Received: 13 September 2021 | Revised: 25 February 2022 | Accepted: 28 February 2022

DOI: 10.1002/hyp.14537

SCIENTIFIC BRIEFING

HP TODAY WILEY

A taxonomy of hydrological processes and watershed function

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Funding information
Division of Earth Sciences, Grant/Award Number: 2124923

Abstract

This paper presents a taxonomy (hierarchical organization) of hydrological processes; specifically, runoff generation processes in natural watersheds. Over 130 process names were extracted from a literature review of papers describing experimental watersheds, perceptual models, and runoff processes in a range of hydro-climatic environments. Processes were arranged into a hierarchical structure, and presented as a spreadsheet and interactive diagram. For each process, additional information was provided: a list of alternative names for the same process, a classification into hydrological function (e.g., flux, storage, release) and a unique identifier similar to a hashtag. We hope that the proposed hierarchy will prompt collaboration and debate in the hydrologic community into naming and organizing processes, towards a comprehensive taxonomy. The taxonomy provides a method to label and search hydrological knowledge, thereby facilitating synthesis and comparison of processes across watersheds.

KEYWORDS
classification, hierarchy, hydrological process, runoff generation, structure, synthesis, taxonomy, watershed function

1 | INTRODUCTION

Hydrological processes describe the movement of water through watersheds, as part of the hydrological cycle. Any hydrologist is familiar with these processes, such as infiltration, evapotranspiration or groundwater flow. Through field experiments, hydrologists have named more specific processes, such as interflow, macropore flow or groundwater ridging. These processes fall within the broader term 'watershed function', defined as 'the actions of the catchment on the water entering its control volume' (Wagener et al., 2007). Building on earlier frameworks (Black, 1997; McDonnell & Woods, 2004; Soulsby et al., 2006), Wagener et al. (2007) classify catchment function into partitioning, storage and release of water.

Previous frameworks largely have the goal of catchment classification: determining clusters of catchment function that can be predicted using physical characteristics such as soils, land use, and topography. Recently, community interest in open data has led to further work on organizing hydrological information, for example in the CUAHSI Hydrologic Information System (CUAHSI-HIS). A significant development is HY_features, a 'Surface Hydrology Features Conceptual Model', and part of the Open Geospatial Consortium WaterML 2.0 standard for online water data (Almoradie et al., 2013). HY_features describes hydrological and hydrographic features (e.g., water bodies, observations) and their relationships. It can be used to describe river networks for GIS and modelling applications (Blodgett et al., 2021) and builds on previous work on ontologies for hydrology (Stephen & Hahmann, 2017).

These previous frameworks, however, do not explicitly list the types of processes (e.g., macropore flow) that hydrologists use when describing runoff generation. There are many applications that would benefit from a standard list of processes, such as labelling and searching hydrological descriptions to compare processes and synthesize knowledge across sites, collating watershed information for machine learning ground-truth, and providing descriptors in perceptual models to share hydrological knowledge and identify gaps (Wagener et al., 2021). These needs echo those of the biological sciences to provide systematic nomenclature for plants and animals (von Linnaeus, 1758). Writing in Nature for Linnaeus' 300th anniversary, Godfray (2007) reminds us that 'to understand anything in science, things have to have a name that is recognized and is universal'.

Therefore, this technical note describes a taxonomy (hierarchical organization) of hydrological processes, including primary and alternative names. The taxonomy is designed to augment textual watershed descriptions with a summary of the constituent processes. As in biological taxonomy, future revision and expansion is expected. For example, to limit the scope, we focused on processes in natural watersheds that might be included in a typical runoff generation model. We do not include process definitions, and direct the reader to appropriate glossaries and encyclopaedia sources (Anderson & McDonnell, 2005; NSIDC, 2021; WMO, 2012). These glossaries do not however include all the specialist terms used by catchment hydrologists. Future work might include more detailed treatment of specific environments (e.g., cold regions) and expansion to additional environments and domains (e.g., wetlands, water quality, deep groundwater, human influences on hydrology).

