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Discussions

HESS Opinions: The need for process-based evaluation of large-domain hyper-resolution models

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Abstract

A meta-analysis on 192 peer-reviewed articles reporting applications of the Variable Infiltration Capacity (VIC) model in a distributed way reveals that the spatial resolution at which the model is applied has increased over the years, while the calibration and validation time interval has remained unchanged. We argue that the calibration and validation time interval should keep pace with the increase in spatial resolution in order to resolve the processes that are relevant at the applied spatial resolution. We identified six time concepts in hydrological models, which all impact the model results and conclusions. Process-based model evaluation is particularly relevant when models are applied at hyper-resolution, where stakeholders expect credible results both at a high spatial and temporal resolution.

1 Introduction

One of the famous paradoxes of the Greek philosopher Zeno of Elea (∼ 450 BC) concerns a shot arrow (Fearn, 2001): if one shoots an arrow, and cuts its motion into such small time steps that at every step the arrow is standing still, the arrow is motionless, because a concatenation of nonmoving pieces cannot create motion. Only ages later, this reasoning could be refuted by the invention of integral and differential calculus by Newton and Leibniz (Stillwell, 1989), accepting infinitely small rates of change. Motion is a change of location over time, thus motion links time and space.

In hydrology, it is essential to understand and predict the motion of water within the Earth system, which implies that both space and time have to be considered. In hydrological models space can be accounted for by using distributed (spatially explicit) models, where space is "cut in small pieces", to paraphrase Zeno. Different types of distributed hydrological models exist; Todini (1988) distinguished roughly two different classes. The first class consists of distributed differential models. These models explicitly simulate lateral fluxes by means of differential equations. The second class are

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the distributed integral models which consist of one-dimensional columns and ignore lateral fluxes between the columns (lateral fluxes can be accounted for with an extra routing scheme, although this does not allow for lateral re-distribution). These models have a wide application in land-surface modelling (Clark et al., 2015). In this discussion we focus on the latter.

The constant development in computational power, the increased understanding of physical processes, and the increased availability of high-resolution hydrological information stimulated the development of increasingly complex and distributed hydrological models (Boyle et al., 2001; Liu and Gupta, 2007). Increasing the spatial resolution of Global Hydrological Models (GHMs) has been labelled as one of the current "Grand Challenges" in hydrology by Wood et al. (2011) and Bierkens et al. (2014), who call for global modelling at the so-called hyper-resolution scale ($\sim$ 1 km and smaller). Arguably, there is a growing societal need for hydrological information at the (sub-)km scale. Whereas model products at the 1 or 0.5° resolution may provide relevant information for policy makers at the (inter)national level, hyper-resolution results will become relevant for local water managers or even individual farmers (see e.g. Bastiaanssen et al., 2007; Beven et al., 2015). The scientific challenge is not to simply provide information based on a model with default parameters, but to provide credible information which matches the actual situation in the field at a time scale which is consistent with the spatial resolution of the model. These scales are linked through the characteristic speed (including both velocity and celerity, McDonnell and Beven, 2014) of the involved hydrological processes (Blöschl and Sivapalan, 1995), see Fig. 1. The figure shows that there is a general tendency for the temporal process scale to decrease with the spatial process scale, although there is quite a broad bandwidth and local changes might occur stepwise. Policy makers might be able to deal with monthly model products, whereas resource managers and farmers expect credible daily or hourly model products at the hyper-resolution scale.

Although increasing the resolution of hydrological models is claimed to provide the opportunity to improve physical process respresentation in hydrological models

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(Bierkens et al., 2014; Bierkens, 2015), almost every hydrological model requires calibration of the model parameters (Beven, 2012). Models can contain conceptual parameters, which have no directly measurable physical meaning and thus need calibration. In addition, the measurement scale of parameters which do have a physical meaning often differs from the model scale, making calibration necessary to determine the effective parameter values to account for sub-grid variability (Kim and Stricker, 1996). Beven and Cloke (2012) responded to the hyper-resolution challenge by emphasizing that the focus of hydrologic modelling should be on determining and accounting for epistemic uncertainty and appropriate parametrizations at different resolutions, rather than on maximizing the spatial resolution. Increasing the model resolution (towards hyper-resolution) is not a solution to sub-grid variability, since many of the relevant processes take place on even smaller scales (Wood et al., 1992; Kim and Stricker, 1996; Arora et al., 2001; Montaldo and Albertson, 2003; Beven and Cloke, 2012; Clark et al., 2015). Hence, despite their increasing spatial resolution, also GHMs require calibration in order to obtain effective parameters, and validation to determine model credibility. Even if a correct physical representation of hydrological processes is impossible, the goal of the model should be to mimic realism and hydrological processes as closely as possible (Wagener and Gupta, 2005; Kirchner, 2006; McDonnell et al., 2007). This implies that the models should be subject to a process-based calibration and validation procedure (Gupta et al., 1998, 2008; Clark et al., 2011). Since different hydrological processes dominate at different scales (Fig. 1), the temporal and spatial scale are linked. Because the spatial resolution of GHMs is currently being increased to meet societal needs (Wood et al., 2011), the temporal scale should decrease accordingly to meet these needs. We argue that this should be reflected in the calibration and validation time interval of the model in order to resolve the dominant processes at the applied spatial resolution.

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2 Example for VIC model studies

To illustrate the development of temporal and spatial scales in large scale hydrological modelling, we carried out a meta-analysis on the use of GHMs. The Variable Infiltration Capacity (VIC) model (Liang et al., 1994) was chosen for this analysis, because it is widely used and therefore enough studies were available for a meta-analysis. The VIC model is mentioned explicitly in Bierkens et al. (2014) as a type of model being run at the hyper-resolution, sub-grid variability is parameterized as a distribution of responses without explicit treatment of the pattern. We believe this model is representative for the much larger class of global hydrological models.

The VIC model was initially constructed to couple climate model output to hydrological processes: it is capable of solving both the energy and the water balance. Lohmann et al. (1996) developed a horizontal routing model to couple the individual grid cells of the VIC model. This facilitated the distributed application of VIC for rainfall-runoff processes at large scales. No explicit definition of a spatial derivative or scale appears in the equations of the VIC model, the spatial resolution of the model only appears in the routing scheme through the horizontal flow velocity (see Kampf and Burges (2007) for a description of space-time representation in other distributed hydrologic models).

In our analysis we assembled 242 peer-reviewed studies that used the VIC model. Of these, 192 studies used the model in a distributed way and performed a calibration or validation on the model output (see Table 1). Figure 2 presents a space-time perspective on the application of the VIC model during the past two decades. As expected, the spatial resolution at which the model is applied has increased steadily over the years (Fig. 2a). While the model was initially constructed for spatial resolutions in the order of 0.5 to 2°, it is now mostly applied at 1/8° and smaller. The main driver for the increase in spatial resolution is the availability of high-resolution spatial data-sets, like presented by Maurer et al. (2002). The increase in resolution, however, does not apply to the employed calibration and validation time interval. Figure 2b shows that the time interval at which the model has been calibrated and validated has remained steady

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over the years. So, while the spatial resolution of the model has increased, the model output is still calibrated and validated at the original coarse time interval. Processes with short characteristic time scales, which become more important when the spatial resolution increases, will likely be overlooked during the calibration and validation of the model if the time interval is too coarse. Several studies have already shown that calibration on a coarser time interval does not guarantee credible results for shorter time intervals (Melsen et al., 2015; Kavetski et al., 2011; Littlewood and Croke, 2013). Figure 1 indicates the initial development scale of the VIC model ("A"), the scale where it is heading to right now ("B"), and the direction where it should go in order to resolve relevant hydrometeorological processes ("C"). Therefore, VIC models with a high spatial resolution should be calibrated and/or validated at time intervals short enough to catch the processes relevant at those particular spatial scales.

