Graphical representation of global water models

Hannes Müller Schmied[1,2], Simon Newland Gosling[3], Marlo Garnsworthy[4], Laura Müller[1], Camelia-Eliza Telteu[1], Atiq Kainan Ahmed[5], Lauren Seaby Andersen[6], Julien Boulange[7], Peter Burek[8], Jinfeng Chang[9], He Chen[10], Lukas Gudmundsson[11], Manolis Grillakis[12], Luca Guillaumot[13], Naota Hanasaki[14], Aristeidis Koutroulis[12], Rohini Kumar[15], Guoyong Leng[16], Junguo Liu[17,18,10], Xingcai Liu[16], Inga Menke[19,20], Vimal Mishra[21,22], Yadu Pokhrel[23], Oldrich Rakovec[15,24], Luis Samaniego[15,25], Yusuke Satoh[26], Harsh Lovekumar Shah[27], Mikhail Smilovic[8], Tobias Stacke[28], Edwin Sutanudjaja[29], Wim Thiery[30], Athanasios Tsilimigkras[12], Yoshihide Wada[31], Niko Wanders[29], and Tokuta Yokohata[14]

[1]Institute of Physical Geography, Johann Wolfgang Goethe University Frankfurt, 60438 Frankfurt am Main, Germany
[2]Senckenberg Leibniz Biodiversity and Climate Research Centre (SBiK-F), 60325 Frankfurt am Main, Germany
[3]School of Geography, University of Nottingham, Nottingham, NG7 2RD, United Kingdom of Great Britain and Northern Ireland
[4]Icebird Studio
[5]Institute for Population and Social Research, Mahidol University, Nakhon Pathom, Thailand
[6]Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany
[7]Institute of Agriculture, Tokyo University of Agriculture and Technology, 183-8509 Tokyo, Japan
[8]Water Security Research Group, Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), A-2361, Laxenburg, Austria
[9]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China
[10]School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China
[11]Institute for Atmospheric and Climate Sciences, ETH Zürich, Zürich, Switzerland
[12]School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece
[13]BRGM, F-45060 Orléans, France
[14]National Institute for Environmental Studies, 305-8506 Tsukuba, Japan
[15]Helmholtz-Centre for Environmental Research, Permoserstraße 15, 04318 Leipzig, Germany
[16]Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[17]Henan Provincial Key Laboratory of Hydrosphere and Watershed Water Security, North China University of Water Resources and Electric Power, Zhengzhou, 450046, China
[18]School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou, 450046, China
[19]Humboldt Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
[20]Climate Analytics, Ritterstraße 3, 10969 Berlin, Germany
[21]Civil Engineering, Indian Institute of Technology (IIT) Gandhinagar, Gandhinagar, India
[22]Earth Sciences, Indian Institute of Technology (IIT) Gandhinagar, Gandhinagar, India
[23]Department of Civil and Environmental Engineering, Michigan State University, East Lansing, 48823, United States
[24]Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic
[25]University of Potsdam, Institute of Environmental Science and Geography, Am Neuen Palais 10, 14469 Potsdam, Germany
[26]Moon Soul Graduate School of Future Strategy, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea
[27]AgroCast Analytics Pvt Ltd - Research Park, Indian Institute of Technology Gandhinagar, Palaj, Gujarat, India -382355
[28]Climate Dynamics Department, Max Planck Institute for Meteorology, 20146 Hamburg, Germany
[29]Department of Physical Geography, Faculty of Geosciences, Utrecht University, The Netherlands

[30]Vrije Universiteit Brussel, Department of Water and Climate, Brussels, Belgium

[31]Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

Correspondence: Hannes Müller Schmied (hannes.mueller.schmied@em.uni-frankfurt.de)

Abstract. Numerical models are simplified representations of the real world at a finite level of complexity. Global water models are used to simulate the terrestrial part of the global water cycle and their outputs contribute to the evaluation of important natural and societal issues, including water availability, flood risk and ecological functioning. Whilst global water modelling is an area of science that has developed over several decades, and individual model-specific descriptions exist for some models, there has to date been no attempt to visualize the ways that several models work, using a standardized visualization framework. Here, we address this gap by presenting a community-driven process that developed a framework to visualize several global water models. The models considered participate in the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b). The diagrams were co-produced between a graphics designer and 16 modelling teams, based on extensive discussions and pragmatic decision-making that balanced the need for accuracy and detail against the need for effective visualization. The model diagrams are based on a standardized "ISIMIP2b-complete" global water model that represents what is theoretically possible to represent in the current generation of state-of-the-art global water models participating in ISIMIP2b. Model-specific diagrams are then copies of the "ISIMIP2b-complete" model, with individual processes either included or greyed out. An open source tool has been developed and published jointly with the diagrams, which allows someone to generate a diagram for their own global water model by adapting the diagrams presented here. As well as serving an educational purpose, we envisage that the diagrams will help researchers in and outside of the global water model community to select suitable model(s) for specific applications, stimulate a community learning process, and identify missing components to help direct future model developments.

1 Introduction

Graphical visualizations, or more simply put, diagrams, are essential communication tools in science. They are helpful for researchers, in education, for management, and policy-related processes (Linton, 2008; Abbott et al., 2019; Cardak, 2009; Fandel et al., 2018). Here, we focus on diagrams of the water cycle, as it is represented in a set of model approaches that simulate the terrestrial part of the water cycle. We call these models global water models according to Telteu et al. (2021) and use the term water cycle with focus on these models and the terrestrial part for the remaining paper. Global climate models that simulate the global water cycle including the oceans and the atmosphere are explicitly not the focus of this study. Linton (2014) showed that the development of water cycle diagrams is associated with an increasing awareness of the social dimensions of water. Some water cycle diagrams have received much attention in a scientific context, for example the visualization of the terrestrial water balance including model-based quantifications of global fluxes and storages by Oki and Kanae (2006). In an educational experiment, Cardak (2009) explored misconceptions in the understanding of the global water cycle by undergraduate students, from interviews, and by specifically letting them draw the water cycle. Elsewhere, the co-creation of diagrams between environ-

mental modellers, design creatives, and policy-makers has facilitated the generation of infographics and visuals that improve scientific understanding and better contextualize the degree of trust placed in modelling results. Examples of such efforts to balance academic integrity and detail alongside maintaining policy-relevance are the IPCC reports and the EU Green Deal (European Commission, 2023).

There are no commonly accepted guidelines for designing a global water diagram, although best practices for scientific illustration of water cycle diagrams for dryland environments are discussed by Fandel et al. (2018). The design of global water diagrams has in the past been criticised, e.g. Abbott et al. (2019) who explored the water storages, fluxes, and processes incorporated in 464 water cycle diagrams and found that human interactions were not included in a majority (85%) of the diagrams. In total, they found rather similar diagrams despite differences in the intended target audience and year of creation. The reviews mentioned earlier (Abbott et al., 2019; Linton, 2008; Fandel et al., 2018) also include several very popular diagrams of the global water cycle. Recently, and also as a reflection of the findings of Abbott et al. (2019), a new version of the USGS water cycle diagram has been published (Nell et al., 2023) that illustrates components of human inferences to the water cycle.