2 | METHOD

Our investigation was structured by process class (Anderson & McDonnell, 2005), for example, 'evapotranspiration', 'overland flow', or 'groundwater'. McMillan (2020) provided a list of papers describing processes in experimental watersheds. We searched literature on perceptual models, including recent discussions of perceptual model use and scope (Beven & Chappell, 2021; Wagener et al., 2021), perceptual models of well-known watersheds such as Panola (Aulenbach et al., 2021), Maimai (McGlynn et al., 2002) and the Attert Basin (Wrede et al., 2015), and perceptual models of specific processes such as infiltration (Beven, 2004). Many papers do not explicitly refer to perceptual models but equivalently describe runoff generation processes. We surveyed these papers with particular attention to studies from a wide range of climate and landscape types. These included arid (Ries et al., 2017), humid (Dunne & Black, 1970; Hewlett & Hibbert, 1967), cold region (Peters et al., 1995; Pomeroy et al., 1999; Quinton & Marsh, 1999; Rango, 1993), forested (Bonell, 1993; Jones, 2000) and karst watersheds (Hartmann et al., 2013).

From each paper, we extracted all names or short phrases describing runoff generation processes. Where available, we referred to previous process classifications such as the typology of groundwater–surface water interaction by Dahl et al. (2007), and processes in earth system models (Clark et al., 2015; Fan et al., 2019; Pomeroy et al., 2007). We noted alternative names for each process, although it was sometimes difficult to ascertain minor differences in meaning between terms; see further comment in the Discussion section.

To integrate the new taxonomy with previous classification systems, we specified a functional class for each process. Bracken et al. (2013) divided hydrological function into *structural* knowledge—to do with stores—and *process-based* knowledge—to do with fluxes. Wagener et al.'s classification (2007) adds *release*. Subcategories of each class were added as needed (Table 1).

TABLE 1 Listing of functional classes assigned to each named process

Functional type	Function	Example
Storage	Store	Soil water storage
	Store, temporary	Perched water tables
	Store characteristics, temporary	Snowpack change in grain size
	Store characteristics, permanent	Storage-discharge relationship
	Filling of store	Canopy interception
	Release from store	Snowmelt
Flux	In-catchment flux	Infiltration
	In-store flux	Vertical matrix flow
Release	Release	Transpiration

The process taxonomy was collated into spreadsheet format that tracked the hierarchical structure by assigning a 'parent' to each process name (see Data S1). The spreadsheet was processed in *R* using the *collapsibleTree* package to create an interactive tree diagram (Khan et al., 2018). Processes were shown as nodes that expand and collapse, and were coloured by functional class. Tool tips displayed alternative names and the identifier.

3 | RESULTS

Our investigation returned over 130 named processes; see Data S1 for a complete list. Processes could be satisfactorily arranged into a four-level hierarchical structure Domain—Class—Process—Subprocess, such that items at the same level have a comparable level of detail for hydrologists. *Domain* classifies surface, subsurface or channel processes, *Class* provides a group of related processes, *Process* names a single process at a level of complexity that would typically be included in a catchment-scale runoff generation model and *Subprocess* names a subcategory beyond typical model complexity. Processes often had many alternative names, and these were recorded. For example, runoff generation by displacement of groundwater is also referred to as pressure wave translatory flow, hydraulic displacement, translatory wave, old water mobilization and pre-event water mobilization.

Each process was assigned a unique identifier, similar to a hashtag. The identifiers use dots to signify hierarchical level, with each level given a text tag of at most six characters. Thus, change in grain size during snowpack aging is classified as Surface—Snow Processes—Snowpack Aging—Change in grain size, with the identifier *Surf.Snow.Age.Grain*. This provides a short reference string for any process. If a different hierarchical structure is used in future, it would be relatively simple to remap the identifiers.

Some names could be disputed as representing stores rather than processes, and might be classed as a physical entity in an ontological framework. However, water storage has long been regarded as part of watershed function, and was therefore included in the taxonomy. Functional classes are listed in Table 1, and give more detail than previous classifications, for example differentiating between 'store', 'filling of store' and 'release from store'. For example, snowmelt is designated as 'release from store' as only the origin store is specified. An overview of the taxonomy is presented in Figure 1. We further created an interactive version of the taxonomy that can be accessed at http://mcmillanhydrology.org/ProcessTaxonomy/ProcessTaxonomyDiagram.html and includes functional classes and alternative process names. A view of the interactive taxonomy with overland flow processes expanded is given in Figure 2. The taxonomy is available as a spreadsheet, with accompanying documentation of the articles reviewed and processes described in each article: see the Data Availability section.

When hydrologists described watershed function, a variety of information types were provided. Information could relate to the existence or magnitude (of stores, fluxes), spatial variation (location), temporal variation (seasonal variation or wetness conditions for processes to occur or stores to fill) or response time. These types could be used as an additional descriptor of hydrological information when stored in a database or similar.

