasons,~~

884 ~~the physically-based model~~PhyM1 produces steeper rising and falling limbs in the

885 hydrographs, corresponding to the intensive precipitation ~~during wet seasons~~, as

886 depicted in Figure ~~5~~4. This behavior aligns with ~~its~~the physical basis~~.~~ of the study

887 area. The ~~conceptual model~~ConM2, on the other hand, ~~struggles~~tend to ~~simulate~~either

888 overestimate or underestimate the peak flows ~~accurately, especially during the~~

889 ~~validation period~~.

890

891 ~~Figure 5. Hydrograph of the best-fit spatially hybrid model.~~

892

893 ~~The spatially hybrid model, as a result, combines the strengths of both models.~~

894 ~~While it tends to slightly overestimate baseflow, it outperforms both the physically-~~

895 ~~based model (which underestimates) and the conceptual model (which overestimates)~~

896 ~~and provides more precise and steeper peak flows during the wet season. This~~

897 ~~represents an enhancement to the advantages of the physically-based model. In areas~~

898 ~~with gentle terrain, groundwater tends to accumulate. However, during the period~~

899 ~~from October 2015 to May 2016, when overall precipitation was low, the physically-~~

900 ~~based model's process-based simulations may have resulted in an underestimation of~~

901 ~~groundwater levels. In contrast, the conceptual model, through adjustments to~~

902 ~~parameters governing groundwater outflow, can reconcile these levels with observed~~

903 ~~values. In the mountainous regions within the watershed, characterized by rapid~~

904 ~~runoff generation and routing, the conceptual model may not accurately capture these~~

905 ~~dynamics, resulting in less precise simulations of rainfall-induced runoff. However,~~

906 ~~this limitation is offset within the hybrid model due to the inclusion of the physically-~~

907 ~~based model.~~

908 ~~An additional merit of the spatially hybrid model lies in the computational efficiency.~~
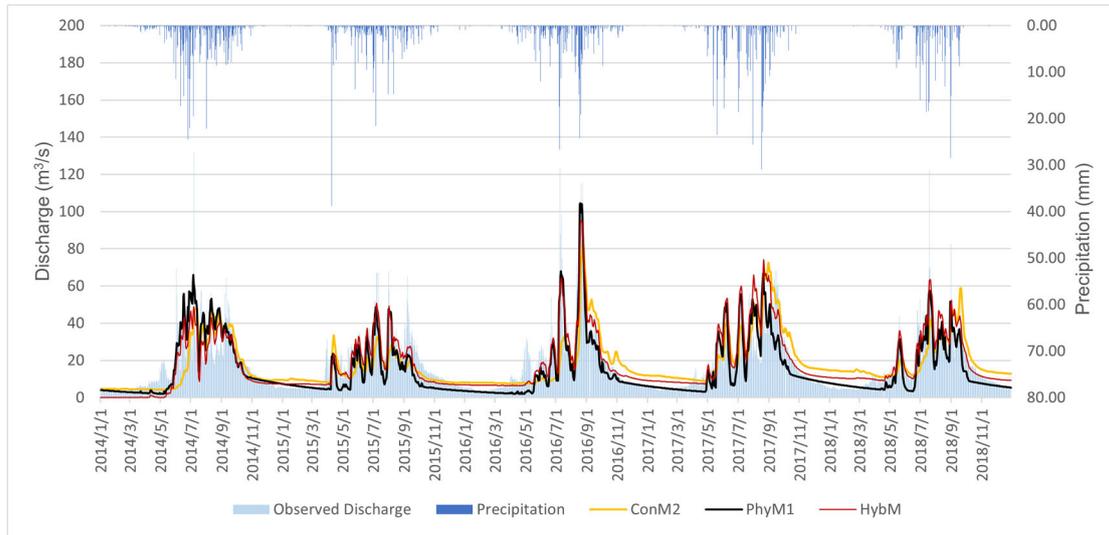
909

914

915   The spatially hybrid model HybM, as a result, combines the strengths of both the

916 physically-based and the conceptual model structures. Especially, the HybM exhibited

917 a more accurate simulation of peak flows and recession all through the simulation

918 periods, better than both the PhyM1 and the ConM2. And for the rising limbs, the

919 HybM reacted close to the PhyM1, which fitted better than the ConM2. While for the

920 baseflow, the HybM showed a compromising between the PhyM1 and the ConM2,

921 which turns out to be a n overestimation but better than the PhyM1.

