

RESEARCH ARTICLE

How do hydrologists perceive watersheds? A survey and analysis of perceptual model figures for experimental watersheds

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Abstract

To describe process knowledge at the watershed scale, hydrologists commonly refer to a 'perceptual model', an expert summary of the watershed and its runoff processes often supported by field observations. Perceptual models are often presented as a schematic figure, although such a figure will necessarily simplify the hydrologist's complex mental model. In this paper, our aim was to understand what constitutes a visual expert summary of watershed process knowledge, and to evaluate how perceptual models could be used to share hydrological process information at larger scales. To do so, we conducted a systematic review of the literature and found 63 perceptual model figures. We counted and categorized the stores and fluxes in each figure using a taxonomic classification and quantified a variety of figure attributes including spatial or temporal zonation, inclusion of vegetation, soils, topographical and geological data and consideration of uncertainty. Our analysis showed that a typical figure has 1 surface flux, 4 subsurface fluxes, 3–4 subsurface stores and 0–1 channel stores; 28 out of 63 figures use sub-figures to show temporal dynamics (e.g., wet/dry conditions), and 12 out of 63 show spatial zones. Perceptual model figures, therefore, provide a concise summary of watershed processes with a complexity comparable to that of many conceptual hydrological models. However, only four figures showed any information on uncertainty or knowledge gaps. We recommend that perceptual figure value could be easily increased by consistent captioning of figures to assist automated search, and wider use of standard figure annotations such as legends and scale markings to ensure that information is fully conveyed to the user. If perceptual figures are proposed as a primary method for sharing process information, the hydrological community should consider how to link more detailed text descriptions to figures, and how to represent process uncertainty.

KEYWORDS

perceptual figure, perceptual model, process knowledge, runoff processes, systematic review, taxonomy

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1 | INTRODUCTION

Hydrologic processes describe the flow paths and mechanisms that move water from the canopy and land surface to its release as streamflow, deep groundwater flow or evapotranspiration. Process knowledge is widely needed in hydrology, including for modelling, for watershed management, and to develop fundamental theories about watershed response. Process knowledge is typically described at the hillslope or watershed scale, by field hydrologists and local experts. One method that experts use to communicate their knowledge is a 'perceptual model', an expert summary of the watershed and its most important hydrological processes that is commonly presented as a figure (Beven & Chappell, 2021). However, a challenge for knowledge-sharing methods is that hydrologists are increasingly developing models and analysing water use at national or global scales, requiring process knowledge on similarly large scales. The question we address here is therefore, how can we learn from watershed-scale perceptual models to understand what constitutes a typical summary of watershed process knowledge? Answering this question is a first step towards developing datasets of process knowledge across large samples of watersheds.

Process knowledge for large samples of watersheds is needed for multiple reasons. Large-scale streamflow prediction and earth system models now offer flexible model structures (Clark et al., 2015), and process knowledge is needed to choose between structures, simulate spatially variable processes, and improve model performance and model realism (Markstrom et al., 2016; Prieto et al., 2021, 2022; Wagener, 2003). Models that provide 'the right answers for the right reasons' are vital for trustworthy predictions under novel climate or land use conditions (Kirchner, 2006). In watershed management, process knowledge is needed to design successful restoration programs that mimic the natural water transport, storage and release processes that control flow regime and sediment and nutrient supply to the stream (EPA, 2012; Roni et al., 2002). Overall, large-sample process knowledge is essential to understanding how emergent hydrologic behaviour derives from patterns of climate and landscape (Fan et al., 2019; Sivapalan, 2006), and understanding knowledge gaps can guide future monitoring and data collection needs (Wagener, Dadson, et al., 2021).

Despite its usefulness, process knowledge is not simple to define. Processes include all functions of a watershed, which can be grouped into partitioning (e.g., infiltration), storage (e.g., groundwater storage) and release of water (e.g., evapotranspiration) (Black, 1997; Wagener et al., 2007). The scope of all possible processes of interest is very large, and the processes of interest will depend on the purpose of the perceptual model. Many processes cannot be measured directly, and must be inferred from measurements of stores or fluxes. For example, at Panola watershed, Georgia, groundwater level and piezometric data were used first to infer subsurface flow direction, then to infer variation in water and nutrient fluxes, and lastly to analyse hydrologic connectivity between hillslopes and channel (Bracken et al., 2013; Hopp & McDonnell, 2009). This example shows the key role of experts in translating raw field measurements into derived knowledge

of a watershed's dominant flow pathways. Derived process knowledge is also known as 'soft data' and it provides a valuable way to draw conclusions about system behaviour and choose appropriate model complexity based on expert interpretation (Fenicia et al., 2008; Seibert & McDonnell, 2002).

Derived process knowledge can be communicated using a perceptual model, a 'qualitative (and personal) summary of our knowledge about a system and its complexities, which evolves over time' (Beven, 2001; Westerberg et al., 2017). These models are often presented in journal articles as a schematic figure showing watershed stores and runoff pathways, although such a figure will necessarily simplify the hydrologist's complex mental model. Perceptual models have great potential to accumulate and share hydrologic knowledge (Wagener, Gleeson et al., 2021), identify knowledge gaps (Wagener, Dadson, et al., 2021), and condition or evaluate predictive models (Beven & Chappell, 2021). For example, Hartmann et al. (2015) used perceptual model figures to organize knowledge of carbonate rock regions and improve recharge predictions, while Viglione et al. (2018) used perceptual model figures to promote knowledge sharing between geologists and hydrologists. Further, perceptual model figures can be used to illustrate how process understanding has evolved over time (McGlynn et al., 2002).

Recent advances in large-scale modelling, big data science and open science provide the opportunity and the motivation to extend perceptual model concepts to larger samples of watersheds. Learning for large samples offers new opportunities to use comparisons between watersheds to understand which physical features drive the differences in runoff generation processes (Lohse & Dietrich, 2005; Soulsby et al., 2006; Zimmer & Gannon, 2018). Development so far has focused on the need to create systematic procedures for developing perceptual models. Tetzlaff et al. (2008) discuss the need for 'simple rules and/or clear procedures to determine the dominant processes', while Wrede et al. (2015) suggest a four-stage process where perceptual models are developed through the sequential use of physiographic analysis, soil and drilling surveys, streamflow and tracer responses, and computer models. Dominant Runoff Process (DRP) mapping produces an alternative style of perceptual model consisting of a watershed map with each area labelled according to its DRP. Antonetti et al. (2016) show that automatic DRP methods based on GIS analysis can come close to reproducing manually derived maps. A recent study advances the concept of a distributed perceptual model, demonstrated across a 27 000 km² catchment (Fenicia & McDonnell, 2022). The model was created using five streamflow signatures as indicators of runoff processes in the upstream catchment, together with expert analysis of the influence of climate and landscape attributes that cause variability in each signature. These examples demonstrate the continued relevance of understanding what constitutes a good summary of watershed process knowledge and how this can be captured in a perceptual model.