4 | EXAMPLE APPLICATION

We provide two examples to demonstrate how textual process descriptions could be mapped onto our taxonomy (Tables 2 and 3). These examples use the summaries of processes provided by McGlynn et al. (2002) for the Maimai watershed in New Zealand, and Weyman (1973) for the East Twin Brook watershed, Burrington, Somerset, UK. Tables 2 and 3 give each description from the article, and

FIGURE 1 Overview radial network diagram showing all processes in the taxonomy (note that a small number of process names were abbreviated for clarity)

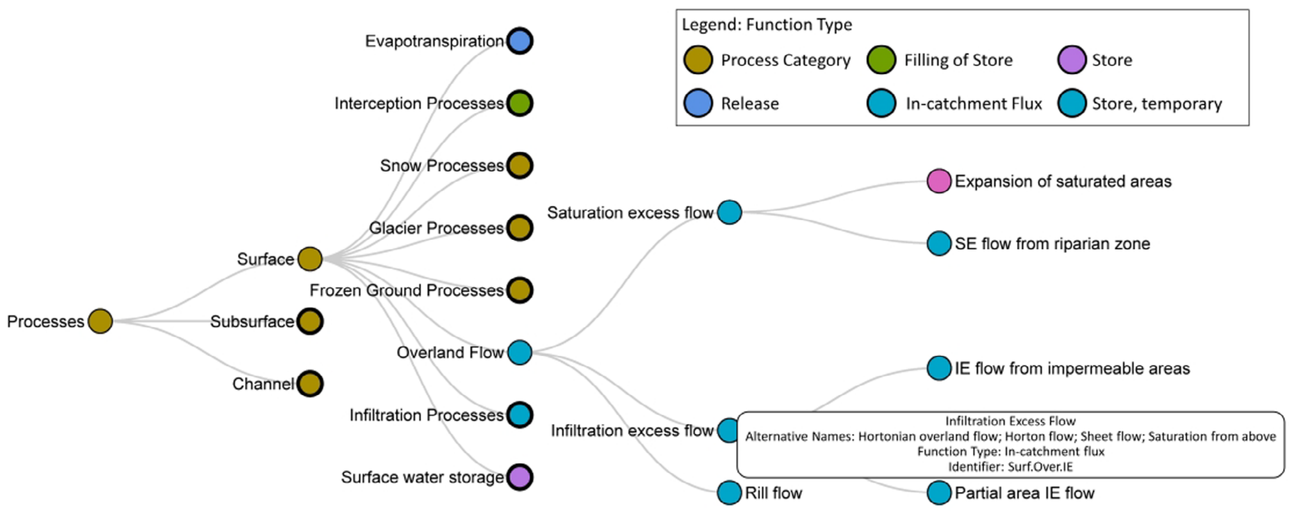

FIGURE 2 Example output from taxonomy diagram, with overland flow processes expanded, and showing tooltip information for infiltration excess flow process

TABLE 2 Process descriptions in the summary section of McGlynn et al.'s (2002) description of processes in the Maimai watershed, New Zealand

Description in journal article	Domain	Class	Process	Sub-process	Type of information
High infiltration rates well in excess of maximum precipitation intensities	Surface	Infiltration Processes	Infiltration		Magnitude
Transient water table development on hillslopes	Sub-surface	Groundwater	GW Storage	Perched water tables	Spatial
Topographic convergence of water flow into hollows	Sub-surface	Subsurface stormflow	Topographic convergence		Spatial
Vertical bypass flow to depth with large events	Sub-surface	Soils	Vertical macropore flow		Temporal
Uniform wetting front propagation with small and protracted events	Sub-surface	Soils	Vertical matrix flow		Temporal
Rapid lateral throughflow response to precipitation following threshold water table development	Sub-surface	Subsurface stormflow			Temporal, response time
Two domains of lateral throughflow that include rapid pipeflow at the soil bedrock interface	Sub-surface	Subsurface stormflow	Lateral macropore flow	Lateral macropore flow at soil-bedrock interface	Existence, response time
and slow, more uniform matrix flow	Sub-surface	Subsurface stormflow	Lateral matrix flow		Existence, response time
Old water dominated throughflow (resident soil water as opposed to new rainfall)	Sub-surface	Soils	Mixing		Existence
High degree of throughflow variability across seemingly planar hillslopes	Sub-surface	Subsurface stormflow			Spatial
Bedrock topographical control on the spatial distribution of mobile subsurface saturated flow	Sub-surface	Subsurface stormflow	Topographic convergence		Spatial