Two causes for the discrepancy in the joint development of spatial resolution and calibration time interval come to mind: lack of computational power, or a lack of (using) observations with a high temporal frequency. Figure 2c shows that the total number of grid cells that was used in the studies has on average increased over time. This is as expected: computational power has increased significantly over the years. According to Moore's law (Moore, 1965), computational power roughly doubles every two years. The grey lines in Fig. 2c indicate the corresponding slope in computational power on a log-log scale. The largest numbers of grid cells per year likely indicate the limit of technical capability. Overall, the trend in the studies, even in the higher quantiles, is much lower than the computational limit, suggesting that computational power is not a constraint for most studies. This implies that, nowadays, the main constraint for calibration and validation of distributed hydrological models at a certain time interval (Fig. 2b) is not the computational power, but the lack of (using) observations with a high temporal frequency. A possible explanation for this may be that many (global) studies rely on data from the Global Runoff Data Centre (GRDC), which are often available only at the monthly time interval. Also important is that for large basins, the typical application scale of VIC and other GHMs, flow is often regulated by dams for hydropower and flood control. Naturalized flows for these basins are often estimated at the monthly time interval. Our results reinforce the conclusion of Kirchner (2006) that field observations should account for the spatial and temporal heterogeneity of hydrometeorological processes, and the statement from Kavetski et al. (2011) that in most cases, temporal resolution is fixed by the data collection procedure.

3 Time scales

Our meta-analysis on VIC studies confirms the impression that for scaling issues in large-scale hydrology the main focus mostly has been on the spatial scale rather than on its temporal counterpart (Klemeš, 1983; Dooge, 1986, 1988; Gupta et al., 1986; Feddes, 1995; Kalma and Sivapalan, 1995; Sposito, 1998; Beven, 1995; Gentine et al., 2012). Many concepts have been developed to describe representative areas and volumes (Gray et al., 1993). In soil physics, the Representative Elementary Volume (REV) is an often used concept which describes the volume for which a measurement can be considered representative (Whitaker, 1999). Wood et al. (1988) explored a similar concept with applications in hydrology, namely the Representative Elementary Area (REA), the critical area at which the pattern of small-scale heterogeneity becomes unimportant. Reggiani et al. (1998) proposed the Representative Elementary Watershed (REW), allowing closure of the balance equations averaged over time and space. Similar concepts which statistically integrate temporal variations have not been reported in the literature. The lack of attention for the temporal scale, however, is remarkable, because hydrological states and fluxes are mostly studied as a function of time. As an illustration of the lack of attention for the aspects of temporal scale, it should be noted that in the recent papers by Wood et al. (2011) and Bierkens et al. (2014) on hyper-resolution modelling, the temporal resolution of these models is referred to only once. One of the reasons why the development of a Representative Elementary Timestep (RET) is more complex, is that several different time concepts play a role in hydrological modelling.

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As a guideline and first step for the discussion on time dimensions in hydrological models, we identify six time concepts which in practice are often mixed up and misinterpreted. A distinction is made between "scale", which is defined as a continuous variable, "resolution", defined as discrete variable being a model property, and "time interval", which is a discrete variable independent of the used model. The six concepts are:

1. the process time scale;
2. the input resolution;
3. the numerical resolution ("time step");
4. the output resolution ("temporal resolution");
5. the calibration/validation time interval;
6. the interpretation time interval.

Firstly, the *process time scale* is defined, as the characteristic time scale of the hydrological process considered. This is the typical time period over which the process takes place. Infiltration excess overland flow, for instance, has a relatively short time scale, whereas regional groundwater flow has a longer time scale.

Secondly, the temporal resolution of the input data or *input resolution* is relevant for the modelled process. The input resolution of the forcing data can differ from the output resolution of the model, and this can impact the results of the model. An example is given in the upper panels of Fig. 3, showing an application of the Green and Ampt (1911) infiltration model.

The *numerical resolution* (or the "time step") of the model is the time interval over which the model calculates the states and the fluxes internally. A model can only deterministically resolve a process if the numerical resolution is higher than the characteristic time scale of the process. The panels in the second row of Fig. 3 show how the

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numerical resolution impacts model output for the process of ponding, which leads to different conclusions about ponding, based on the model output.

The *output resolution* (often referred to as simply "temporal resolution") is the time interval at which the model output yields the states and fluxes. This time interval can be equal to the numerical resolution of the model, or aggregated from the numerical resolution. The modelled process can only be identified if the output time interval is shorter than the characteristic time scale of the process, which is shown in the lower panels of Fig. 3.

The *calibration and validation time interval* of the model is defined here as the time interval at which the model output is being confronted with observations. Calibration and validation of the model output can be conducted at another time interval than the output resolution, by aggregating the model output. Ideally, the calibration time interval should have the same order of magnitude as the characteristic time scale of the process or smaller.

Finally, the *interpretation time interval* is defined as the time interval at which the model output is eventually analysed or interpreted. This can be equal to the calibration time interval, or the model output can be further aggregated resulting in a larger interpretation time interval (e.g. from daily to monthly). Since the model has not been validated or calibrated on time intervals smaller than the calibration time interval, the credibility of the results will be unknown for time interval smaller than the calibration time interval.

It is critical to note that some of these time concepts are necessarily equal or larger than related time concepts, sometimes for logical reasons (the output resolution cannot be higher than the numerical resolution), sometimes for model credibility reasons (the interpretation time interval should not be smaller than the calibration time interval). It is also important to note that the first time concept, the process scale, explicitly links the temporal and the spatial scale (Stommel, 1963; Blöschl and Sivapalan, 1995; Brutsaert, 2005). Conversely, the spatial resolution of a model will set a minimum time scale determining which processes need to be resolved.

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4 Problem statement and outlook

The meta-anlysis on VIC studies showed that the spatial resolution at which the model is applied has increased over the years, while the calibration time interval has remained steady (Fig. 2). The examples are shown for the VIC model only, but we have the impression that the obtained trends apply for all GHMs. There is a general tendency to move towards higher spatial resolution in large-scale hydrological models (induced by e.g. Wood et al., 2011; Bierkens et al., 2014), whereas the available data for calibration and validation are model independent. Although coarse scale data can be used to constrain model uncertainty, the ambition to move towards hyper-resolution hydrological models with predictive capabilities should keep pace with the data that are required to run, calibrate and validate the models. Only in this way can hydrological models produce results that are interpretable over a range of time scales. Increasing the spatial resolution of the model implies modelling different relevant hydrometeorological processes (there are some interesting developments concerning parameter transferability over spatial resolutions, see e.g. Samaniego et al., 2010; Kumar et al., 2013; Rakovec et al., 2015), which in turn requires calibration and validation to be performed on a smaller time interval. It should be recognized that discharge data only, especially at a monthly time scale, does not provide sufficient information for a process-based model evaluation at the hyper-resolution scale. Possible paths forward are the use of tracer data to identify different flow paths (Tetzlaff et al., 2015), the use of multiple objectives (Gupta et al., 1998), and the use of satellite and remote sensing data (Pan et al., 2008), all at a representative spatial ánd temporal resolution.