The aim of this paper is therefore to leverage the extensive expert knowledge contained in perceptual models published in the hydrologic literature, and to analyse how experts describe watersheds they know well. We survey papers describing well-studied watersheds

where authors provide a perceptual model figure, that is, a figure providing an integrated description of watershed processes. For each figure, we evaluate which stores and fluxes are included, and whether the figure describes spatial or temporal heterogeneity (e.g., processes under wet and dry conditions, or in different spatial zones), flux magnitudes, uncertainties, and more. Our analysis will provide insight into which processes and temporal/spatial variations are viewed by watershed experts as most critical in defining watershed function. Our results will contribute to guidance on how perceptual models could be used to share process knowledge over large numbers of watersheds.

2 | METHODS

Our method had three parts. First, we collected source papers that included perceptual model figures. Second, we extracted set information from each perceptual model figure, such as how many and which stores and fluxes were included. Third, we analysed the extracted data for patterns in how experts formulate perceptual model figures.

2.1 | Collection of perceptual model figures

Our aim is to conduct a systematic review of perceptual model figures in the hydrologic literature, focused on runoff generation processes. As Wagener, Gleeson, et al. (2021) argue, a clearly communicated strategy for the choice of reviewed papers strengthens the grounding and contribution of hydrological studies. Best practices for systematic reviews are summarized by the PRISMA method, which includes a checklist for considerations such as eligibility criteria, sources and screening and elimination strategies (Moher et al., 2009). In our case, it is not easy to identify criteria for a citation database search that would return all papers that include a perceptual model of runoff generation processes. We therefore used a combined method of a systematic search, augmented by specific lists of papers relating to experimental watersheds.

Our database search used the following search criteria on Google Scholar: 'Runoff generation' and ('perceptual model' or 'conceptual model' or 'conceptual diagram'). We used the first 500 results from this search, ordered by relevance. The following pre-compiled lists were added to the results: reference list for taxonomy of hydrological processes (McMillan, 2022), reference list of process descriptions in critical zone observatories (McMillan et al., 2022), reference lists from experimental watersheds in the Experimental hydrology wiki (<https://experimental-hydrology.net>), and papers contained in the Hydrological Processes special issue on 'Research and Observatory Catchments: the Legacy and the Future'.

After removing duplicates, the results returned from the search were first screened using eligibility criteria as follows. The article should be a peer-reviewed journal article (not a conference abstract, book, or thesis), written in English. The article should be about a specific watershed and not a general class of watersheds. For articles meeting those criteria, we searched the article for a perceptual model

figure. The figures were further screened for eligibility as follows. The figure should represent runoff generation throughout the watershed and not just in some sub-system. The figure should have stores and/or fluxes labelled in the figure or in the caption. The figure should relate to understanding of the physical system and not its representation in a computer model.

These eligibility criteria reflect our interpretation of what is meant by a perceptual model figure. Alternative interpretations might return a different set of figures, for example, those that focus on the sources of water used by vegetation and released as evapotranspiration (e.g., Brooks et al., 2010). We selected figures that represented runoff generation mechanisms, and while many of the figures we found also referred to residence and transit times of water, we did not insist that this was included. The terminology 'perceptual model' has been used to refer to generalized concepts of how water moves through a watershed (e.g., the fill and spill concept, McDonnell et al., 2021), but we restricted our review to perceptual models related to a specific watershed. Finally, we found large variations in the extent of the field-work used to create perceptual model figures, from those developed over many years and papers (e.g., Hewlett & Hibbert, 1967; Sidle et al., 2000), to those based on a single study. We included both extremes within our definition of a perceptual model figure, but some early-stage figures might be considered more akin to hypotheses, while late-stage figures have been confirmed by multiple investigators.

2.2 | Extraction and coding of data from perceptual model figures

We manually collected the following data for each instance of an eligible perceptual model figure.

In some cases, expert judgement was needed to determine which stores/fluxes to include and how to classify them. The following rules were applied to ensure consistency. Precipitation was not included in the flux list as this is assumed to occur in all watersheds, and although it might form part of a hydrologist's perceptual model it was only occasionally labelled. Stores that were labelled but not shown as interacting with water movement (e.g., impermeable bedrock) were not recorded. Water table was recorded as a store in addition to groundwater as these were both commonly marked on figures, although the water table is not always simple to define or measure (Baird & Low, 2022). Fluxes or stores not matching those in the process taxonomy were recorded as new items. Where multiple items in the figure mapped to the same taxonomy item, these were recorded as duplicates (e.g., Soil Water Storage 1, Soil Water Storage 2). Fluxes or stores marked with an arrow or water level but not labelled in the diagram were recorded if they were described in the caption or if the meaning was clear from the diagram. Fluxes marked with a generic term in the figure but described with more specificity in the caption or surrounding text (e.g., 'surface runoff' in figure described as 'saturation excess runoff' in text) were recorded with the more specific term.

2.3 | Collection of perceptual model figures

The analysis of information in the perceptual models was structured around a series of overarching questions, designed to provide an overview of what constitutes a typical summary of watershed process knowledge.

2.3.1 | How detailed or complex a description of runoff generation processes is typical?

To provide an overview of the amount of information in perceptual model figures, we counted the number of stores and fluxes marked on each figure. To determine which parts of the hydrological cycle were most commonly included in perceptual figures, we used the list of equivalent names from the hydrological process taxonomy. The taxonomy separates process names into three Domains (Surface, Subsurface and Channel), and within those provides three further levels of hierarchy as Class, Process, and Sub-process. Items at the same level are intended to have a comparable complexity, with 'Process' being at the typical level of a pathway included in a runoff generation model (McMillan, 2022). Using the taxonomy classification, we quantified the number of stores and fluxes in each Domain, Class, Process and Sub-process and at each level of the hierarchy. By plotting the numbers of processes throughout the taxonomy, we could visualize the parts of the hydrological cycle that were more or less well represented, and the hierarchical levels commonly provided.

2.3.2 | How can watershed heterogeneity be described in a perceptual diagram?