Abbott et al. (2019) classified the format of the diagrams into a) three-dimensional, large-scale catchments, b) two-dimensional small-scale hillslopes, c) site-specific for certain aspects of a catchment and hillslopes, and d) schematics that typically consist of boxes and arrows and are the most abstract representations. In the scientific community of global water modelling, it is nowadays common to publish model description papers alongside the output data. Typically, these descriptions also include a graphical representation of the model scheme, namely the water storages, fluxes, and processes included in the model. The format and approach differ largely, with the most popular approaches being three dimensional diagrams (e.g. Hanasaki et al., 2018; Lawrence et al., 2019; Burek et al., 2020) and abstract illustrations with boxes and arrows (e.g. Stacke and Hagemann, 2021; Müller Schmied et al., 2021).

When it comes to model inter-comparison exercises, a typical goal is, next to comparing model outputs, the exploration of commonalities and differences between models (Haddeland et al., 2011). This understanding helps to explain why the model outputs differ. The global water sector in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) consists of around 20 active global water models (Gosling et al., 2023b, a) that follow a specific modelling protocol to ensure a consistent cross-model assessment (Warszawski et al., 2014; Frieler et al., 2017, 2024).

The global water models participating in ISIMIP were developed from multiple backgrounds and as such they contain different concepts and components. A common way of differentiating model types is to group them into Land Surface Models (LSMs, relying on solving the terrestrial energy balance), Global Hydrological Models (GHMs, often relying on solving the terrestrial water balance), Dynamic Global Vegetation Models (DGVMs, with a specific focus on functional plant development) and hybrids. Table 1 relates the models to each type. To avoid over-complication, we focus on the water balance, as it is addressed by all models, and we use the term 'global water model' for all models that participated in this study. More details on the model backgrounds can be found in Telteu et al. (2021).

Telteu et al. (2021) reviewed the global water models that participated in the ISIMIP phase 2b, in terms of their components, to analyze which water storages and fluxes are included in the models. Furthermore, they developed a common notation for the equations of each model component, resulting in a compendium of model-specific equations. No visual depictions of the model

Table 1. The three types of global water models that participated in this study: GHM: Global Hydrological Model; LSM: Land Surface Model; and DGVM: Dynamic Global Vegetation Model. For more details, the reader is referred to Telteu et al. (2021).

Model type	Models in this study
GHM	CWatM, H08, Mac-PDM.20, mHM, MPI-HM, PCR-GLOBWB, VIC, WaterGAP2, WAYS
LSM	CLM4.5, CLM5.0, DBH, JULES-W1, MIROC-INTEG-LAND (formally MATSIRO), ORCHIDEE
DGVM	LPJmL

components were shown though. Even though all the models follow basic hydrological principles, such as the conservation of mass, the individual calculation procedures and the relative complexities of the models differ (Telteu et al., 2021). This previous exercise was a community-driven effort and the modelling groups were intensively involved, leading to a better understanding of each other's models inside the community. While the exercise served as a critical stepping-stone for the global water model community, the wealth of information in Telteu et al. (2021) may be difficult to interpret for those unfamiliar with the specific equations and principles used in hydrology. This highlights the need for a visual depiction of different modelling components which can act as important additional information for model improvement, inter-model comparison, science communication, and education.

To this end, herein we present the efforts of the global water community within ISIMIP2b to describe the structure of the computational models in a common diagram scheme, whilst including some of the information from Telteu et al. (2021). The visualization of the models should support:

– Familiarising people outside of the global water model community with the features and concepts included in global water models. This could be lay audiences, university students learning about hydrology and/or modelling, or researchers.

– Model developers to identify missing model components, which could help to define areas for future model development.

– Researchers, giving them the possibility to reflect structural model uncertainty by visualizing the model structure including storages, processes, and fluxes, which builds the basis for assessing model output to generate a multi-model water budget considering this uncertainty.

– Users of the ISIMIP model output data repository who want to conduct and communicate numerical assessments, in selecting the most suitable models for their analyses. For example, users interested in specific components of the water cycle might select only those models that have a certain representation of these processes implemented. Thus, we envision that the diagrams will support users select models appropriate for the intended purpose, both for historical periods and future projections.

– End users, stakeholders and decision-makers towards a better understanding of the benefits and limitations of specific models, in relation to the intended application of the models. For example, a model that is specifically designed as a vegetation model has benefits in simulating such processes but might have limitations in other areas, such as the

representation of water management. A visualization could help identify those features quickly and build trust in results outside the modelling community.

The expected audience of our diagrams is relatively wide and comprises a) model output users, b) people who are new in the global water modelling community and want to learn about the existing models, c) people in educational settings (in particular academic education), d) policy-makers and civil society organisations, as well as e) model developers seeking inspiration for improving their models.

The diagrams are aimed at a broad audience, so they are kept as simple as possible to assist with communication. To this end, the diagrams focus primarily on describing whether a process is included or not, or stating the number of layers in a specific storage, for example, rather than elaborating on the specifics of how that process is represented internally within the model. This means that the diagrams do not show the varying levels of complexity between models in representing any given process. For more detailed information about how each model represents each process, the reader is referred to Telteu et al. (2021).

The remaining paper is structured as follows. In Sect. 2 we describe the general methodology from the first idea to the finalization of the diagrams. The "ISIMIP2b-complete" model as well as the individual model diagrams are then shown in Sect. 3. A discussion about limitations and potential improvements, how the diagrams may be used, as well as an outlook, is in Sect. 4, followed by concluding remarks in Sect. 5.

2 Methods

2.1 ISIMIP and community-driven demand for a structural model intercomparison

In a project funded by the European Union (WATCH project under EU grant number 36946, runtime 2007-2011), the global water model community initiated a model intercomparison and hydrological assessment study. Based on this foundation, the global water sector in ISIMIP was formed and has been active since ISIMIP was started in 2012. There has been a wide range of studies focusing on model evaluation (e.g., Veldkamp et al., 2018; Zaherpour et al., 2018; Zhao et al., 2017; Masaki et al., 2017; Kumar et al., 2022; Gudmundsson et al., 2012a, b) and impact assessment (e.g., Gudmundsson et al., 2021; Reinecke et al., 2021; Prudhomme et al., 2014; Dankers et al., 2014; Schewe et al., 2014; Thompson et al., 2021; Gosling et al., 2017) but also considering other sectors like agriculture and health (e.g., Schewe et al., 2019; Thiery et al., 2021). The creation phase of such contributions, and specifically when trying to explain *why* model results differ, was hindered by the unavailability of a consistent and comparative model overview. This was the motivation for working collaboratively on an overview of the models participating in the global water sector of ISIMIP.