We acknowledge that calibration and validation at the appropriate time interval is only one of the many challenges of hyper-resolution hydrological modelling. Even with enough observations available for calibration and validation, disinformative data (Beven and Westerberg, 2011), correct subgrid parameterizations (Beven et al., 2015) and model structural uncertainty remain outstanding challenges. However, we believe that all these challenges can only be tackled if the models are subject to critical and

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process-based validation (Gupta et al., 2008; Clark et al., 2011). In the end, the goal is to model hydrological processes in an appropriate way (Beven, 2006; McDonnell et al., 2007).

Along with an increased spatial resolution of the model products, there will be a shift in users' expectations of those products. Whereas coarse-scale (0.5 to 1°) products may provide relevant information for policy makers at the national or state level, products at the hyper-resolution (0.1 to 1 km) are potentially of interest to a much wider range of users, including for instance farmers that want to schedule their irrigation. At the sub-kilometer scale, new processes such as infiltration excess overland flow and ponding can (and should) be resolved, but at the same time these processes cannot be explicitly resolved at the daily or monthly resolution. Thus, the recent call for increasing the spatial resolution of distributed models (Wood et al., 2011; Bierkens et al., 2014) should not focus solely on the spatial resolution, but should aim to increase the evaluation time interval simultaneously, at a balanced rate consistent with the characteristic time and space scales of the relevant hydrological processes (Fig. 1). We believe that such a balanced approach will serve societal needs best.

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References

Anderson, M. and Burt, T.: Process Studies in Hillslope Hydrology, in: chap. Subsurface runoff, Wiley, Chichester, 365–400, 1990. 13379

Arora, V., Chiew, F., and Grayson, R.: Effect of sub-grid-scale variability of soil moisture and precipitation intensity on surface runoff and streamflow, J. Geophys. Res., 106, 17073–17091, doi:10.1029/2001JD900037, 2001. 13362

Bastiaanssen, W., Allen, R., Droogers, P., D'Urso, G., and Steduto, P.: Twenty-five years modeling irrigated and drained soils: state of the art, Agr. Water Manage., 92, 111–125, doi:10.1016/j.agwat.2007.05.013, 2007. 13361

Beven, K.: Linking parameters across scales: subgrid parameterizations and scale dependent hydrological models, Hydrol. Process., 9, 507–525, doi:10.1002/hyp.3360090504, 1995. 13365

Beven, K.: Searching for the Holy Grail of scientific hydrology: $Q_t = H(S, R, \Delta t)A$ as closure, Hydrol. Earth Syst. Sci., 10, 609–618, doi:10.5194/hess-10-609-2006, 2006. 13369

Beven, K. and Cloke, H.: Comment on "Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water" by Eric F. Wood et al., Water Resour. Res., 48, W01801, doi:10.1029/2011WR010982, 2012. 13362

Beven, K. and Westerberg, I.: On red herrings and real herrings: disinformation and information in hydrological inference, Hydrol. Process., 25, 1676–1680, doi:10.1002/hyp.7963, 2011. 13368

Beven, K., Cloke, H., Pappenberger, F., Lamb, R., and Hunter, N.: Hyperresolution information and hyperresolution ignorance in modelling the hydrology of the land surface, Sci. China Ser. B, 58, 25–35, doi:10.1007/s11430-014-5003-4, 2015. 13361, 13368

Beven, K. J.: Down to basics: runoff processes and the modelling process, in: Rainfall-Runoff modelling, The Primer, 2nd Edn., Ch. 1, John Wiley & Sons, Chichester, UK, 2012. 13362

Bierkens, M., Bell, V., Burek, P., Chaney, N., Condon, L., David, C., De Roo, A., Döll, P., Drost, N., Famiglietti, J., Flörke, M., Gochis, D., Houser, P., Hut, R., Keune, J., Kollet, S., Maxwell, R., Reager, J., Samaniego, L., Sudicky, E., Sutanudjaja, E., Van de Giesen, N., Winsemius, H., and Wood, E.: Hyper-resolution global hydrological modelling: What's next?, Hydrol. Process., 29, 310–320, doi:10.1002/hyp.10391, 2014. 13361, 13362, 13363, 13365, 13368, 13369

Bierkens, M. F. P.: Global hydrology 2015: State, trends, and directions, Water Resour. Res., 51, 4923–4947, doi:10.1002/2015WR017173, 2015. 13362

Blöschl, G. and Sivapalan, M.: Scale issues in hydrological modelling: a review, Hydrol. Process., 9, 251–290, doi:10.1002/hyp.3360090305, 1995. 13361, 13367, 13379

Boyle, D., Gupta, H., Sorooshian, S., Koren, V., Zhang, Z., and Smith, M.: Towards improved streamflow forecasts: Value of semidistributed modeling, Water Resour. Res., 37, 2749–2759, doi:10.1029/2000WR000207, 2001. 13361

Brutsaert, W.: Hydrology: An Introduction, Cambridge University Press, 2005. 13367, 13379

Clark, M., McMillan, H., Collins, D., Kavetski, D., and Woods, R.: Hydrological field data from a modeller's perspective: Part 2: process-based evaluation of model hypotheses, Hydrol. Process., 25, 523–543, doi:10.1002/hyp.7902, 2011. 13362, 13369

Clark, M., Nijssen, B., Lundquist, J., Kavetski, D., Rupp, D., Woods, R., Freer, J., Gutmann, E., Wood, A., Brekke, L. D., Arnold, J., Gochis, D., and Rasmussen, R.: A unified approach for process-based hydrologic modeling: 1. Modeling concept, Water Resour. Res., 51, 2498–2514, doi:10.1002/2015WR017198, 2015. 13361, 13362

Dooge, J.: Scale problems in hydrology, in: Reflections in Hydrology: Science and Practice, Kiesel Memorial Lecture, American Geophysical Union, Washington, D.C., 85–145, 1986. 13365

Dooge, J.: Hydrology in perspective, Hydrolog. Sci. J., 33, 61–85, 1988. 13365

Dunne, T.: Field studies of hillslope flow processes, in: Hillslope Hydrology, Wiley, Chichester, UK, 227–293, 1978. 13379

Fearn, N.: Zeno and the Tortoise: How to think like a Philosopher, Atlantic Books, London, Great Brittain, 2001. 13360

Feddes, R.: Space and Time Scale Variability and Interdependencies in Hydrological Processes, Cambridge University Press, 1995. 13365

Fortak, H.: Meteorologie, Dietrich Reimer, Berlin, 1982. 13379

Gentine, P., Troy, T., Lintner, B., and Findell, K.: Scaling in surface hydrology: progress and challenges, J. Contemp. Water Res. Educ., 147, 28–40, 2012. 13365

Gray, W., Leijnse, A., Kolar, R., and Blain, C.: Mathematical Tools for Changing Scale in the Analysis of Physical Systems, CRC Press, Boca Raton, Florida, USA, 1993. 13365

Green, W. and Ampt, G.: Studies of soil physics, part I – The flow of water and air through soils, J. Agr. Sci., 4, 1–24, doi:10.1017/S0021859600001441, 1911. 13366

Gupta, H., Sorooshian, S., and Yapo, P.: Toward improved calibration of hydrologic models: Multiple and noncommensurable measures of information, Water Resour. Res., 34, 751–763, doi:10.1029/97WR03495, 1998. 13362, 13368