It is well known that topography, vegetation, soils and other features are heterogeneous below the watershed scale. Even when processes are considered to be emergent at larger scales, they often exhibit variability in space and time. For example, processes may vary during an event as different flow paths are activated, or seasonally as temperature and precipitation patterns shift. We were therefore interested in how heterogeneity was represented in perceptual model figures. We tallied the numbers of figures that used sub-panels for spatial or temporal zones, and described the most common categories. We further analysed whether figures showed variability in magnitudes between flow pathways, and if so what qualitative or quantitative method was used to show the differences.

2.3.3 | Are there different approaches to creating a perceptual model diagram?

The use of perceptual models and their accompanying figures is something that has developed organically in the hydrological community. We were therefore interested in whether different approaches to

developing the figures had been developed for different applications or by different authors. Based on the 'Figure Information' data described in Section 2.2, and other notable features of the figures, we described possible classification types for the figures.

3 | RESULTS

3.1 | Collection of perceptual data sources

Our systematic search returned 1404 potential papers, of which 500 came from the keyword search, 103 from the Hydrological Processes special issue on 'Research and Observatory Catchments: the Legacy and the Future', 669 from the reference lists in the Experimental hydrology wiki, 24 from critical zone observatory references and 108 from hydrological taxonomy references. From those papers, we found 63 perceptual model figures that met the criteria as described in Section 2.1 (3% of papers). The low percentage reflects the wide scope of articles returned by our search, and the difficulty in finding search terms that pinpoint papers that summarize runoff generation processes. Examples of perceptual model figures that met our criteria are shown in Figure 1. The reference list in BibTex file format is available in Data S1.

3.2 | Extraction and coding of data from perceptual model figures

For each of the 63 perceptual model figures, we collected information as described in Table 1. This included transcribing lists of the stores and fluxes shown in the figure, and matching each of these to their equivalent term in the hydrological process taxonomy (McMillan, 2022).

3.3 | Analysis of perceptual model information

3.3.1 | How detailed or complex a description of runoff generation processes is necessary?

On average, perceptual model figures contained 4–5 stores (mode = 4, mean = 4.2), of which a mean of 3.3 related to the subsurface, 0.3 to the surface and 0.6 to the channel. They contained 4–5 fluxes (mode = 4, mean = 4.6), of which a mean of 3.6 related to the subsurface, 0.8 to the surface and 0.2 to the channel. We interpret these numbers as related to the extent of expert knowledge on runoff generation available for watersheds, and the quantity of information needed for experts to provide a runoff generation summary to other hydrologists. An understanding of the complexity of the average expert-drawn perceptual model figure will provide an initial guide as to the complexity we might aim for when collecting or developing perceptual models for large samples of watersheds.

To analyse which parts of the hydrological cycle are most commonly included in perceptual figures, in Figure 2 we overlaid our

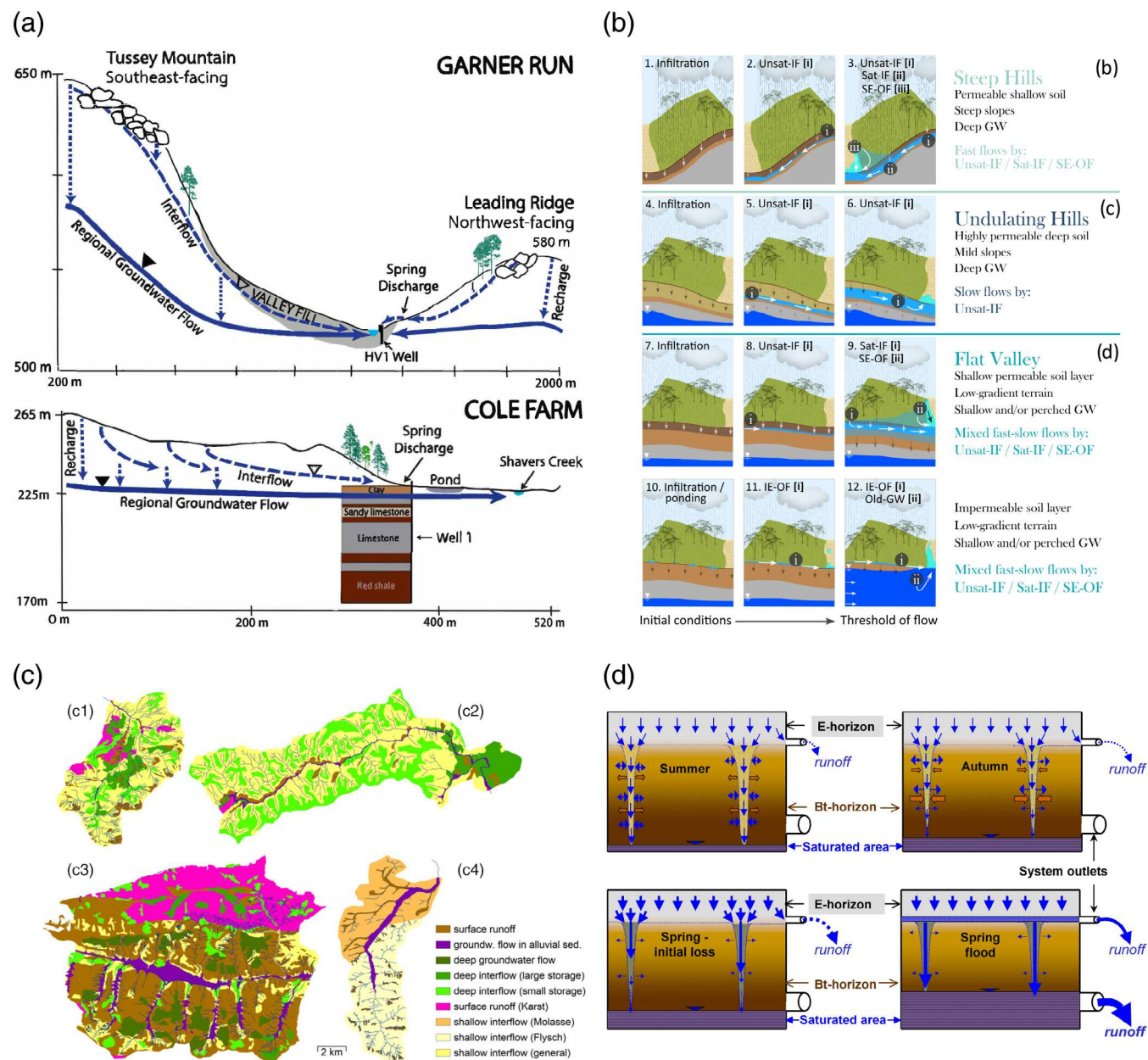


FIGURE 1 Examples of perceptual model figures included in our review. (a) Two watersheds in the Susquehanna Shale Hills critical zone observatory. Source: Reproduced from Li et al. (2018). (b) Pedler Creek in South Australia. Source: Reproduced from Gutierrez-Jurado et al. (2021). (c) Four Austrian catchments: (c1) Dornbirnerach; (c2) Gail; (c3) Wimitzbach; and (c4) Perschling. Source: Reproduced from Viglione et al. (2018). (d) The Upper Volga basin. Source: Reproduced from Helms et al. (2006).