The entire process was a community effort. The overarching goal were to review the models through group discussions, identify the main hydrological components represented by each model, and to visualize each model's parametrization schemes in a consistent manner. The process to reach this goal was not predefined, nor subject of a funded, specific research project. As a result, this process was not accompanied by social scientists who could have provided a formal staged process and documented its diverse stages. The approach was therefore less formalized and *ad hoc*, driven by curiosity and a strong commitment to

Year	Milestone/Activity	Meetings
2016	• Submission of ISIpedia proposal with HMS as Co-PI	
2017	• ISIpedia was funded (and a 0.5 FTE position to work with HMS) by German Federal Ministry of Education and Research (grant no. 01LS1711F) • At EGU2017, Ted Veldkamp presented a collection of model schemes from different models and all agreed it is hard to relate differences of model output to the model schemes when they differ so much. This could be seen as seed for this activity. • Discussion within ISIMIP modelling teams and agreement to start the activity.	• ISIMIP/ISIpedia Workshop Potsdam
2018	• SNG, HMS and CET submitted a proposal to ISIMIP to host a paper writing workshop • Presentation of the overall idea in a working group and 1) collect all components of the hydroloical cycle that are important for the models, 2) find a symbol, 3) form a diagram as a "puzzle" and 4) to draw a diagram of the water cycle on a paper • Information to modelling teams with outline of the idea and the invite to collaborate • In-depth discussion about the activity at the paper writing workshop, Frankfurt • Presentation of workshop results to the ISIMIP audience and discussion • Discussion about diagram styles, abstraction level and presentation to stakeholders • Call for information from modelling teams to fill out information for each model in tables	• ISIMIP paper writing workshop Frankfurt • ISIMIP strategy group meeting • ISIpedia stakeholder workshop Krakow
2019	• Presentation and discussion with broad scientific audience at EGU2019 and AGU2019 • Decision to split the activity into two contributions: the model review and the generation of diagrams and as the whole effort became much larger than anticipated • Developing a common mathematical notation and a definition and collecting from all modelling teams the equations for the fluxes and storages	• EGU, AGU • ISIMIP workshop Paris • ISIpedia stakeholder workshop Burkina Faso
2020	• Submission of the review paper to the journal Geoscientific Model Development	• EGU, JpGU-AGU • ISIMIP workshop online
2021	• Model review paper published: 10.5194/gmd-14-3843-2021 • Arrangement with the graphics designer to support the activity • Evolving from pen and paper to first professional drawn version of the diagrm • Continued discussion of diagrams with modelling teams via E-Mail and virtual meetings, feedback loops to graphics designer and modelling teams	
2022	• Next version of the diagrams, and WaterGAP model as example with greyed out components that repesent missing parts of a "ISIMIP2b-complete" model as example for discussion • Drafts of individual model diagrams with marks what to grey out for each model • Several interactions with co-authors to provide information what to grey out • Discussion of the diagrams and the manuscript at a paper writing workshop	• ISIMIP paper writing workshop Frankfurt
2023	• E-Mail interactions to reach consensus about the ISIMIP2b-complete diagram • Developing the idea of a script-based generation of the individual model diagrams • First draft circulated in the core writing team (HMS, SGN, LM)	
2024	• Circulation of the manuscript draft to all co-authors and subsequent improvements • Script-based generation of the individual model diagrams used as basis for diagram creation	• ISIMIP paper writing workshop Mainz • EGU • ISIMIP workshop Potsdam

Figure 1. Overview of the key milestones and meetings to discuss the progress to reach a community-based review of models including its graphical representation.

achieving the goal. In hindsight, the missing involvement of social scientists to document and guide the process was a missed opportunity. Nevertheless, a summary of the main activities and milestones is shown in Fig 1 and a detailed history of the process is given in Table S1. Later, we provide reflections and recommendations based on the lessons learned from the process, to assist other researchers with similar efforts in the future.

There have been diverse stages to draft the diagrams and with the Supplementary Figures S1-S8 we provide an insight into a selection of these diagrams to highlight their development. Finally, we decided to generate a three-dimensional diagram of the water cycle that also shows the vertical water balance in a second diagram. The motivation for this separation was to first provide an overview of the individual model's representation of the water cycle but then also to focus on a more detailed level of the vertical water balance.

2.2 From initial drafts to a final diagram

The initial stage was to collect the components (fluxes, storages) of the water cycle that should be displayed in a diagram of the hydrological cycle, as represented by a model participating in ISIMIP2b. We began compiling a list of fluxes in each storage compartment (e.g., soil, snow, canopy), which formed the basis for the visualization of the model diagrams. We then searched the internet for graphical representations of each of the components, printed them out and created a diagram as a puzzle of the single components. Furthermore, in a group exercise, we asked the members of the hydrology working group at Goethe University Frankfurt, Germany, to sketch with pen and paper, a diagram of the water cycle that included the list of fluxes we had identified (Fig. S1 for one example). Based on the pen and paper exercise, a first draft of a diagram (Fig. S2) was sent to the modelling teams. In an international paper writing workshop during the summer of 2018 in Frankfurt am Main, Germany, initial ideas were discussed for conducting a thorough review of the global water models participating in ISIMIP phase 2b, the current active phase of ISIMIP at that time. The main outcome of this workshop was the commitment to review the models in terms of how they represent the water cycle as well as to create diagrams in a consistent way. We discussed how such diagrams should be drawn, and what they should include. These discussions led to the realization that a realistic visual representation could be difficult to achieve, owing to the complexity of the water cycle and the models. To this end we attempted to present the components of each model in an abstract schematic (Fig. S3). However, it turned out that visualization on such an abstract level was not attractive for both the modellers involved and also the audience (potential users) at the ISIMIP Strategy Group Meeting in Potsdam in the same year. We therefore agreed to work towards developing a more realistic visualization scheme but kept in mind that it might be necessary to include a degree of abstraction in the diagrams.

The next important step was to present the next iteration of the drawings at two ISIpedia stakeholder workshops (Table S4). Attendees were national policy-makers, in civil society organisations, international organisations, consultancies, companies, and academic institutions. The first workshop was held in 2018 in Krakow, Poland, bringing together 21 participants from 11 countries mostly from Eastern Europe. The participants were shown three types of diagrams (Fig. S2, S4, S5). Feedback from the on-site workshop and an email survey, indicated that a conceptual "block" model diagram with mathematical symbols (Fig. S5) was hard to understand and that a more realistic visualization with words instead of equations would make the diagrams easier to interpret.

The second ISIpedia stakeholder workshop took place in 2019 in Ouagadougou, Burkina Faso, with 41 participants from 16 countries, mostly from West Africa with small delegations from East and Southern Africa. There, we reflected on the feedback of the first workshop, and developed a new diagram (Fig. S6). We also distributed a survey in English and French at the workshop.