Gupta, H., Wagener, T., and Liu, Y.: Reconciling theory with observations: elements of a diagnostic approach to model evaluation, Hydrol. Process., 22, 3802–3813, doi:10.1002/hyp.6989, 2008. 13362, 13369

Gupta, V., Rodríguez-Iturber, I., and Wood, E.: Scale problems in hydrology, D. Reidel Publishing Company, Dordrecht, the Netherlands, 1986. 13365

Kalma, J. and Sivapalan, M.: Advances in Hydrological Processes – Scale issues in Hydrological modelling, John Wiley & Sons, Chichester, UK, 1995. 13365

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Kampf, S. and Burges, S.: A framework for classifying and comparing distributed hillslope and catchment hydrologic models, Water Resour. Res., 43, W05423, doi:10.1029/2006WR005370, 2007. 13363

Kavetski, D., Fenicia, F., and Clark, M. P.: Impact of temporal data resolution on parameter inference and model identification in conceptual hydrological modeling: Insights from an experimental catchment, Water Resour. Res., 47, W05501, doi:10.1029/2010WR009525, 2011. 13364, 13365

Kim, C. P. and Stricker, J. N. M.: Influence of spatially variable soil hydraulic properties and rainfall intensity on the water budget, Water Resour. Res., 32, 1699–1712, doi:10.1029/96WR00603, 1996. 13362

Kirchner, J.: Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology, Water Resour. Res., 42, W03S04, doi:10.1029/2005WR004362, 2006. 13362, 13365

Klemeš, V.: Conceptualization and scale in hydrology, J. Hydrol., 65, 1–23, 1983. 13365

Kumar, R., Samaniego, L., and Attinger, S.: Implications of distributed hydrologic model parameterization on water fluxes at multiple scales and locations, Water Resour. Res., 49, 360–379, doi:10.1029/2012WR012195, 2013. 13368

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res., 99, 14415–14458, 1994. 13363

Littlewood, I. and Croke, B.: Effects of data time-step on the accuracy of calibrated rainfall-streamflow model parameters: practical aspects of uncertainty reduction, Hydrol. Res., 44, 430–440, doi:10.2166/nh.2012.099, 2013. 13364

Liu, Y. and Gupta, H. V.: Uncertainty in hydrologic modeling: Towards an integrated data assimilation framework, Water Resour. Res., 43, W07401, doi:10.1029/2006WR005756, 2007. 13361

Lohmann, D., Nolte-Holube, R., and Raschke, E.: A large-scale horizontal routing model to be coupled to land surface parameterization schemes, Tellus A, 48, 708–721, 1996. 13363

Maurer, E., Wood, A., Adam, J., Lettenmaier, D., and Nijssen, B.: A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States, J. Climate, 15, 3237–3251, doi:10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2, 2002. 13363

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McDonnell, J. and Beven, K.: Debates – The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities and residence time distributions of the headwater hydrograph, Water Resour. Res., 50, 5342–5350, doi:10.1002/2013WR015141, 2014. 13361

McDonnell, J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M. L., Selker, J., and Weiler, M.: Moving beyond heterogeneity and process complexity: a new vision for watershed hydrology, Water Resour. Res., 43, W07301, doi:10.1029/2006WR005467, 2007. 13362, 13369

Melsen, L., Teuling, A., Torfs, P. J., Zappa, M., Mizukami, N., Clark, M., and Uijlenhoet, R.: Representation of spatial and temporal variability in hydrological models: Case study for a mesoscale prealpine basin, Hydrol. Earth Syst. Sci., submitted, 2015 13364

Montaldo, N. and Albertson, J.: Temporal dynamics of soil moisture variability: 2. Implications for land surface models, Water Resour. Res., 39, 1275, doi:10.1029/2002WR001618, 2003. 13362

Moore, G. E.: Cramming More Components onto Integrated Circuits, Electronics, 38, 114–117, 1965. 13364, 13380

Orlanski, I.: A rational subdivision of scales for atmospheric processes, B. Am. Meteorol. Soc., 56, 527–530, 1975. 13379

Pan, M., Wood, E., Wójcik, R., and McCabe, M.: Estimation of regional terrestrial water cycle using multi-sensor remote sensing observations and data assimilation, Remote Sens. Environ., 112, 1282–1294, doi:10.1016/j.rse.2007.02.039, 2008. 13368

Rakovec, O., Kumar, R., Mai, J., Cuntz, M., Thober, S., Zink, M., Attinger, S., Schäfer, D., Schrön, M., and Samaniego, L.: Multiscale and multivariate evaluation of water fluxes and states over European river basins, J. Hydrometeorol., doi:10.1175/JHM-D-15-0054.1, in press, 2015. 13368

Reggiani, P., Sivapalan, M., and Hassanizadeh, S.: A unifying framework for watershed thermodynamics: balance equations for mass, momentum, energy and entropy, and the second law of thermodynamics, Adv. Water Resour., 22, 367–398, doi:10.1016/S0309-1708(98)00012-8, 1998. 13365

Samaniego, L., Kumar, R., and Attinger, S.: Multiscale parameter regionalization of a grid-based hydrologic model at the mesoscale, Water Resour. Res., 46, W05523, doi:10.1029/2008WR007327, 2010. 13368

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Sposito, G. (Ed.): Scale dependence and scale invariance in hydrology, Cambridge University Press, 1998. 13365

Stillwell, J.: Mathematics and its History, Springer, New York, NY, USA, 1989. 13360

Stommel, H.: Varieties of oceanographic experience, Science, 139, 572–576, 1963. 13367

Tetzlaff, D., Buttle, J., Carey, S.K., McGuire, K., Laudon, H., and Soulsby, C.: Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: a review, Hydrol. Process., 29, 3475–3490, doi:10.1002/hyp.10412, 2015. 13368

Todini, E.: Rainfall-runoff modeling – past, present and future, J. Hydrol., 100, 341–352, doi:10.1016/0022-1694(88)90191-6, 1988. 13360

Wagener, T. and Gupta, H.: Model identification for hydrological forecasting under uncertainty, Stoch. Env. Res. Risk A., 19, 378–387, doi:10.1007/s00477-005-0006-5, 2005. 13362

Whitaker, S.: Theory and Applications of Transport in Porous Media: The Method of Volume Averaging, Springer, Dordrecht, the Netherlands, 1999. 13365

Wood, E., Sivapalan, M., Beven, K., and Band, L.: Effects of spatial variability and scale with implications to hydrologic modeling, J. Hydrol., 102, 29–47, 1988. 13365

Wood, E., Lettenmainer, D., and Zartarian, V.: A land-surface hydrology parameterization with subgrid variability for general circulation models, J. Geophys. Res., 97, 2717–2728, doi:10.1029/91JD01786, 1992. 13362

Wood, E., Roundy, J., Troy, T., van Beek, L., Bierkens, M. P., Blyth, E., de Roo, A., Döll, P., Ek, M., Famiglietti, J., Gochis, D., van de Giesen, N., Houser, P., Jaffé, P., Kollet, S., Lehner, B., Lettenmaier, D., Peters-Lidard, C., Sivapalan, M., Sheffield, J., Wade, A., and Whitehead, P.: Hyperresolution global land surface modeling: meeting a grand challenge for monitoring earth's terrestrial water, Water Resour. Res., 47, W05301, doi:10.1029/2010WR010090, 2011. 13361, 13362, 13365, 13368, 13369

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Table 1. All articles used to create Fig. 2, with their highest spatial resolution (in degrees) and the time interval used for calibration and validation.