results on a diagram of the taxonomy of hydrological processes (McMillan, 2022; their Figure 1). The area of each circle represents the total number of times each store or flux was found. The type of process is indicated by the sector of the diagram, and the level of detail in which stores or fluxes are described (process class, process, or sub-process) is indicated by the inner to outer rings. The results show that Subsurface Processes in yellow dominate the perceptual model figures (428 instances), followed by Surface Processes in green (82) and Channel Processes in blue (50). The most common classes in Subsurface Processes were Groundwater (209), Soils (130) and Sub-surface Stormflow (72). The most common classes in Surface

Processes were Overland Flow (36), Infiltration (16) and Evapotranspiration (11). The most common class in Channel Processes was Channel Storage (36). For level of detail, diagrams most commonly contained Processes (301), followed by Sub-Processes (177) and Classes (87).

Some parts of the hydrological cycle were poorly represented in our survey. This is partly due to our selection of perceptual model figures that represent runoff generation processes and not, for example, figures that focus on evapotranspiration or floodplain processes. There were many surface processes recorded in the taxonomy that were never found in perceptual model diagrams, particularly in the

TABLE 1 Information collected from each perceptual model figure.

Article information	Citation, watershed name, watershed location (Lat/Lon)
Figure information	Figure number, number and description of figure sub-panels for spatial or temporal zones (e.g., wet/dry conditions), inclusion of flux magnitudes (e.g., by arrow width), inclusion of vegetation/soil/geology names, inclusion of topographic or 3D information, inclusion of uncertainty information.
Store and flux information	Numbers of stores/fluxes, names of stores/fluxes on figure, equivalent store/flux names from hydrologic process taxonomy (McMillan, 2022)

classes of snow, glacier, frozen ground, and evapotranspiration. Channel processes apart from channel storage were rarely found. These are in contrast to the subsurface processes where almost all processes in the taxonomy were found in at least one perceptual model figure. These results point to a greater emphasis on water transport and storage processes, and a lesser emphasis on the surface partitioning and channel processes that control the quantity of water entering and leaving the watershed. This contrast was further emphasized by the fact that few figures showed details or labels for surface features and vegetation. Only three articles used labels or legend entries to describe vegetation (differentiating vegetation category, species or dormant and active vegetation), and a further 15 had unlabelled icons (of grasses, conifers) that might be intended to confer vegetation information.

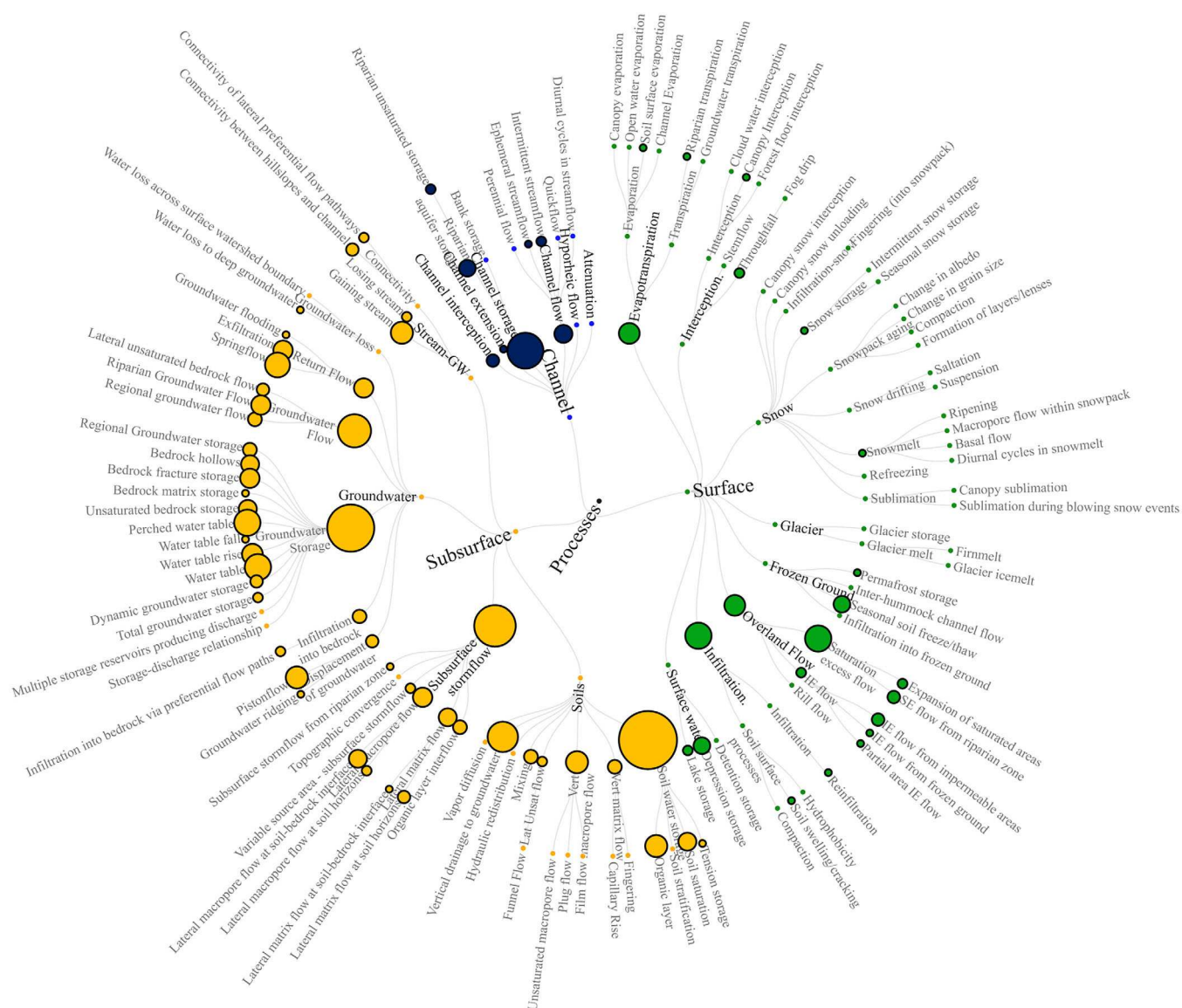


FIGURE 2 Number of instances of each store and flux found in the review of perceptual model figures, overlaid on the taxonomy of hydrological processes reproduced from McMillan et al. (2022). Areas of black-edged circles are proportional to the number of instances of each process. Smallest dots without edging indicate processes in the taxonomy that were not found in any perceptual figure. Colours indicate surface processes (green), subsurface processes (yellow) and channel processes (blue).