Scientific conferences such as the general assemblies of the European Geoscience Union (EGU) and the American Geophysical Union (AGU) were welcome opportunities to discuss the development of the diagrams (Telteu et al., 2019b, a) with a broad scientific audience. Further avenues for discussion have been the ISIMIP workshops that took place annually in different formats. In these discussions, we sought input on the level of detail to include in the diagrams. Whereas discussants with a more scientific view suggested adding more details to reflect the complexity of the water cycle, stakeholders in the two ISIpedia workshops expressed the wish for a simplified representation and felt overwhelmed by too much complexity. Also, we discussed avoiding some of the classical misconceptions, e.g., to draw the aquifer as a sub-surface lake or river (Fandel et al., 2018).

Finding a common basis for such a model diagram and agreeing on the level of detail of the hydrological storages and fluxes was challenging as the focus of the diagrams was to represent how different model structures represent the global water cycle, rather than representing the entire global water cycle with all possible processes, as intended e.g., in Nell et al. (2023). Hence, the required level of abstraction as well as realism was discussed at length. These discussions resulted in the drafts of Fig. S7 and S8.

To provide a clear way forward to ourselves, we decided to focus on two main pieces of work: 1) the descriptive part of the models together with a standardized notation of how each flux in each storage is represented by each model (Telteu et al., 2021) and 2) the visualization by diagrams.

A milestone was reached in early 2021 when we involved MG, a graphics designer and science communicator. We provided the latest drafts and received the first professionally designed versions, and circulated them. After a joint virtual meeting, we decided on the final appearance of the "ISIMIP2b-complete" model. We found consensus on generating a diagram of an "ISIMIP2b-complete" global water model, characterised by its broad inclusion of water fluxes, storages, and processes represented in at least one of the models described in Telteu et al. (2021) and taking part in ISIMIP2b, without implying it to be the most thorough or exhaustive representation. The climatic input variables are shown as well as the vertical and lateral water balance and the sectors considered for the human water use. Based on this "ISIMIP2b-complete" model, we derived the diagrams for the individual models by greying out (and for people with color vision deficiency also by "x"ing out) the components that are not represented in the specific individual model. The number of layers in snow, glacier, soil, and groundwater storage are considered in the individual model diagrams, for the "ISIMIP2b-complete" diagram, the notation of "1+n" indicates that at least one layer should be represented. Please note that the inclusion of a specific flux, storage, or process can be reached at very different levels of complexity. For example, the process that reflects the CO_2 concentration on plant growth and related water use is implemented in the models in different ways and levels of detail. However, this variety cannot be accurately captured as binary information (present or absent) in such diagrams. In a series of further feedback rounds with the individual modelling teams and the graphics designer, the diagrams converged towards a final set of illustrations, which are presented here (Fig. 4).

To ensure the sustainability of the visualization approach described here, we have developed a Python-tool to automatically generate the model diagrams based on a JSON-notation of the components included in each model (Müller Schmied,

2025b). This tool was used to generate the corresponding figures represented in this study. The resulting figures are available at Müller Schmied (2025a).

3 Results

3.1 The "ISIMIP2b-complete" global water model

In the "ISIMIP2b-complete" model representation, all processes and features that could be included in a global water model based on current modelling capability within ISIMIP2b are shown (Figs. 2, 3). Thus, all names, components, and input data are displayed in colour. The term "ISIMIP2b-complete" refers to a hypothetical global water model that includes all the fluxes and storages represented in at least one model participating in ISIMIP2b. However, it does not imply that this is the optimal/best way of representing the water cycle in a model. None of the individual models considers all of these components together, so it is a hypothetical representation of the currently "ISIMIP2b-complete" global water model.

This model shows the vertical water balance (indicated with A), the lateral water balance (B), and the water management components (C) in Fig. 2. The specific illustration of the vertical water balance (Fig. 3) is also provided because, for a number of assessments, the model output of this part of the water cycle (e.g., for indicators of groundwater recharge, runoff or the variation of soil water storage) is not only relevant for society but also exhibits consistency among the models. In contrast, the components of the lateral water balance and the river routing approach differ substantially between the models and this part of the water cycle is also much more integrated with water management than the vertical water balance.

3.2 The individual ISIMIP2b global water models

The individual model diagrams are displayed in an overview for the full water balance (Fig. 4) and the vertical water balance (Fig. 5) from left to right and top to bottom in order from the highest number of included fluxes and storages to the lowest. In the Supplement (Figs. S9-S40), the individual models are shown separately and are ordered alphabetically according to their model name.

The appearance of the 16 model representations next to each other reveals that all models commonly consider snow and soil water storage (Fig. 5). Most models include canopy storage (13 out of 16), groundwater storage (11 out of 16), but only 2 models (different versions of CLM) have a representation of glacier storage. All models consider the water fluxes transpiration, soil evaporation, infiltration, and (surface) runoff, which can be considered, together with the storages described above as the core components of the hydrological cycle. Specific processes like capillary rise (included in 5 out of 16 models) and interflow (5 out of 16) are less often included, whereas fluxes like groundwater recharge are represented more frequently (15 out of 16). Interestingly, groundwater recharge is also presented for some models that lack an explicit representation of groundwater storage.

Other than for the vertical water balance, there is no commonality in the lateral water balance and water use sectors (B- and C-part of Fig. 4, respectively). Whereas a model like WaterGAP2 considers all lateral water storage types of the
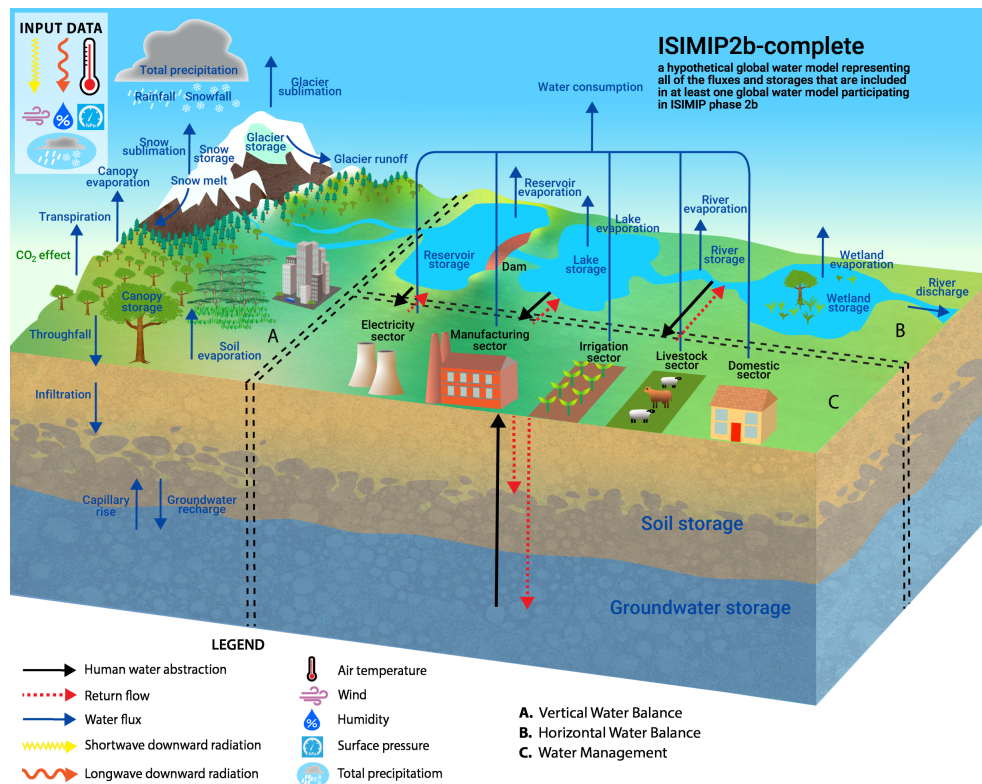
Figure 2. The representation of the components of the "ISIMIP2b-complete" global water model that participates in ISIMIP. The vertical water balance is indicated with A, the lateral water balance with B, and the water management components with C.