Authors	Journal	Year	Title	Spat.	Temp.
Abdullah, F. A. and Lettenmaier, D. P.	J. Hydrol.	1997	Application of regional parameter ...	1.000	monthly
Acharya, A., et al.	J. Hydrol.	2011	Modeled streamflow response ...	0.125	monthly
Adam, J. C., et al.	J. Geophys. Res.	2007	Simulation of reservoir influences ...	1.000	monthly
Agboma, C. O., et al.	J. Hydrol.	2009	Intercomparison of the total storage ...	0.300	monthly
Ahmad, S., et al.	Adv. Water Resour.	2010	Estimating soil moisture ...	0.125	daily
Andreadis, K. M. and Lettenmaier, D. P.	Adv. Water Resour.	2006	Assimilating remotely sensed ...	0.125	daily
Arora, V. K. and Boer, G. J.	J. Climate	2006	The temporal variability of ...	2.000	monthly
Ashfaq, M., et al.	J. Geophys. Res.	2010	Influence of climate model ...	0.125	daily
Bao, Z., et al.	J. Hydrol.	2012	Comparison of regionalization ...	0.250	monthly
Bao, Z., et al.	J. Hydrol.	2012	Attribution for decreasing ...	0.250	monthly
Bao, Z., et al.	Hydr. Process.	2012	Sensitivity of hydrological ...	0.250	monthly
Bohn, T. J., et al.	Env. Res. Letters	2007	Methane emissions from ...	1.000	daily
Bohn, T. J., et al.	J. Hydrometeorol.	2010	Seasonal Hydrologic Forecasting ...	0.125	monthly
Bowling, L. C. and Lettenmaier, D. P.	J. Hydrometeorol.	2010	Modeling the Effects of ...	0.125	hourly
Chang, J., et al.	Quater. Int.	2014	Impact of climate change ...	0.500	daily
Cherkauer, K. A., and Lettenmaier, D. P.	J. Geophys. Res.	1999	Hydrologic effects of frozen soils ...	0.500	daily
Christensen, N. S., et al.	Climatic Change	2004	The effect of climate change on ...	0.125	daily
Christensen, N. S. and Lettenmaier, D. P.	Hydrol. Earth Syst. Sc.	2007	A multimodel ensemble approach ...	0.125	daily
Costa-Cabral, M., et al.	Climatic Change	2013	Snowpack and runoff response ...	0.125	monthly
Crow, W. T., et al.	J. Geophys. Res.	2003	Multiobjective calibration of ...	0.125	hourly
Cuo, L., et al.	J. Hydrol.	2013	The impacts of climate change ...	0.250	daily
Demaria, E. M. C., et al.	J. Hydrol.	2013	Climate change impacts on ...	0.250	daily
Demaria, E.M.C., et al.	Int. J. River Bas. Manag.	2014	Satellite precipitation in ...	0.125	monthly
Díaza, A., et al.	Int. J. River Bas. Manag.	2013	Multi-annual variability of ...	0.125	daily
Drusch, M., et al.	Gephys. Res. Lett.	2005	Observation operators for the ...	0.125	daily
Eum, H., et al.	Hydr. Process.	2014	Uncertainty in modelling the ...	0.063	daily
Feng, X., et al.	J. Hydrometeorol.	2008	The Impact of Snow Model ...	0.125	daily
Ferguson, C. R., et al.	Int. J. Remote Sens.	2010	Quantifying uncertainty in ...	0.125	monthly
Ferguson, C. R., et al.	J. Hydrometeorol.	2012	A Global Intercomparison of ...	0.250	daily
Gao, H., et al.	J. Hydrometeorol.	2004	Using a Microwave Emission ...	0.125	daily
Gao, H., et al.	J. Hydrometeorol.	2006	Using TRMM/TMI to Retrieve ...	0.125	daily
Gao, H., et al.	J. Hydrometeorol.	2007	Copula-Derived Observation ...	0.125	daily
Gao, H., et al.	Int. J. Remote Sens.	2010	Estimating the water budget ...	0.500	monthly
Gao, Y., et al.	J. Geophys. Res.	2011	Evaluating climate change ...	0.125	monthly
Garg, V., et al.	J. Hydr. Eng.	2013	Hypothetical scenario?based ...	0.250	yearly
Gebregiorgis, A. and Hossain, F.	J. Hydrometeorol.	2011	How Much Can A Priori Hydrologic ...	0.125	daily
Gebregiorgis, A. S., et al.	Water Resour. Res.	2012	Tracing hydrologic model ...	0.125	daily
Gu, H., et al.	Stoch. Environ. Res. Risk Ass.	2014	Impact of climate change ...	0.125	daily
Guerrero, M., et al.	Int. J. River Bas. Manag.	2013	Parana River morphodynamics ...	0.125	monthly
Guo, J., et al.	J. Hydrol.	2004	Impacts of different precipitation ...	0.125	daily
Guo, J., et al.	Proc. Env. Sci.	2011	Daily runoff simulation in ...	0.042	daily
Haddeland, I., et al.	Gephys. Res. Lett.	2006	Anthropogenic impacts on ...	0.500	monthly
Haddeland, I., et al.	J. Hydrometeorol.	2006	Reconciling Simulated Moisture ...	0.125	hourly
Haddeland, I., et al.	J. Hydrol.	2006	Effects of irrigation on the ...	0.500	daily
Hamlet, A. F., et al.	J. Climate	2005	Effects of Temperature and ...	0.125	monthly
Hamlet, A. F., and Lettenmaier, D. P.	Water Resour. Res.	2007	Effects of 20th century warming ...	0.125	monthly

Table 1. Continued.