3.3.2 | How is watershed heterogeneity described in perceptual model diagrams?

Most perceptual models had only one figure panel, that is, they did not use multi-part figures to show spatial or temporal heterogeneity across the watershed (Figure 3). This might reflect insufficient information to summarize processes under multiple conditions, or that authors felt that readers would intuitively understand that some processes such as surface flow or interflow would only occur during events. Where multi-part figures were used, temporal zoning was more common than spatial zoning. Most figures have only one spatial zone (51 figures), with seven figures having two zones and five figures having more than two zones. Example spatial zonings included hill-slope steepness, aspect and thickness of weathered bedrock. Thirty-five figures have one temporal zone, with 11 figures having two zones and 17 figures having more than two zones. Most temporal zonings related to wetness conditions, seasonality, or event stage. The figure with the largest number of temporal zones (5; Wang et al., 2020) used multiple thresholds relating to the infiltration and storage capacities of soil and epikarst subsurface layers. Therefore, we found that catchment wetness was the most important heterogeneity when describing

runoff generation processes. This matches Beven's (2001) description of a perceptual model of runoff generation as a summary of 'how the catchment responds to rainfall under different conditions'.

We analysed the perceptual model figures for whether they showed variability of magnitude between fluxes, or showed one flux as dominant. Most figures (51) gave no indication, while nine figures used varying size or width of arrows to show magnitude. These differences are assumed to be qualitative, that is, the width is not directly proportional to flux magnitude, as arrow size was not typically described in the legend or caption. For two diagrams the arrows were somewhat different in size but it was unclear if this had significance.

3.3.3 | Are there different approaches to creating a perceptual model figure?

We reviewed the collection of perceptual model figures to elicit themes or variations in the style of figures. We found several choices in the way that figures are presented, these are depicted in Figure 4.

Despite these differences, we found that most figures conformed to the expected format of showing a watershed cross-section that

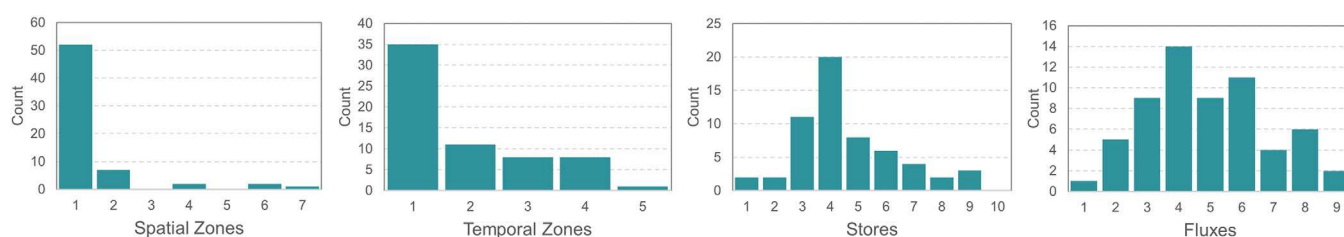


FIGURE 3 Histograms of numbers of spatial and temporal zones, stores and fluxes found in the perceptual model figures.

Role of the figure	Figure early in paper to inform study	Figure towards end of paper as study result
Independence of figure	Figure is stand-alone	Figure is better/only understood with text
Focus of paper	Hydrometric or tracer data	Modeling
Point of view	Cross-section	Plan View or Longitudinal
Arrows shown	One arrow per flux	Many arrows show water pathways
Fluxes shown	Water only	Includes water age, nutrient flux or other
Features shown	Only flow paths shown	Background features e.g. soil, vegetation
Legend	Legend shown	No legend
Scale bars	Scale bar(s) shown	No scale bars
Scale of the figure	Watershed scale	Hillslope scale
Uncertainty information	Some uncertainty	No uncertainty information

FIGURE 4 Styles of perceptual model figures identified in our study. Bar size indicates the proportion of figures in each category.



FIGURE 5 ArcGIS Dashboard viewer for Perceptual Model Database.

(at minimum) marked the major water flow paths. Of note as a different style of figure were the ‘process maps’ used by Viglione et al. (2018) (reproduced in Figure 1c), which use a plan view to break up the watershed into detailed hydrologic regions, and display only the dominant flow path in each region. These are similar to maps used by Schmocker-Fackel et al. (2007) and Antonetti et al. (2017; see also references in their table 1) to show DRP estimated using GIS techniques.

3.4 | Perceptual model visualization and search

Our search returned 63 perceptual figures, which we coded according to the stores and fluxes included, as well as other characteristics of the figures (see Section 3.2). To make these figures discoverable and searchable, we created a GIS dashboard that can be viewed at www.mcmillanhydrology.org/PerceptualModelDashboard.html (Figure 5). In the left panel, the dashboard allows search for figures that contain a given store or flux, specified using plain text or by hashtag identifier from the process taxonomy (McMillan, 2022). The hashtag allows search for process groups, for example, the partial hashtag ‘Surf.Over’ contains all overland flow processes such as ‘Surf.Over.IE.Frozen’, meaning infiltration excess flow from frozen ground. Figures can be filtered according to whether they show spatial or temporal zoning, by other features, and by watershed area. Clicking on an icon displays a panel with a link to the article, displaying the perceptual model figure if it is open access, and with store, flux and other information. This dashboard will be updated in future as we collect additional perceptual model figures, and we invite readers to contact the first author if they are aware of new figures that meet our eligibility criteria.

Figure 5 shows that our review contained perceptual model figures from six continents, having a reasonable global spread with bias towards North America and Europe. Given that we expect the stores and fluxes found in the figures to depend on the watershed hydroclimate, we tested the representativeness of the watersheds' climate zones using three climate indices (Figure 6). Using the location of each watershed, we calculated aridity, seasonality and snow fraction indices as defined by Knoben et al. (2018). Aridity and seasonality indices are based on the mean and range of monthly Thornthwaite's moisture index MI (Willmott & Feddema, 1992). Snow fraction index represents the fraction of precipitation falling as snow (Woods, 2009). Equations for these climate indices are given in Appendix A. Indices for the perceptual figure locations are overlaid on those for all global pixels, showing that the figures succeed in capturing almost the full global range of each index. Compared with the global distribution, perceptual figure watersheds are somewhat more likely to be located in humid, less seasonal and mostly snow-free environments.