"ISIMIP2b-complete" representation, models like DBH, WAYS and MacPDM do not integrate any storage of the lateral water balance. Nevertheless, even though WaterGAP2 has all the surface water storages included, it does not (in contrast to e.g. PCR-GLBOWB) include evaporation from rivers and might therefore not be seen as a model that fully represents the lateral part of the water cycle.

For 9 out of 16 models, water use sectors are considered, at least with the irrigation sector. Fewer models include other sectors, and only 2 models (CWatM and WaterGAP2) consider all 5 water use sectors that are part of the "ISIMIP2b-complete" global water model. Reservoirs are included in 7 models, interestingly also in models that do not consider any water use sector (e.g. VIC). The effect of varying CO_2 concentrations is included in 8 out of 16 models.

The overview also quickly reveals differences between model versions, in particular for CLM4.5 and CLM5.0, where the different numbers of snow and soil layers are visible.
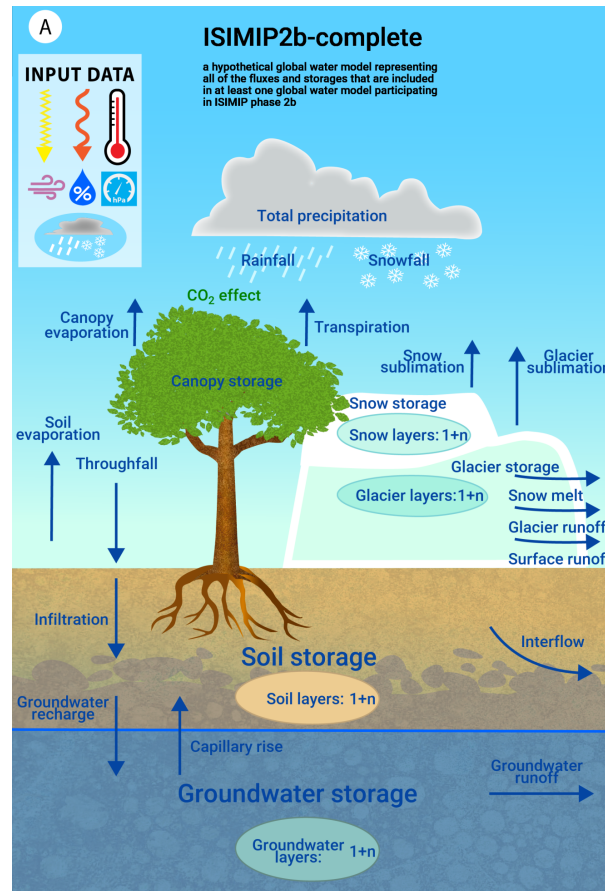
Figure 3. The representation of the vertical water balance (part A of Fig. 2) for the "ISIMIP2b-complete" global water model that participates in ISIMIP.

4 Discussion

Here we reflect on the design process, elaborate on opportunities for improvement and provide an outlook for similar activities (e.g., in the recent ISIMIP phase 3).

4.1 Reflection of the design process

The stages in developing a visual model description are quite different from the stages involved in describing the models with formulas and equations (Telteu et al., 2021). The latter required individual elements of model processes and parameterisations to be studied and compared between models, while the development of the diagrams required a higher level of aggregation, where individual processes had to be lumped together to a higher order, and consideration given as to whether they fell into any one particular part of the "ISIMIP2b-complete" model diagram.
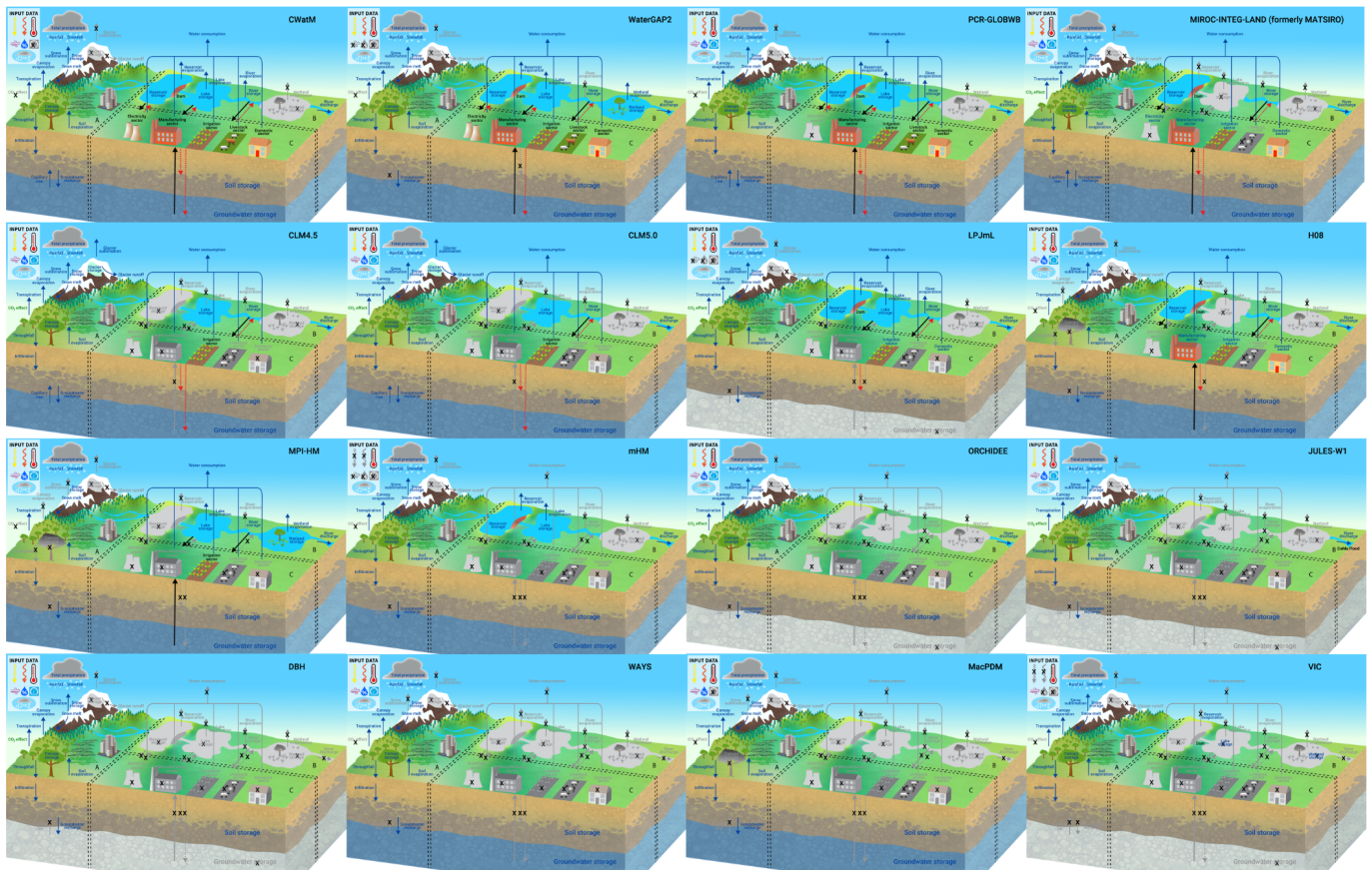
Figure 4. The components of the individual ISIMIP2b global water models, ordered by decreasing number of included fluxes and storages from left to right and top to bottom.