TABLE 3 Process descriptions in the summary section of Weyman's (1973) description of processes in the east twin brook watershed, Burrington, Somerset, UK

Description in journal article	Domain	Class	Process	Sub-process	Type of information
infiltration capacity of the soil […] is too high to permit the generation of infiltration-excess overland flow	Surface	Overland Flow	Infiltration excess flow		Existence
response of the hillslope to rainfall is dominated by saturated throughflow	Sub-surface	Subsurface stormflow			Existence
no evidence to suggest that lateral unsaturated flow contributes to the storm response	Sub-surface	Soils	Lateral unsaturated flow		Existence
saturated lateral flow is dependent upon some break in the vertical permeability profile […] which occurs at the soil profile base and at the base of the B horizon.	Sub-surface	Subsurface stormflow	Lateral matrix flow	Lateral matrix flow at soil horizons	Spatial
response […] is delayed […] because the lateral flow system is at some depth below the surface and peak discharge is relatively low because lateral velocity is very slow.	Sub-surface	Subsurface stormflow	Lateral matrix flow	Lateral matrix flow at soil horizons	Response time, Magnitude
the zone of saturation expands during the course of a storm in the form of a wedge. The top of the saturation zone [does not] intersect the ground surface	Sub-surface	Groundwater	Groundwater storage	Perched water tables	Spatial
During drainage the saturated zone contracts and is replaced by vertical unsaturated flow	Sub-surface	Soils	Vertical matrix flow		Temporal
to an unsaturated lateral flow system in the B/C horizon […] capillary pores dominate unsaturated flow.	Sub-surface	Soils	Lateral unsaturated flow		Temporal
upwards capillary movement to an evaporating surface becomes increasingly important as drainage progresses	Sub-surface	Soils	Vertical matrix flow	Capillary rise	Temporal

map it to the process hierarchy. The final column encodes the type of information (magnitude, spatial variation, temporal variation or response time). By tagging each text string with the taxonomical name, this information could be more easily compared with descriptions of other watersheds, or other sources of information about the same watershed.

5 | DISCUSSION

5.1 | Hydrological process descriptions in journal articles

We found that information about processes could be difficult to extract from journal articles. Descriptions were often complex and multi-faceted, with multiple processes described in one sentence. Process interpretations were mixed with narrative text on observations, and description of observations often dominated process inference. Such text makes process information slower to extract and re-use. With an increasing emphasis on synthesis of process understanding across sites (Jackisch et al., 2021), efforts to increase data sharing are important. We recommend the process summary in McGlynn et al. (2002); see Table 2) as an example of good practice. The article has a separated section that lists the dominant runoff processes in the watershed. However, we recognize the difficulty of summarizing process information that facilitates re-use without losing important detail.

5.2 | Alternative process names

In our investigation, we commonly found multiple names for the same or very similar process. This plurality has been discussed in the literature, for example, Weiler et al. (2006) write that

> Subsurface stormflow is also known in the hydrological literature as interflow, lateral flow, subsurface runoff, transient groundwater, or soil water flow. These multiple terms often confuse the process understanding of subsurface stormflow response to rainfall or snowmelt.

We found that hydrologists sometimes use multiple terms in the same article, for example, through-flow and subsurface saturated flow. It is difficult for the reader to determine whether the authors intended nuanced differences between these terms, or whether they refer to the same process. The same term might also be used with different meanings in different sources, for example, throughflow is variously defined as lateral flow in unsaturated or saturated conditions. We recommend that authors consistently use the same process name throughout an article, and define the term where there is a possibility of confusion.

6 | CONCLUSION

This paper introduced a hierarchical organization of hydrological processes, derived from literature review of journal articles describing experimental watersheds, perceptual models and runoff generation processes. We hope that this proposal will prompt an organized discussion within the hydrologic community and lead to improvement and finalization of the taxonomy in a community effort. The taxonomy includes over 130 named processes, which are recorded alongside their functional type (e.g. storage, flux), alternative names and a unique identifier. Processes often had multiple alternative names, which can hinder extraction and sharing of hydrological information. We recommend that authors of journal articles use consistent terms for processes throughout, and consider a separate section with succinct process inference information. The taxonomy can promote hydrological information sharing and synthesis by providing a method to label and search process knowledge.