Authors	Journal	Year	Title	Spat.	Temp.
Hidalgo, H. G., et al.	J. Hydrol.	2013	Hydrological climate change ...	0.500	monthly
Hillarda, Y., et al.	Remote Sens. Environ.	2003	Assessing snowmelt dynamics ...	0.125	daily
Huang, M., et al.	J. Geophys. Res.	2003	A transferability study of model ...	0.130	daily
Hurkmans, R. T. W. L., et al.	Water Resour. Res.	2008	Water balance versus land ...	0.088	daily
Hurkmans, R. T. W. L., et al.	Water Resour. Res.	2009	Effects of land use changes ...	0.050	daily
Hurkmans, R., et al.	J. Climate	2010	Changes in Streamflow Dynamics ...	0.088	daily
Jayawardena, A. W., et al.	J. Hydrolog. Eng.	2002	Meso-Scale Hydrological ...	1.000	daily
Kam, J., et al.	J. Climate	2013	The Influence of Atlantic ...	0.125	daily
Lakshmi, V., et al.	Gephys. Res. Lett.	2004	Soil moisture as an ...	0.125	monthly
Li, J., et al.	J. Hydrometeorol.	2007	Modeling and Analysis ...	0.042	daily
Li, H., et al.	J. Hydrometeorol.	2013	A Physically Based Runoff ...	0.063	monthly
Liang, X. and Xie, Z.	Adv. Water Resour.	2001	A new surface runoff ...	0.125	daily
Liang ,X. and Xie, Z.	Global Planet. Change	2003	Important factors in land? ...	0.125	daily
Liang, X., et al.	J. Geophys. Res.	2003	A new parameterization ...	0.125	daily
Liang, X., et al.	J. Hydrol.	2004	Assessment of the effects ...	0.031	daily
Liu, Z., et al.	Hydr. Process.	2010	Impacts of climate change on ...	0.500	daily
Liu, L., et al.	J. of Flood Risk Manag.	2013	Hydrological analysis for water ...	0.010	daily
Liu, H., et al.	Hydrol. Earth Syst. Sc.	2013	Soil moisture controls on ...	0.500	monthly
Liu, X., et al.	Hydrol. Earth Syst. Sc.	2014	Effects of surface wind speed ...	0.250	monthly
Livneh, B., et al.	J. Climate	2013	A Long-Term Hydrologically ...	0.063	monthly
Lohmann, D., et al.	Hydrolog. Sci. J.	1998	Regional scale hydrology: ...	0.167	daily
Lu, X. and Zhuang, Q.	J. Geophys. Res.	2012	Modeling methane emissions ...	0.333	daily
Lucas-Picher, P., et al.	Atmosphere-Ocean	2003	Implementation of a ...	0.405	monthly
Luo, Y., et al.	J. Hydrometeorol.	2005	The Operational Eta Model ...	0.125	monthly
Luo, L. and Wood, E. F.	Gephys. Res. Lett.	2007	Monitoring and predicting ...	0.125	monthly
Luo, L. and Wood, E. F.	J. Hydrometeorol.	2008	Use of Bayesian Merging ...	0.125	monthly
Lutz, E. R., et al.	Water Resour. Res.	2012	Paleoreconstruction of cool ...	0.063	monthly
Mao, D. and Cherkauer, K. A.	J. Hydrol.	2009	Impacts of land-use change ...	0.125	monthly
Mao, D., et al.	Water Resour. Res.	2010	Development of a coupled ...	0.125	daily
Marshall, M., et al.	Climate Dynamics	2012	Examining evapotranspiration ...	1.000	monthly
Matheussen, B., et al.	Hydr. Process.	2000	Effects of land cover change ...	0.250	monthly
Maurer, E. P., et al.	J. Geophys. Res.	2001	Evaluation of the land ...	0.125	monthly
Maurer, E. P., et al.	J. Climate	2002	A Long-Term Hydrologically ...	0.125	monthly
McGuire, M., et al.	J. Water Resour. Plan. Manage.	2006	Use of Satellite Data for ...	0.125	monthly
Meng, L. and Quiring, S. M.	Int. J. Climatol.	2010	Observational relationship of ...	0.500	monthly
Miguez-Macho, G., et al.	Bull. Am. Meteor. Soc.	2008	Simulated water table ...	0.008	monthly
Miller, W. P., et al.	J. Water Res. Pl. Manag.	2012	Water Management Decisions ...	0.125	monthly
Minihane, M. R.	Phys. Chem. Earth	2012	Evaluation of streamflow ...	0.250	monthly
Mishra, V., et al.	J. Hydrometeorol.	2010	Parameterization of Lakes ...	0.125	daily
Mishra, V. and Cherkaue, K. A.	Agric. For. Meteorol.	2010	Retrospective droughts in ...	0.125	monthly
Mishra, V., et al.	J. Hydrometeorol.	2010	Assessment of Drought due ...	0.125	monthly
Mishra, V., et al.	Int. J. Clim.	2010	A regional scale assessment ...	0.125	monthly
Mishra, V., et al.	Global Planet. Change	2011	Lake Ice phenology of ...	0.125	daily
Mishra, V., et al.	Global Planet. Change	2011	Changing thermal dynamics ...	0.125	daily
Mishra, V. and Cherkauer, K. A.	J. Geophys. Res.	2011	Influence of cold season ...	0.125	daily
Mo, K. C.	J. Hydrometeorol.	2008	Model-Based Drought Indices ...	0.500	monthly
Mo, K. C., et al.	J. Hydrometeorol.	2012	Uncertainties in North American ...	0.500	monthly
Munoz-Arriola, F., et al.	Water Resour. Res.	2009	Sensitivity of the water resources ...	0.125	monthly

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Table 1. Continued.

Authors	Journal	Year	Title	Spat.	Temp.
Nijssen, B., et al.	Water Resour. Res.	1997	Streamflow simulation for ...	0.500	monthly
Nijssen, B., et al.	J. Climate	2001	Global Retrospective Estimation ...	2.000	monthly
Nijssen, B., et al.	Climatic Change	2001	Hydrologic sensitivity of global ...	1.000	monthly
Niu, J., et al.	J. Hydrol.	2013	Impacts of increased CO2 ...	1.000	monthly
Niu, J. and Chen, J.	Hydrological Sciences Journal	2014	Terrestrial hydrological responses ...	1.000	daily
Niu, J. and Sivakumar, B.	Stoch Environ Res Risk Assess	2014	Study of runoff response to ...	1.000	monthly
Niu, J., et al.	Hydrol. Earth Syst. Sc.	2014	Teleconnection analysis of ...	1.000	monthly
Null, S. E. and Viers, J. H.	Water Resour. Res.	2013	In bad waters: Water year ...	0.125	monthly
O'Donnell, G. M., et al.	J. Geophys. Res.	2000	Macroscale hydrological modeling ...	0.500	monthly
Oubeidillah, A. A., et al.	Hydrol. Earth Syst. Sc.	2014	A large-scale, high-resolution ...	0.042	monthly
Ozdogan, M.	Hydrol. Earth Syst. Sc.	2011	Climate change impacts on ...	0.125	monthly
Pan, M. and Wood, E. F.	J. Hydrometeorol.	2006	Data Assimilation for ...	0.500	daily
Parada, L. M. and Liang, X.	J. Geophys. Res.	2004	Optimal multiscale Kalman ...	0.125	daily
Parada, L. M. and Liang, X.	J. Geophys. Res.	2008	Impacts of spatial resolutions ...	0.125	daily
Park, D. and Markus, M.	J. Hydrol.	2014	Analysis of a changing ...	0.125	daily
Parr, D. and Wang, G.	Global and Planetary Change	2014	Hydrological changes in the ...	0.030	daily
Qiao, L., et al.	Water Resources Management	2014	Climate Change and ...	0.125	daily
Qin, S., et al.	Int. J. Remote Sens.	2013	Development of a hierarchical ...	0.030	daily
Raje, D. and Krishnan, R.	Water Resour. Res.	2012	Bayesian parameter uncertainty ...	1.000	monthly
Raje, D., et al.	Hydr. Process.	2014	Macroscale hydrological modelling ...	1.000	monthly
Ray, R. L., et al.	Remote sensing of environment	2010	Landslide susceptibility mapping ...	0.010	daily
Rhoads, J., et al.	J. Geophys. Res.	2001	Validation of land surfacemodels ...	1.000	daily
Rosenberg, E. A., et al.	Water Resour. Res.	2011	Statistical applications of...	0.063	monthly
Rosenberg, E. A., et al.	Hydrol. Earth Syst. Sc.	2013	On the contribution of ...	0.125	daily
Saurral, R. I.	J. Hydrometeorol.	2010	The Hydrologic Cycle of the ...	0.125	monthly
Schaller, M. F. and Fan, Y.	J. Geophys. Res.	2009	River basins as groundwater ...	0.125	monthly
Schumann, G.J.-P., et al.	Water Resour. Res.	2013	A first large-scale flood ...	0.250	monthly
Sheffield, J., et al.	J. Geophys. Res.	2003	Snow process modeling ...	0.125	daily
Sheffield, J., et al.	J. Hydrometeorol.	2012	Representation of Terrestrial ...	0.500	monthly
Shi, X., et al.	Env. Res. Letters	2011	The role of surface energy ...	1.000	weekly
Shi, X., et al.	J. Climate	2013	Relationships between Recent ...	1.000	monthly
Shrestha, R. R., et al.	Hydr. Process.	2012	Modelling spatial and ...	0.063	monthly
Shrestha, K. Y., et al.	J. Hydrometeorol.	2014	An Atmospheric?Hydrologic ...	0.250	daily
Shrestha, R. R., et al.	J. Hydrometeorol.	2014	Evaluating Hydroclimatic ...	0.063	daily
Shrestha, R. R., et al.	Hydr. Process.	2014	Evaluating the ability of a ...	0.063	monthly
Shukla, S., et al.	Hydrol. Earth Syst. Sc.	2012	Value of medium range ...	0.500	2-weeks
Shukla, S., et al.	Hydrol. Earth Syst. Sc.	2012	On the sources of global land ...	0.500	monthly
Sinha, T., et al.	J. Hydrometeorol.	2010	Impacts of Historic Climate ...	0.125	weekly
Sinha, T. and Cherkauer, K. A.	J. Geophys. Res.	2010	Impacts of future climate ...	0.125	weekly
Sinha, T. and Sankarasubramanian, A.	Hydrol. Earth Syst. Sc.	2013	Role of climate forecasts and ...	0.125	monthly
Slater, A. G., et al.	J. Geophys. Res.	2007	A multimodel simulation of ...	1.000	monthly
Sridhar, V., et al.	Climate Dynamics	2013	Explaining the hydroclimatic ...	0.125	monthly
Stephen, H., et al.	Hydrol. Earth Syst. Sc.	2010	Relating surface backscatter ...	0.125	daily
Su, F., et al.	J. Geophys. Res.	2005	Streamflow simulations of ...	1.000	monthly
Su, F., et al.	J. Geophys. Res.	2006	Evaluation of surface water ...	1.000	monthly
Su, F., et al.	J. Hydrometeorol.	2008	Evaluation of TRMM Multisatellite ...	0.125	daily
Su, F., and Lettenmaier, D. P.	J. Hydrometeorol.	2009	Estimation of the Surface ...	0.125	monthly