It became clear that this process could only be successful with a strong commitment from the modelling participants. It was challenging to achieve this, and it is perhaps one of the main reasons why so few studies have been published that use visualizations to compare environmental models. Specific challenges included the limited duration of funding to support the activity (a few months) and variability in academic staff contracts (e.g., PhD candidates graduating and then moving to new places of work with new priorities).

Communication, and the interaction with different groups (modellers, stakeholders, the broad ISIMIP audience) have been essential. The feedback from these discussions was presented at international conferences such as EGU and AGU, as well as to the ISIMIP modelling community. Abstract deadlines for these opportunities for discussion were helpful with working towards finding a timely consensus.

Intense interaction with the graphic designer was important for discussing and agreeing on how complex processes could be represented in a relatively simple, visual form. Much time was spent in developing a consensus on the right balance between visual complexity, accuracy, detail, and simplicity. For example, groundwater is often drawn like a large sub-surface lake or

river (Abbott et al., 2019; Fandel et al., 2018) but it is not trivial to represent a water-filled bedrock without creating such a misconception. Also, we discussed which shapes and icons could be used to illustrate specific features, such as vegetation. The main intention was to show a tree as in the final version to represent the canopy storage. Intrinsically, we initially sketched a typical Northern Hemisphere broad-leaf tree but during the discussion, it became clear that this inadvertently ignored the diversity of different canopy types that exist around the world in different biomes (e.g., the vegetation of an African savanna).

It took several general discussion rounds (online meetings), countless bilateral email discussions as well as several review rounds to reach a commonly agreed diagram. It was challenging to find the right balance between creating an appealing and realistic visualization while also maintaining a degree of abstractness that typically mirrors how the environment is represented in a computer model. One way that the balance was achieved, was by implementing knowledge and feedback from the experiences that modellers have had when working with non-modellers, e.g. policy-makers. Also, communication with the graphics designer helped, as she was able to provide insights from her own expertise and experiences on how complex processes can be better visualized for wide audiences. Through this process and in particular while discussing what should be greyed out or not, the modelling teams achieved an enhanced level of understanding about the representation of specific fluxes and storages in the models.

4.2 Potential uses of the model diagrams and further directions

The development of a consistent design style for visualizing the models has several benefits and uses.

Model evaluation studies show that the outputs from the models differ, even when the models are forced with consistent input data (Veldkamp et al., 2018; Zaherpour et al., 2018; Kumar et al., 2022). Whilst it is useful to understand the extent to which the models perform differently, it is also important to understand *why* the models perform differently. The latter is often challenging to address, largely because the models have been developed by multiple groups over many years (in some cases decades, e.g. MacPDM (Gosling and Arnell, 2011) or WaterGAP (Döll et al., 2003)) and because detailed knowledge of how each model works is required (Melsen, 2022). The reasons for inter-model differences are thus often only rather vaguely explained in the literature (e.g. Zaherpour et al., 2018; Veldkamp et al., 2018). We anticipate that the model illustrations will be used alongside the numerical description of different modelling components such as in Telteu et al. (2021). By comparing consistently created diagrams, we can begin to understand the differences among the models at a glance. This will further help researchers understand *why* certain model outputs differ in future model evaluation studies.

One of the underlying rationales of model evaluation studies is that they identify opportunities for model development and improvement. Given that the "ISIMIP2b-complete" model was co-created by many members of the global water modelling community, it can be used to help plan the integration of missing components or schemes into individual models. The equations and concepts detailed in Telteu et al. (2021) should also help to build the basis for model development planning. We acknowledge that the "ISIMIP2b-complete" model diagram is missing some components from the observed water cycle, including aspects of water management like flood protection measures (both green and grey (O'Donnell et al., 2021)) and inter-basin water transfer, as well as natural processes like permafrost and the role of animals such as beavers that can significantly modify river hydrology largely through dam construction (Larsen et al., 2021). Thus, the "ISIMIP2b-complete" model should

not be seen as the best way to describe and visualize the full water cycle. Rather, it should be viewed as a representation of current capabilities of the models participating in the ISIMIP2b global water sector and the specifications of the ISIMIP2b protocol. The "ISIMIP2b-complete" model diagram is likely to evolve, also as the spatial and temporal resolution is refined and finer-scale processes are represented, and also as computing power improves along with advances in artificial intelligence (Zaherpour et al., 2019), which are already leading to improvements in the capability of weather and climate prediction (Lam et al., 2023).

Given the range of inherent uncertainties and performance differences between the models (Zaherpour et al., 2019), it is often difficult to know which of the models are better suited for some applications than others, e.g., for simulating hydrology in dry regions only (see the discussion in Krysanova et al., 2020; Zaherpour et al., 2019), or for analysing only droughts (Kumar et al., 2022). Some studies focus on human interactions with the natural water cycle (Haddeland et al., 2014). The model diagrams we present here, help to illustrate the types of human interactions they include, to what extent, and how. This helps with selecting appropriate models to incorporate into selected studies. For example, if someone wants to assess the amplification of streamflow (river discharge) due to reservoir management and human water use, the user can use the diagrams to determine whether a model includes this process. Although this information can also be obtained from the equations described in Telteu et al. (2021), the graphical illustration provides a more intuitive and rapid overview of model components and structure. The value of the diagrams in the way outlined above is not limited to just human water use, e.g., they will also facilitate the identification of models suitable for studies on energy balance, CO_2 effects, vegetation dynamics, and evapotranspiration.