DATA AVAILABILITY STATEMENT

The taxonomy is available as a spreadsheet, with an R script to create the interactive diagram, at https://github.com/mcmillanhk/ProcessTaxonomy

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REFERENCES

Almoradie, A., Jonoski, A., Popescu, I., & Solomatime, D. (2013). Web based access to water related data using OGC WaterML 2.0. *International Journal of Advanced Computer Science and Applications* EnviroGRIDS Spec. Issue "Building Reg. Obs. Syst. Black Sea Catchment, *3*, 83–89.

Anderson, M. G., & McDonnell, J. J. (2005). *Encyclopedia of hydrological sciences*. Wiley.

Aulenbach, B. T., Hooper, R. P., van Meerveld, H. J., Burns, D. A., Freer, J. E., Shanley, J. B., Huntington, T. G., McDonnell, J. J., & Peters, N. E. (2021). The evolving perceptual model of streamflow generation at the Panola Mountain research watershed. *Hydrological Processes*, *35*, e14127.

Beven, K. (2004). Robert E. Horton's perceptual model of infiltration processes. *Hydrological Processes*, *18*, 3447–3460.

Beven, K. J., & Chappell, N. A. (2021). Perceptual perplexity and parameter parsimony. *Wiley Interdisciplinary Reviews Water*, *8*, e1530.

Black, P. E. (1997). Watershed functions 1. *Journal of the American Water Resources Association*, *33*, 1–11.

Blodgett, D., Johnson, J. M., Sondheim, M., Wieczorek, M., & Frazier, N. (2021). Mainstems: A logical data model implementing mainstem and drainage basin feature types based on WaterML2 part 3: HY features concepts. *Environmental Modelling and Software*, *135*, 104927.

Bonell, M. (1993). Progress in the understanding of runoff generation dynamics in forests. *Journal of Hydrology*, *150*, 217–275.

Bracken, L. J., Wainwright, J., Ali, G. A., Tetzlaff, D., Smith, M. W., Reaney, S. M., & Roy, A. G. (2013). Concepts of hydrological connectivity: Research approaches, pathways and future agendas. *Earth Science Reviews*, *119*, 17–34. https://doi.org/10.1016/j.earscirev.2013.02.001

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P., Kumar, M., Leung, L. R., & Mackay, D. S. (2015). Improving the representation of hydrologic processes in earth system models. *Water Resources Research*, *51*, 5929–5956.

Dahl, M., Nilsson, B., Langhoff, J. H., & Refsgaard, J. C. (2007). Review of classification systems and new multi-scale typology of groundwater–surface water interaction. *Journal of Hydrology*, *344*, 1–16.

Dunne, T., & Black, R. D. (1970). Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research*, *6*, 1296–1311.

Fan, Y., Clark, M., Lawrence, D. M., Swenson, S., Band, L. E., Brantley, S. L., Brooks, P. D., Dietrich, W. E., Flores, A., & Grant, G. (2019). Hillslope hydrology in global change research and earth system modeling. *Water Resources Research*, *55*, 1737–1772.

Godfray, H. C. J. (2007). Linnaeus in the information age. *Nature*, *446*, 259–260.

Hartmann, A., Wagener, T., Rimmer, A., Lange, J., Brielmann, H., & Weiler, M. (2013). Testing the realism of model structures to identify karst system processes using water quality and quantity signatures. *Water Resources Research*, *49*, 3345–3358.

Hewlett, J. D., & Hibbert, A. R. (1967). Factors affecting the response of small watersheds to precipitation in humid areas. *Forest Hydrology*, *1*, 275–290.

Jackisch, C., Hassler, S. K., Hohenbrink, T. L., Blume, T., Laudon, H., McMillan, H., Saco, P., & van Schaik, L. (2021). Preface: Linking landscape organisation and hydrological functioning: From hypotheses and observations to concepts, models and understanding. *Hydrological and Earth System Sciences*, *25*, 5277–5285.

Jones, J. A. (2000). Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western cascades, Oregon. *Water Resources Research*, *36*, 2621–2642.

Khan, A., Shah, D., Bostock, M., 2018. Package 'collapsibleTree'. Retrieved from https://cran.r-project.org/web/packages/collapsibleTree/collapsibleTree.pdf.

McDonnell, J. J., & Woods, R. (2004). On the need for catchment classification. *Journal of Hydrology*, *299*, 2–3.