Table 1. Continued.

Authors	Journal	Year	Title	Spat.	Temp.
Tang, C. and Piechota, T. C.	J. Hydrol.	2009	Spatial and temporal soil ...	0.125	monthly
Tang, Q. and Lettenmaier, D. P.	Int. J. Remote Sens.	2010	Use of satellite snow-cover ...	0.063	monthly
Tang, C., et al.	J. Hydrol.	2011	Relationships between ...	0.125	monthly
Tang, Q., et al.	J. Hydrometeorol.	2012	Predictability of Evapotranspiration ...	0.063	daily
Tang, C., et al.	Global Planet. Change	2012	Assessing streamflow sensitivity ...	0.063	monthly
Tang, C. and Dennis, R. L.	Global Planet. Change	2014	How reliable is the offline ...	0.125	monthly
Fan, Y., et al.	J. Hydrometeorol.	2011	Verification and Intercomparison ...	0.125	monthly
Vano, J. A., et al.	J. Hydrometeorol.	2012	Hydrologic Sensitivities of ...	0.125	monthly
VanShaar, J. R., et al.	Hydr. Process.	2012	Effects of land-cover changes ...	0.125	monthly
Vicuna, S., et al.	J. Am. Water Resour. As.	2007	The sensitivity of California ...	0.125	monthly
Voisin, N., et al.	J. Hydrometeorol.	2008	Evaluation of Precipitation ...	0.500	monthly
Voisin, N., et al.	Weather Forecast.	2011	Application of a Medium-Range ...	0.250	daily
Wang, A., et al.	J. Geophys. Res.	2008	Integration of the variable ...	0.125	monthly
Wang, J., et al.	Int. J. Clim.	2010	Quantitative assessment of climate ...	0.125	monthly
Wang, G. Q., et al.	Hydrol. Earth Syst. Sc.	2012	Assessing water resources in ...	0.500	daily
Werner, A. T., et al.	Atmosphere-Ocean	2013	Spatial and Temporal Change ...	0.063	daily
Wen, Z., et al.	Water Resour. Res.	2012	A new multiscale routing ...	0.031	daily
Wenger, S. J., et al.	Water Resour. Res.	2010	Macroscale hydrologic ...	0.063	daily
Wojcik, R., et al.	J. Hydrometeorol.	2008	Multimodel Estimation of ...	0.125	hourly
Wood, A. W., et al.	J. Geophys. Res.	2002	Long-range experimental ...	0.125	monthly
Wood, A. W., et al.	J. Geophys. Res.	2005	A retrospective assessment ...	0.125	monthly
Wu, Z., et al.	Atmosphere-Ocean	2007	Thirty-Five Year (1971?2005) ...	0.300	daily
Wu, Z. Y., et al.	Hydrol. Earth Syst. Sc.	2011	Reconstructing and analyzing ...	0.300	daily
Wu, H., et al.	Water Resour. Res.	2014	Real-time global flood ...	0.125	daily
Xia, Y., et al.	J. Geophys. Res.	2012	Continental-scale water ...	0.125	daily
Xia, Y., et al.	Hydr. Process.	2012	Comparative analysis of ...	0.125	monthly
Xia, Y., et al.	Hydr. Process.	2014	Evaluation of NLDAS-2 ...	0.125	daily
Xie, Z., et al.	J. Hydrometeorol.	2007	Regional Parameter Estimation ...	0.500	monthly
Yang, G., et al.	J. Hydrometeorol.	2010	Hydroclimatic Response of ...	0.125	daily
Yang, G., et al.	Landscape Urban Plan.	2011	The impact of urban development ...	0.125	daily
Yang, G. and Bowling, L. C.	Water Resour. Res.	2014	Detection of changes in ...	0.125	daily
Yearsley, J.	Water Resour. Res.	2012	A grid-based approach for ...	0.063	daily
Yong, B., et al.	Water Resour. Res.	2010	Hydrologic evaluation of ...	0.063	daily
Yong, B., e al.	J. Hydrometeorol.	2013	Spatial?Temporal Changes of ...	0.063	daily
Yuan, F., et al.	Can. J. Rem. Sens.	2004	An application of the VIC-3L ...	0.250	daily
Yuan, X., et al.	Hydr. Sci. J.	2009	Sensitivity of regionalized ...	0.500	monthly
Yuan, X., et al.	J. Hydrometeorol.	2013	Probabilistic Seasonal ...	0.250	monthly
Zeng, X., et al.	J. Hydrometeorol.	2010	Comparison of Land?Precipitation ...	0.125	monthly
Zhang, X., et al.	Phys. Chem. Earth	2012	Modeling and assessing ...	0.031	monthly
Zhang, B., et al.	Agr. Water Manage.	2012	Drought variation trends in ...	0.500	yearly
Zhang, B., et al.	Theor. Appl. Climatol.	2013	A drought hazard assessment ...	0.500	yearly
Zhang, B., et al.	Hydr. Process.	2014	Assessing the spatial and ...	0.500	yearly
Zhang, X., et al.	J. Hydrometeorol.	2014	A Long-Term Land Surface ...	0.250	monthly
Zhang, B., et al.	Hydr. Process.	2014	Spatiotemporal analysis of climate ...	0.500	yearly
Zhao, F., et al.	J. Hydrometeorol.	2012	Application of a Macroscale ...	0.050	daily
Zhao, X. and Wu, P.	Natural Hazards	2013	Meteorological drought over ...	0.500	yearly
Zhao, Q., et al.	Env. Earth Sci.	2013	Coupling a glacier melt model ...	0.083	daily
Zhao, F., et al.	J. Hydrol.	2013	The effect of spatial rainfall ...	0.050	daily
Zhu, C. and Lettenmaier, D. P.	J. Climate	2007	Long-Term Climate and ...	0.125	monthly
Ziegler, A. D., et al.	J. Climate	2003	Detection of Intensification in ...	2.000	monthly
Ziegler, A. D., et al.	Climatic Change	2005	Detection of time for plausible ...	0.125	monthly