Previous diagrams of the global water cycle have been criticized (Abbott et al., 2019; Fandel et al., 2018) for not accurately representing the magnitude of uncertainties that exist in current scientific understanding of the fluxes and stores that constitute the cycle. For example, the use of equally thick lines for fluxes, or values of water balances without error, gives the incorrect impression that the water cycle is fully understood and not subject to refinements or scientific discussion. Our diagrams have the same limitation, in that the fluxes and stores do not have an uncertainty range associated with them. This was not the goal of our exercise, but we acknowledge that such information is important. Our diagrams do, however, illustrate the concept of structural uncertainty. The model-specific differences in the diagrams of the individual models (Sect. 3.2) show that the water cycle can be represented in different, yet plausible, ways (Butts et al., 2004). In follow-on studies, the model outputs could be assessed to quantify the magnitude of uncertainty associated with the fluxes and storages. This information could then be included in the model diagrams by representing the fluxes and storages with different drawn thicknesses that correspond to the magnitude of uncertainty.

Lastly, the diagrams serve an educational purpose and support end-users. The illustration of the "ISIMIP2b-complete" global water model helps to show what is potentially feasible based on current modelling capability in the ISIMIP2b scientific community, while the individual model diagrams help to show the different ways that models approach the process of simplifying the environment and human interactions into a numerical model form. However, advances in modelling the water cycle that are taking place in the wider scientific community, and which may happen in the future, are not directly represented in our diagram, because they are happening, or will happen, outside of ISIMIP. For example, enhancements in the spatial and temporal resolution of water models (Bierkens et al., 2015; Van Jaarsveld et al., 2025), coupling with glaciers (Hanus et al., 2024)

325   or using sophisticated ways of integrating additional information from remote sensing and calibration (Döll et al., 2024). The illustrations also help with understanding the different degrees of complexity that exist in modelling, e.g. the number of soil layers. From an educational standpoint, this helps to support understanding of the underlying basis of modelling the water cycle, and it opens the floor for a more detailed discussion about the way that processes are implemented in the models (Telteu et al., 2021). Also, this visualization of the structural model uncertainty of the current generation of global water models can

330   help to better inform end users such as readers of assessment reports (e.g., those from IPCC).

4.3   Updating the diagrams for ISIMIP3

The model diagrams presented here are for the models that have participated in phase 2b of ISIMIP. ISIMIP is currently in phase 3 (Frieler et al., 2024). Some of the models that participated in ISIMIP2b have been updated for phase 3, and, in addition, some new models are participating in phase 3 that did not participate in earlier phases. The new models do not differ significantly

335   in their representation of the water cycle compared to the 2b models. Therefore, the model diagrams presented here need only minor adaptations to accommodate the new models. Furthermore, the notation of the equations in Telteu et al. (2021) can also be used.

    In the future, the modelling teams running new or updated models will be able to provide details on the components included in their models in a structured JSON-format. Based on the (potentially updated) diagram generation tool and the provided

340   component details, a model diagram could easily be created for that model.

    We are also considering to develop an interactive, web-based version of the diagrams. This would link to the underlying equations for each part of the diagram. There could also be an option to download the model outputs. We also envisage a search facility, which would allow users to select a specific component of interest and then obtain more information about the model(s) that consider that component, as well as the available model output. Once integrated in the general ISIMIP workflow,

345   this would simplify the usability of output data and also increase the visibility and up-to-date status of the contributing models.

    In the longer term, we anticipate exploring the feasibility of applying the "ISIMIP2b-complete" model visualization to some of the models that participate in other ISIMIP sectors, e.g., global gridded crops models, biomes models, and global water quality models. The tool to generate the diagrams was designed for the specifics of the models participating in the ISIMIP2b global water sector. Hence, this is not a generic tool that can generate model diagrams for other communities but it *can* act as

350   a blueprint for such activities. A similar visualization exercise to what we describe here, taking account of the lessons learned, could be undertaken for other sectors or communities to enhance cross-sectoral understanding of the models and support assessments of model outputs.

4.4   Recommendations for similar exercises

The overall process of producing the model diagrams presented here has taken nearly a decade and we underestimated the

355   effort required to achieve our goal. However, we gained a lot of experience during that time and we use this as a basis for providing below a set of recommendations for similar exercises, based on the lessons learned:

– apply principles of project management so that the process is streamlined, with clear deadlines, responsibilities and goals outlined;

– involve social scientist(s) in the process so that formal methods of collaborative working from other disciplines can be integrated into the process;

– formally document each stage and discussion so that there is a record of (and reasons for) decisions, which will help when new people join the collaboration and also for clarity in later stages (which may be many years later);

– unfunded 'side-of-desk' activities such as this can be challenging to manage and complete, so so we recommend securing funding to support a (group of) dedicated staff member(s) for the project, and to pay the main contributors (modeling groups in our case) for the time needed to commit to the project, if possible;

– conduct regular in-person and virtual meetings for discussing the process to avoid lengthy email discussions;

– consider sustainability from the beginning (e.g. by designing a tool for automatic diagram generation) to focus using funding for the design of the prototype rather than for the individual diagrams;

– generally work in a collaborative online working space to offer every participant the opportunity to see the status and progress at every point in time;

– actively search (and create) occasions to discuss the process and results with potential users, modellers, stakeholders, and other scientists;

– summarize the outcome and ideas of such discussions and sketch the consequences of the recommendations (pros and cons) for the diagram itself but also for the scope of the exercise to have a basis for discussing the next steps for diagram design; and

– discuss this outcome openly with the participants of the exercise and decide as a team the way forward.

5 Conclusions

This study provides insights from a community effort to illustrate the components of the terrestrial part of the global water cycle that are currently simulated by a set of state-of-the-art global water models participating in the ISIMIP phase 2b exercise. Based on inclusive discussions between the modelling teams and a graphics designer, we co-developed an "ISIMIP2b-complete" representation of the global water cycle components that several of the current generation of global water models can theoretically simulate. We then showed how individual models include/exclude some of the processes that appear in the "ISIMIP2b-complete" model by greying out processes where they do not appear, and also by adding the number of layers for different storages.

385   The process has highlighted the challenges and opportunities in creating a set of standardized model description diagrams. The process has been lengthy and required multiple iterations with different user groups, but the final set of diagrams has many potential uses. These include helping to assist with understanding differences in model performance, and identifying which models to include in future studies. The diagrams also serve an educational purpose, foster a better understanding of modelling results and their potential use in e.g. policy-making or adaptation planning, and they provide a basis for future model
390   development.