McGlynn, B. L., McDonnel, J. J., & Brammer, D. D. (2002). A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand. *Journal of Hydrology*, *257*, 1–26.

McMillan, H. (2020). Linking hydrologic signatures to hydrologic processes: A review. *Hydrological Processes*, *34*(6), 1393–1409.

NSIDC, National Snow and Ice Data Center, 2021. Cryosphere Glossary. Retrieved from https://nsidc.org/cryosphere/glossary

Peters, D. L., Buttle, J. M., Taylor, C. H., & LaZerte, B. (1995). Runoff production in a forested, shallow soil, Canadian Shield basin. *Water Resources Research*, *31*, 1291–1304.

Pomeroy, J. W., Granger, R., Pietroniro, A., Elliott, J., Toth, B., & Hedstrom, N. (1999). Classification of the boreal forest for hydrological processes. In S. Woxholtt (Ed.), *Proceedings of the ninth international boreal Forest research association conference*, Oslo, Norway, 21-23 September 1998 (pp. 49–59).

Pomeroy, J. W., Gray, D. M., Brown, T., Hedstrom, N. R., Quinton, W. L., Granger, R. J., & Carey, S. K. (2007). The cold regions hydrological model: A platform for basing process representation and model structure on physical evidence. *Hydrological Processes: An International Journal*, *21*(19), 2650–2667.

Quinton, W. L., & Marsh, P. (1999). A conceptual framework for runoff generation in a permafrost environment. *Hydrological Processes*, *13*, 2563–2581.

Rango, A. (1993). II. Snow hydrology processes and remote sensing. *Hydrological Processes*, *7*, 121–138.

Ries, F., Schmidt, S., Sauter, M., & Lange, J. (2017). Controls on runoff generation along a steep climatic gradient in the eastern Mediterranean. *Journal of Hydrology: Regional Studies*, *9*, 18–33.

Soulsby, C., Tetzlaff, D., Dunn, S. M., & Waldron, S. (2006). Scaling up and out in runoff process understanding: Insights from nested experimental catchment studies. *Hydrological Processes: An International Journal*, *20*, 2461–2465.

Stephen, S., & Hahmann, T. (2017). *An ontological framework for characterizing hydrological flow processes, in: 13th international conference on spatial information theory (COSIT 2017)*. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik.

Linnaeus, C. von, 1758. Systema naturæ per regna tria naturæ, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis. Tomus I. Editio decima, reformata. - pp. [1-4], 1-824. Holmiæ. (Salvius).

Wagener, T., Dadson, S. J., Hannah, D. M., Coxon, G., Beven, K., Bloomfield, J. P., Buytaert, W., Cloke, H., Bates, P., & Holden, J. (2021). Knowledge gaps in our perceptual model of Great Britain's hydrology. *Hydrological Processes*, *35*, e14288.

Wagener, T., Gleeson, T., Coxon, G., Hartmann, A., Howden, N., Pianosi, F., Rahman, S., Rosolem, R., Stein, L., & Woods, R. (2021). On doing large-scale hydrology with lions: Realising the value of perceptual models and knowledge accumulation. *Wiley Interdisciplinary Reviews: Water*. *8*(6), e1550.

Wagener, T., Sivapalan, M., Troch, P., & Woods, R. (2007). Catchment classification and hydrologic similarity. *Geography Compass*, *1*, 901–931.

Weiler, M., McDonnell, J. J., Meerveld, I. T., & Uchida, T. (2006). Subsurface stormflow. In: M. G. Anderson, & J. J. McDonnell, (Eds.), *Encyclopedia of Hydrological Sciences*. Wiley. https://doi.org/10.1002/0470848944.hsa119

Weyman, D. R. (1973). Measurements of the downslope flow of water in a soil. *Journal of Hydrology*, *20*(3), 267–288.

WMO, W.M.O., 2012. International Glossary of Hydrology, WMO-No. 385. Retrieved from https://library.wmo.int/doc_num.php?explnum_id=8209

Wrede, S., Fenicia, F., Martínez-Carreras, N., Juilleret, J., Hissler, C., Krein, A., Savenije, H. H., Uhlenbrook, S., Kavetski, D., & Pfister, L. (2015). Towards more systematic perceptual model development: A case study using 3 Luxembourgish catchments. *Hydrological Processes*, *29*, 2731–2750.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: McMillan, H. (2022). A taxonomy of hydrological processes and watershed function. *Hydrological Processes*, *36*(3), e14537. https://doi.org/10.1002/hyp.14537