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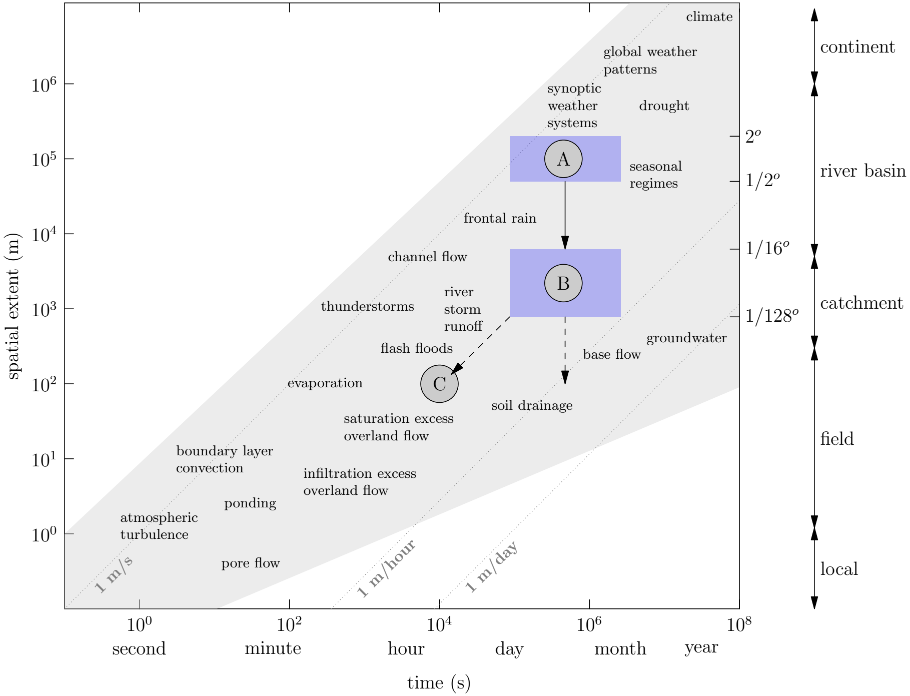

Figure 1. The time and space scales of several hydrometeorological processes. Adapted from Brutsaert (2005) and Blöschl and Sivapalan (1995), who based it on Orlanski (1975), Dunne (1978), Fortak (1982) and Anderson and Burt (1990). The blue areas indicate the time and space scale for which the VIC model has been applied, when it was initially developed (A) and nowadays (B). The dashed arrow pointing downwards shows the ambitions of hyper-resolution modelling, whereas the dashed arrow pointing towards (C) shows the time and space scale of hyper-resolution modelling if it would follow the direction of characteristic velocity of hydrometeorological processes.

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Process-based evalution of hyper-resolution models

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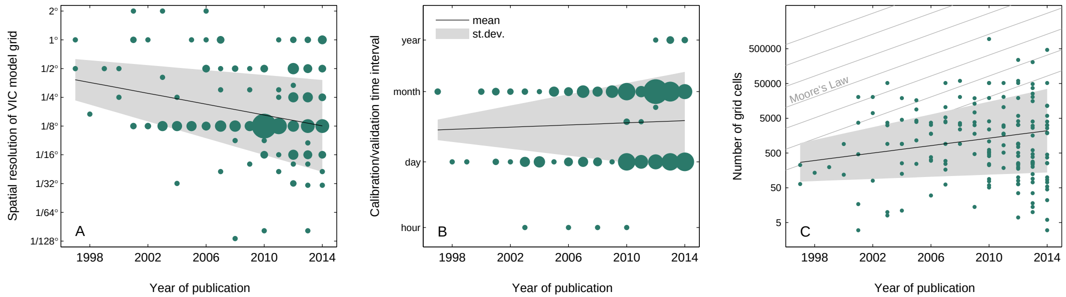

Figure 2. The year of publication versus the highest spatial resolution of the VIC model that was used in the study **(a)**, the smallest time interval on which the calibration and/or validation of the VIC model was performed **(b)**, and the total number of grid cells in the study **(c)** based on 192 peer-reviewed studies. The grey lines in **(c)** show the slope of computational power increase according to Moore's law (Moore, 1965). The point size is proportional to the number of studies that were published in a certain year with a certain spatial or temporal resolution. If the spatial resolution was given in kilometres, it was assumed that 1° = 100 km. For the total number of grid cells, catchment size was divided by cell size, assuming that 1° = 100 km, unless the number of grid cells was explicitly given. To obtain the mean and the standard deviation, both were calculated per year on the logarithmic scale and with linear regression a line was fitted through these points.

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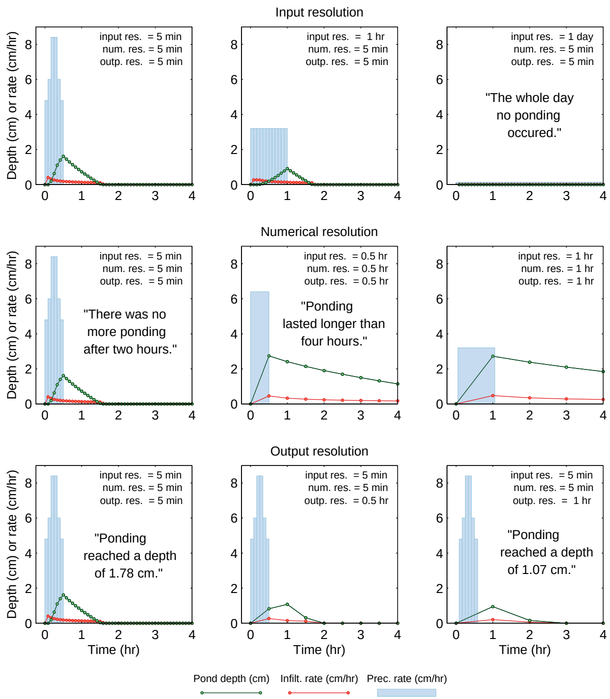

Figure 3. Application of the Green-Ampt infiltration scheme for different input resolutions (upper row panels), different numerical resolutions (middle row panels), and different output resolutions (lower row panels). For each set-up, the model was fed with the same extreme precipitation event of 35 mm of rain in 30 min (4 mm in first 5 min, 5 mm in 5–10 min, 7 mm in 10–20 min, 5 mm in 20–25 min and 4 mm in 25–30 min). The model parameters have been kept constant; saturated hydrologic conductivity $K_s = 0.044\,\mathrm{cm\,h^{-1}}$, initial soilmoisture $\theta_i = 0.1$, saturated soil moisture $\theta_s = 0.5$, matric pressure at wetting front $\Psi = 22.4$ cm. Each of the three time concepts impacts the conclusions that are drawn from the model results, which shows that calibration and validation at the appropriate time interval is essential to resolve the processes taking place.

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