4 | DISCUSSION

4.1 | How complex is an expert perceptual model figure?

The complexity of perceptual model figures shows how much detail experts use when producing a graphical summary of their watersheds, and therefore guides us on how much detail is deemed necessary to summarize key processes. We reiterate that the perceptual model figure will almost certainly simplify the hydrologist's expert understanding. A typical figure had 1 surface flux, 4 subsurface fluxes, 3–4

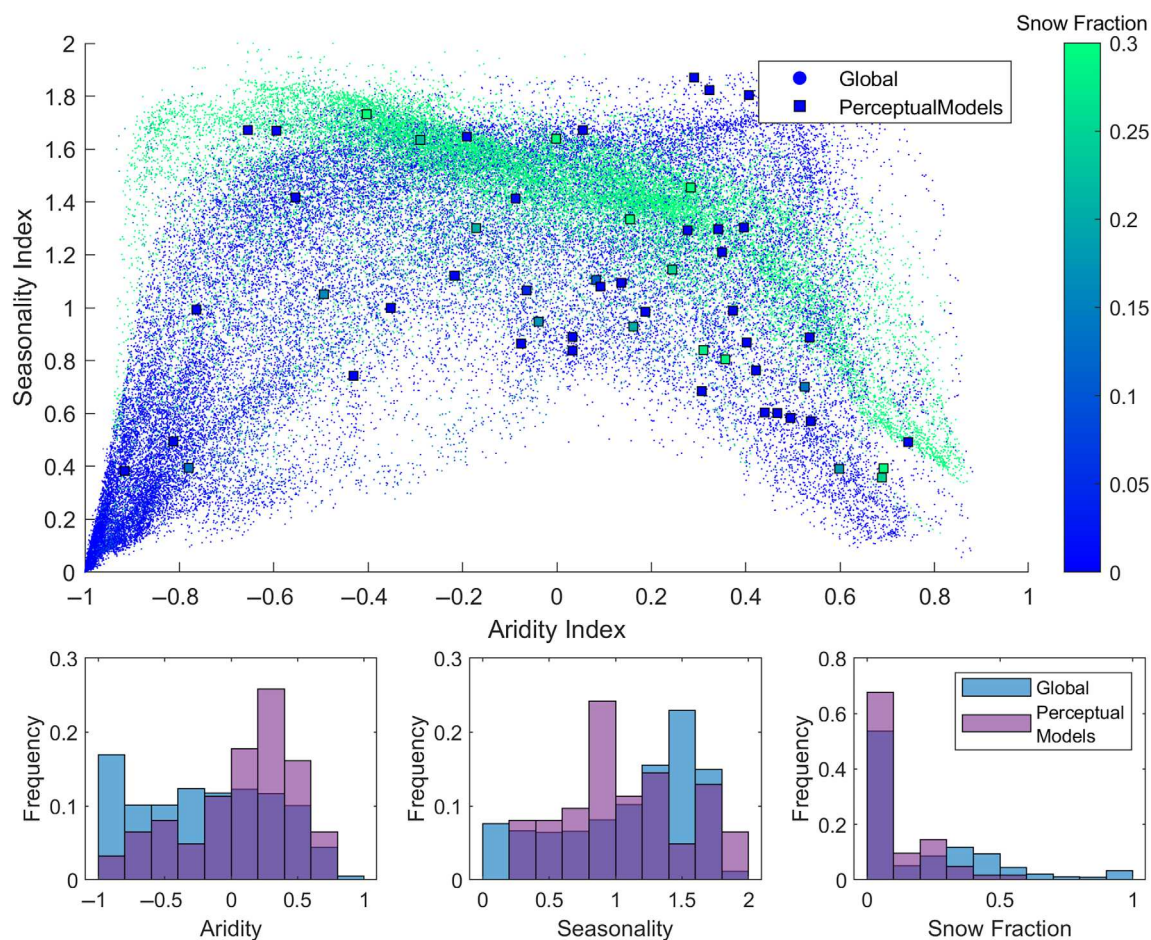


FIGURE 6 2D Scatter plot and 1D histograms of climatic representativeness of perceptual model locations, overlaid on indices for all global pixels. Positive aridity indices indicate humid climates and negative aridity indices indicate arid climates. High seasonality indices indicate strong intra-annual changes in the water budget. Equations for climate indices are given in Appendix A.

subsurface stores and 0–1 channel stores. These numbers reflect the information needed to describe DRP, and how much information is known in well-studied watersheds. They are similar to a conceptual ('bucket') model, suggesting that perceptual model figures might be a useful tool to evaluate model structure choices (Beven & Chappell, 2021). However, as most figures lack flux and store magnitudes timescales, they would not be sufficient to define or constrain parameter values. Most cases used a single figure, without subplots to show spatial heterogeneity. Most figures (46 of 63) were presented at watershed scale, and 17 of 63 were at the hillslope scale. Presentation at watershed scale is consistent with the Representative Elementary Area theory that for areas over 1 km², hydrologic responses stabilize over space (Wood et al., 1988). Therefore, a single figure is suitable for areas over 1 km², whereas a collection of smaller-scale subplots might miss out watershed-scale processes that can include longer, subsurface flow paths (Frisbee et al., 2011). We note however that larger spatial features such as geological boundaries or inter-basin groundwater flow can dominate process regimes (Muñoz et al., 2016; Pfister et al., 2017; Tague & Grant, 2004), an example where perceptual models with multiple spatial zones would be appropriate.

Stores and fluxes in perceptual figures are strongly biased towards the subsurface, with surface and channel processes shown

less often. We can suggest several hypotheses to explain the predominance of subsurface stores. The subsurface emphasis could reflect the bias in our dataset towards humid and snow-free environments (Figure 6). The subsurface emphasis could reflect the strength of its control on runoff dynamics. For example, Fenicia and McDonnell (2022) find that vegetation and soil types do not control streamflow dynamics in their watershed, and so do not include them in the perceptual model. However, their work focused on differences in streamflow dynamics between sub-watersheds; surface processes might be more important when explaining differences between regions. The subsurface emphasis could relate to measurement techniques. Articles using isotopes or tracers were more likely to include perceptual models, perhaps because tracers provide watershed-scale information on flow sources (Tetzlaff et al., 2008). Indeed, McDonnell and Beven (2014) argue that all watershed investigations should include tracer measurements to complement hydrometric measurements and evaluate the velocity as well as the celerity of water; 28 out of our 63 perceptual model figures included tracers as a main data source. As tracer studies often focus on subsurface flow paths, these perceptual models favour the subsurface. More generally, our review searched for perceptual models of runoff generation, in keeping with the definition by Beven (2001) that a perceptual model should describe the rainfall-

runoff process. The perceptual models in our survey were created and used by catchment hydrologists who use fieldwork (54 papers) and models (22 papers) to characterize the rainfall-subsurface-groundwater-channel pathway. Papers that focus on other processes (e.g., ET response) or other environments such as the land surface or the floodplain, might be more likely to emphasize vegetation and details of surface stores and fluxes.