922 4.3 The advantage of SEIMS in implementing the proposed

923 approach

924   The selection of SEIMS in implementing the proposed approach exhibited

925 effectiveness in computing efficiency and modeling flexibility. Due to the detailed

926 representation of various hydrological processes in the physically-based model, its

927 calibration took approximately ~~100~~75 hours for ~~3000~~9000 model runs (~~200~~360

928 population and ~~15~~25 generations). Such a high calibration demand limits its

929 availability to larger watersheds. In contrast, the calibration time for the conceptual

930 model was significantly shorter, approximately ~~15 minutes~~1 hour. Therefore, the

931 spatially hybrid model, which contains both models, exhibited an intermediate

932 calibration time of around ~~50~~30 hours, ~~proportionate to the participation~~average of the

933 two models. This efficiency enhancement suggests a broader applicability to larger

934 watersheds, where specific subbasins of interest can be treated individually. This

935 approach not only saves time but also enables the production of more model runs for

936 parameter ~~optimizations~~calibration or uncertainty analysis.

937   The subbasin-independent design also gives rise to the modeling flexibility.

938 Model developers could implement their models in module-level to simulate a single

939 process or multiple processes, which can then be combined easily with other modules

940 into a customized spatially hybrid model structure. While it is worth noting that the

941 module developers should handle the input requirements and boundary conditions for

942 the single module, and the module users should examine the feasibility of the

943 combined model structure.

5 Conclusion

945   This paper ~~introduces~~introduced a novel spatially hybrid hydrological modeling

946 approach, offering a versatile solution to address the modeling challenges posed by

947 the spatial heterogeneity of complex watersheds. Unlike ~~traditional~~existing distributed

948 hydrological models that allow only spatial variability of parameters, the proposed

949 approach takes a divide-and-conquer idea to accommodate spatially varied and hybrid

950 model structures. ~~It introduces the concept of Model Structure Allocation Units~~

951 ~~(MSAUs) for allocating individual model structures.~~ This approach advocates the

952 hybrid combination of different spatial discretization ~~methods~~schemes and

953 hydrological process representations, enhancing structural flexibility on each ~~MSAU.~~

954 ~~Constraints on the MSAU~~subbasin. The constraints of integrating subbasin model

955 structures ~~are~~were also discussed to ensure ~~their integration into~~the successful
956 construction of the final watershed model.

957   Based on the implementation on the hydrological modeling framework SEIMS,
958 ~~an experiment was~~the comparative experiments were conducted to validate the
959 feasibility and effectiveness of the proposed approach. The spatially hybrid model
960 structure, compared to ~~uniform~~the spatially consistent distributed physically-based
961 and lumped conceptual model structures, demonstrated not only the capability of
962 modeling with spatially varied and flexible structure, but also the ability to synergize
963 the strengths of the ~~constituent~~spatially consistent model structures, potentially
964 leading to reduced uncertainty.

965   This approach empowers researchers to ~~scrutinize~~precisely utilize and fine-tune
966 model structures ~~with precision~~, aligning them with the unique characteristics of
967 specific areas within a watershed. It offers enhanced flexibility and a wider range of
968 available model structures, extending the horizons of hydrological modeling for
969 spatially varying model structures. This extension facilitates the exploration of
970 multiple working hypotheses, ultimately enhancing our understanding of complex
971 watershed systems.

972   However, there are also limitations in the current implementation. ~~First, while~~
973 ~~the concept of MSAUs (model structure allocation units) is theoretically applicable to~~
974 ~~other simulation units, such as HRUs or coarse grid cells, further exploration is~~
975 ~~needed to assess its suitability on these units. Second~~Firstly, the SEIMS module
976 library ~~must~~should undergo further development to encompass a broader
977 ~~spectrum~~range of ~~models and~~simulation algorithms~~, particularly those related to~~ and
978 hydrological processes, for example, implementing tightly coupled simulation
979 methods of several hillslope hydrological processes using rigorously physically-based
980 algorithms as one simulation module, implementing simulation modules for glacier
981 and frozen soil processes, ~~in order to construct model structures for a wider range of~~

982 ~~applications in watersheds with significant spatial heterogeneity. Lastly~~etc. Secondly,

983 as the spatial constitution of the spatially hybrid model structure can be freely

984 configured and revised, determining the optimal spatial constitution for specific

985 application contexts remains a subject for future study.

986

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1000

1001

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