        Although the models included in our study are not exhaustive (not all global water models participate in ISIMIP2b), they provide a point of reference for what is currently achievable from a large set of global water models, some of which have been developed over several decades. Looking to the future, the automated creation of the diagrams enables continuation and adapting of such graphical representations when models are updated and when new models join the ISIMIP exercise. We also
395   hope that our experience and results will inspire other earth system science modellers who are interested in other aspects of the environment, to produce similar model ensemble visualizations that enhance understanding of each others' models.
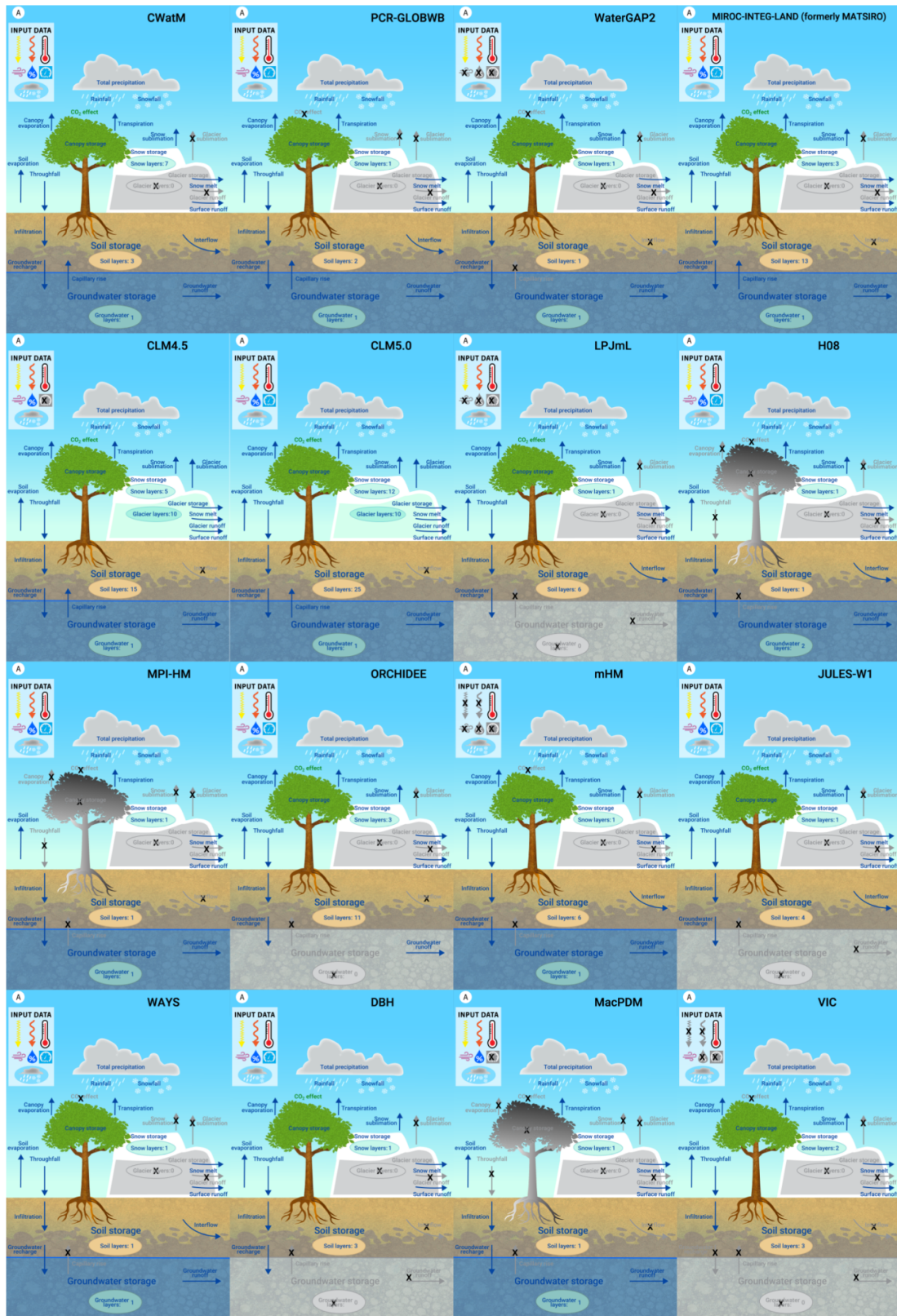
Figure 5. The components of the vertical water balance of the individual ISIMIP2b global water models, ordered by decreasing number of including fluxes and storages from left to right and top to bottom.

Code availability. The diagrams are initially drawn by using Adobe Illustrator. The single elements have then been extracted and composed within a Python-script and based on a json notation of the components of the ISIMIP2b-complete and individual models. The code is available at Müller Schmied (2025b).

400 *Data availability.* No model output is used in this particular study. The resulting diagrams are available at Müller Schmied (2025a).

Author contributions. CET led the conceptualization and organization of the graphical representation of the ISIMIP2b models under guidance of HMS starting in 2017, and HMS took over the process in 2022. The initial idea to commonly provide the graphical representation of the ISIMIP2b models was proposed by HMS, who also obtained funding for the graphics designer. MG initially created the graphics with input and feedback obtained from CET and HMS, who both collected the feedback from the individual modelling teams. All other co-authors
405 (and including CET, SNG, HMS) directly provided feedback to the representation of the "ISIMIP2b-complete" model, and in the particular models of the modelling teams. HMS created the script to automatize the creation of the final figures presented here. CET led and conducted the stakeholder interaction. HMS wrote the initial draft of the manuscript and LM and SNG critically reviewed and revised it. All authors reviewed, commented on and contributed to the final draft.

Competing interests. The authors declare that no competing interests are present.

410 *Acknowledgements.* The present study was possible through the international ISIMIP framework. The authors thank Ted Veldkamp for a presentation at EGU general assembly 2017 where she was trying to relate different model results to model schemes, showed a slide with some published schematics of the models in the global water sector and concluded that it is hard to elaborate on the differences when there is no commonality in those visualizations. This can be seen as seed for this community effort. We thank the ISIMIP coordination team for providing funds for the workshops where this paper could be discussed. This paper is also based upon work from COST Action
415 PROCLIAS, CA19139 supported by COST (European Cooperation in Science and Technology). We thank Antolii Shmurak, Aimé Koudou, Tim Trautmann, Robert Reinecke, Inge de Graaf and Nils Moosdorf for constructive feedback in the workshops. Furthermore, we acknowledge the support from Alicia Böhme for extracting the individual elements of the model diagram that enabled the creation of the model diagram generator. CET and HMS acknowledge the German Federal Ministry of Education and Research (grant no. 01LS1711F). YP acknowledges support from the National Science Foundation (Award number 1752729). OR acknowledges support from the AdAgriF project
420 (CZ.02.01.01/00/22_008/0004635). HMS is grateful to Lotta Müller Schmied for using the background image for Fig. 1 that has been drawn by her. The authors acknowledge the detailed and helpful comments and suggestions by Wouter Knoben and an anonymous referee.

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