4.2 | Using perceptual models to share hydrological process information: Observations and recommendations

Open and shared perceptual models have been proposed as a method to share hydrological process understanding and our current hydrologic knowledge of places (Wagener, Gleeson, et al., 2021). Our analysis leads to recommendations to improve the success of that approach, which are discussed below and summarized in Table 2.

TABLE 2 Summary of recommendations for creating perceptual model figures.

Figure item	Recommendation
Caption	Use the words <i>Perceptual Model</i> or <i>Conceptual Model</i> in the caption to enable automatic search for figures. Consider adding the purpose of the perceptual model, for example, perceptual model of runoff generation, perceptual model of land-atmosphere fluxes.
Process names	• Use one consistent name for each process throughout the paper including the text and the perceptual figure • Define processes in the text where there is any uncertainty in the meaning of process names • If not defining processes in the text, use standard process names from a glossary or taxonomy (e.g., McMillan, 2022) • Be as specific as possible when labelling processes on the figure, for example, write <i>saturation excess overland flow</i> not <i>overland flow</i> • If needed, use a letter or number label on the figure and provide more information about the process in the surrounding text
Legend	Provide a legend that explains all icons or markings on the figure such as vegetation icons (give species or vegetation type if possible), hatching or shading, and arrow styles
Scales	Provide horizontal and vertical scale bars, and the watershed area Provide information on the temporal scale the model represents (e.g., event, seasonal, long-term)
Quantities	Where known, size arrows and stores according to their fluxes and volumes, respectively; and add time scales to fluxes
Uncertainties	Mark unknown processes with ? icons, alternative arrow styles or other annotations

4.2.1 | Current perceptual model figures can be too simple for standalone use

Using a perceptual model figure rather than a text description or other conceptual diagram (e.g., Coenders-Gerrits et al., 2013; Hopp & McDonnell, 2009) enforces a simplified visualization of runoff generation. In many examples, processes in the figure could be more accurately understood from the surrounding text. Overall, 29 of the 63 perceptual model figures could be fully understood without reference to the text, 24 benefitted from extra information in the text and 10 required the surrounding text to be understood. For example, Lortitz et al. (2017) mark macropores on the figure, while the text describes two causes of macropores in different seasons (earthworm, soil cracks). Li et al. (2018) mark an inverted triangle above their interflow flux, while the text describes interflow formed due to a perched water table. 'Surface runoff' marked on a perceptual figure was variously interpreted in the text to mean surface runoff caused by saturation (Viglione et al., 2018), channel interception and saturation excess flow from riparian zone (McMillan et al., 2011), or infiltration excess from frozen ground (Mohammed et al., 2021). There are benefits to providing a concise overview of dominant processes, and having a figure improves readability. However, these examples show that standalone perceptual diagrams can lose important information. One solution may be to use numbered labels or hyperlinks to link runoff mechanisms shown in the figure to more extensive descriptions in the text, as in Beven and Chappell (2021). These more extensive descriptions could be used to aid understanding, while the simpler figure might be sufficient to design a model structure.

Further information is lost because perceptual model figures are often drawn informally, as visually-pleasing figures. Many figures contained arrows, icons, shading and other features whose meaning was unclear. For example, figures may show a watershed cross-section with varying slopes, but it is unclear whether these show exact slope changes or an artist's impression, and whether they signify changes in hydrologic processes. Good practices that we saw included marking vertical and horizontal scale bars on the figure (14 of 63 perceptual model figures used scale bars), and using a legend to communicate where varying plant icons represent known changes in vegetation, or if hatching represents fractures or bedding (23 of 63 perceptual model figures used a legend). We, therefore, recommend annotating figures with standard legend and scale markings to ensure that information in the figure is conveyed to the reader.

4.2.2 | Optimizing perceptual figures for the age of big data

As well as conveying information to human readers, future perceptual models will have a wider range of uses if they are 'machine-readable' and interpretable in the context of big data. For example, to enable perceptual figures to be found by automated search, naming should be consistent. Current figures have a range of captions reflecting the evolving terminology used to describe perceptual

models. These range from easily recognizable ('perceptual model', 'conceptual model' or 'conceptual diagram'), moderately recognizable ('flow paths', 'idealized cross section', '[schematic] representation of', 'major hydrological pathways of'), to difficult-to-recognize names such as a caption that describes the specific watershed. Consistent naming would mitigate the difficulty we found in designing search terms to find perceptual model figures in the hydrological literature.

Consistent and explicit terms to describe fluxes or storages should be chosen to avoid confusion. Terms that we might think are highly specific could be interpreted differently by different hydrological communities, for example, 'fill and spill' is used by catchment hydrologists to imply lateral flow between hollows at the soil-bedrock interface (Tromp-van Meerveld & McDonnell, 2006), but is used by wetland hydrologists to imply 'event water raising the groundwater table until depression storage is satisfied and then flow occurs' (Gibson et al., 2016). As in this study where we mapped figure labels onto taxonomic names, there is a need to 'translate' perceptual models into a common and comparable language.

A possible pathway to improve figure standardization and readability, while also catering to hydrologists lacking an artistic streak, would be to create a visualization tool to generate figures. The user could answer a structured set of questions and specify exactly what information is known. The tool would generate a perceptual figure, allowing adjustments by the user. Although this approach would reduce user freedom, the digital objects produced would promote reuse and open science, and may become an integral part of 'geoscience papers of the future' (Gil et al., 2016).

4.2.3 | Centering uncertainty and knowledge gaps

Including uncertainties in perceptual model figures are critical if these figures are to be used to identify knowledge gaps and therefore to guide new fieldwork and drive hydrological advances. Uncertainties can be large where processes are inferred from sparse measurements, but few figures we surveyed included uncertainty information. Three figures included '?' marks to indicate uncertainties in the extent of the saturated zone, the lower boundary condition, and hillslope-stream connectivity. Only Wrede et al. (2015) showed uncertainties for all fluxes, using different arrow styles to indicate confidence level. Being specific about knowledge gaps can lead to an evolving understanding of runoff generation that recognizes perceptual models as hypotheses (Aulenbach et al., 2021; Flint et al., 2001; McGlynn et al., 2002). This approach encourages further investigations to test the hypotheses and update the model where needed, which might involve revising the processes thought to dominate, or adding newly discovered processes. The evolving perceptual model recognizes the contributions of multiple investigators during long-term discovery science programs. An updated perceptual model can drive improvements in model structure, such as adding karst processes to provide more realistic recharge estimates (Hartmann et al., 2015), or developing watershed-specific models based on geological expertise (Viglione et al., 2018).

Perceptual models currently lack agreement on how to indicate a process that is thought to be important but is poorly understood. This is part of a wider question of how to use and communicate partial process knowledge. Papers in our study used several approaches to partial knowledge. Sometimes processes were excluded: for example, a perceptual figure only shows processes during events and excludes dry conditions, or a perceptual figure focuses on runoff generation in clay shales and excludes surface features (Allen et al., 2005). Some papers inferred missing processes using qualitative information based on expectations from similar sites or across large scales (Fenicia & McDonnell, 2022). Other papers built or constrained perceptual models based on prior understanding of the watershed, and evaluated unknown processes by testing different model structures (Graeff et al., 2009; Hartmann et al., 2013; Hrachowitz et al., 2014). Where processes are excluded, the viewer does not know whether the process is unknown, or whether it is known to be non-dominant in this watershed. Hydrologists would benefit from a structured approach to drawing, collecting and combining partial models, given that partial process knowledge is a necessary step in building a complete understanding of the watershed. Partial models would help to identify transferable knowledge gaps that stretch beyond individual watersheds and relate to processes that are understood in some landscapes but not others, information that is currently very difficult to identify (Wagener, Dadson, et al., 2021).

4.2.4 | Transferability of perceptual models

If we seek to create perceptual models for large numbers of watersheds, it is impractical to conduct detailed experimental work in every watershed before developing the perceptual model. Instead, one aim of developing a perceptual model would be to gain transferable information about processes in a wider region. For example, initial observations of a rock moisture store at the Eel River Critical Zone Observatory led to an understanding that this was a locally-important process, and later that the process was important across large swaths of the United States (McCormick et al., 2021; Rempe & Dietrich, 2018; Salve et al., 2012). Alternatively, understanding of the DRP under one set of landscape characteristics might be transferrable to other landscapes with the same characteristics (Rennó et al., 2008). However, we still lack methods to identify the spatial extent of perceptual knowledge, to specify whether an updated perceptual model in one location can be transferred to a wider region. Further difficulties are introduced when transferring perceptual models between scales, because runoff generation processes are scale-dependent and do not linearly combine from plot to hillslope to watershed and larger scales (McDonnell, 2003; McDonnell et al., 2021; Sidle et al., 2000). In our survey, we found several instances where perceptual model figures were drawn for areas larger than a single watershed. These included Northern basins (Tetzlaff et al., 2015), forested watersheds (Sidle, 2006), and tropical forests (Bonell, 2005). Such development of larger scale models, while retaining process inferences from the underlying individual watershed studies, offers one path towards transferring perceptual knowledge between watersheds.

5 | CONCLUSIONS

We surveyed 1404 papers from the hydrological literature on runoff generation, and found and analysed 63 eligible perceptual model figures. These figures demonstrate how experts describe the dominant processes in the watersheds they study. Figures focus more strongly on the subsurface, typically having 1 surface flux, 4 subsurface fluxes, 3–4 subsurface stores and 0–1 channel stores. Very few perceptual models show sub-panels for spatial zones, but some include sub-panels for different seasons or wetness conditions.

Perceptual figures provide a concise summary of a watershed, that may otherwise be lacking or have to be pieced together from dispersed text descriptions within a paper. Figure complexity is similar to that of conceptual hydrological models, suggesting that perceptual figures could be a useful tool to select model structure within modular modelling frameworks. However, figures are necessarily simpler than a text description, and may need to be read in conjunction with surrounding text to fully understand the processes shown. Especially in an age of big data, we recommend that perceptual figures will be made more valuable by using standard figure names and process names, by including scale bars and legend, and by linking to longer text descriptions if needed. We also recommend a more explicit treatment of uncertainty, which itself constitutes knowledge and helps to identify knowledge gaps. A community effort to create guidelines for perceptual figures could help to make figures more comparable and transferable in future.

Creating perceptual figures can be difficult. Producing a figure requires visualization skills and graphical software that may not be readily available to authors. More fundamentally, creating a figure requires that the author goes beyond descriptions of field data, and interpret these data in terms of dominant runoff pathways. Such interpretation requires deep knowledge of the field site, and of data strengths and gaps, and may be highly uncertain and partly subjective. However, the resulting understanding of hydrological processes is valuable, and the perceptual figure captures and communicates that expert knowledge to the hydrological community. Creating a database of perceptual models, as shown here, adds a layer of value by enabling the figures to be discoverable and searchable. Expansion of the perceptual model database is an ongoing effort, and the authors welcome members of the hydrological community to engage with us to contribute perceptual figures of their study watersheds.

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DATA AVAILABILITY STATEMENT

The database of perceptual model figures created for this paper can be accessed via a GIS dashboard at www.mcmillanhydrology.org/PerceptualModelDashboard.html.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A: DERIVATION OF CLIMATE INDICES

We use the following climate indices, as defined by Knoben et al. (2018). The Thornthwaite moisture index MI (Willmott & Feddema, 1992) is used to define average aridity a and its seasonality s . Snow fraction fs is a numerical implementation of the fraction of annual precipitation that occurs as snowfall (Woods, 2009).

$$MI(t) = \begin{cases} 1 - \frac{E_p(t)}{P(t)} & P(t) > E_p(t) \\ 0 & P(t) = E_p(t) \\ \frac{P(t)}{E_p(t)} - 1 & P(t) < E_p(t) \end{cases},$$

$$a = \frac{1}{12} \sum_{t=1}^{t=12} MI(t),$$

$$s = \max(MI(t)) - \min(MI(t)),$$

$$fs = \frac{\sum_{t=1}^{t=12} P(T(t) \leq T_0)}{\sum_{t=1}^{t=12} P(t)},$$

where $P(t)$, $E_p(t)$ and $T(t)$ are mean monthly values of precipitation, potential evapotranspiration and temperature. T_0 is the threshold temperature below which precipitation is assumed to fall as snow, set to 0°C.