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Historical Development of Rainfall-Runoff Modelling

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Abstract

Rainfall-runoff models are used across academia and industry, and the number and type have proliferated over time. In this primer we briefly introduce the key features of these models and provide an overview of their historical development and drivers behind those developments. To complete the discussion there is a brief section on model choice including model inter-comparison. We also seek to clarify jargon terms for readers new to this area.

1) Introduction

Hydrology is the study of the land component of the hydrological cycle. Hydrologists seek to understand and model water movement through the landscape across a range of spatial and temporal scales, which are crucial for increasing hydrologic knowledge and managing water dependent societal requirements. Unfortunately, as Woolhiser (1973, p. 533) noted, a catchment is *"… an extremely complicated natural system that we cannot hope to understand in all detail."* At the catchment scale, numerous physical processes are involved in water moving onto (*precipitation*, *interception*), into (*infiltration*), within (lateral and vertical water movement through *unsaturated* and *saturated soil* and *groundwater*) and out of the catchment (*evaporation, transpiration, runoff*). At small spatial and temporal scales, these processes are highly complex and exhibit heterogeneous behaviour. Whereas, at larger spatial and temporal scales, process complexity generally reduces through averaging smaller scale complexities (Wood et al., 1988; Grayson et al., 1992; Blöschl et al., 1995; Savenije, 2001). Consequently, the degree of process detail required to understand and model the conversion of rainfall into runoff varies with the spatial and temporal scales of interest. Despite being studied intensely over the past 100 years (Peters-Lidard et al., 2019), numerous questions remain. For example, in 2019 an initial 260 questions were whittled down to twenty-three unsolved problems in hydrology (Blöschl et al., 2019).

This primer provides a very brief overview, for a general audience, of the development of *rainfall-runoff models* (RRMs). Some of the more complex models, especially those that include detailed sub-surface processes, are known as *hydrologic models*. RRMs are a small, yet crucial, part of hydrology. Following this introduction, we describe in Section 2 the features of a RRM. In Section 3 we outline a history of development and types of models. In doing this, we identify the factors that led to each development. In Section 4 we discuss briefly model choice including inter-model comparisons, reviews and overview papers. This is followed by a very brief section on Other Issues. Some conclusions are offered in Section 6.

In this primer we use the term *runoff* as a depth of water (flow volume per unit catchment area) whereas *streamflow* represents a volume of water per unit time. Care needs to be taken with the units of flow as the units of rainfall input to a RRM are usually expressed as depth. There is a range of nomenclature describing RRMs. We adopt the following: (1) empirical (*"… not suitable for spatial extension of streamflow records into ungauged catchments"*), (2) conceptual (*"… use a storage element as the basic building component", "A number of processes are usually aggregated (in space and time) into a single parameter …"*), (3) physical (*"… based on the conservation of mass, momentum and energy", "…*

suffer from extreme data demand …") (Wagener et al., 2004, pp. 2 and 3), and (4) distributed ("… *defining parameter values for every element in the solution mesh.*") (Beven, 2012, p. 40).

2) Rainfall-runoff models

A rainfall-runoff model is a simplified representation of the complicated natural system that partitions rainfall into runoff, evapotranspiration and stored moisture within the soil or groundwater. In this paper, we focus on mathematical models rather than physical or analog models (Clarke, 1973). We also only deal with deterministic rainfall-runoff models rather than stochastic models, although we note that Raphael Bras in presenting the 1999 Horton Lecture observed that *"… hydrologic phenomena can and should be represented, and interpreted, as products of stochastic dynamics"* (Bras, 1999, p. 1154). Deterministic RRMs are tools to estimate catchment runoff from a set of climate variables (rainfall and potential evapotranspiration or air temperature) and catchment characteristics. Models with an emphasis on snow and permafrost and other forms of hydrological modelling systems including stochastic models are not discussed. Moreover, space precludes discussion of updating RRMs for real time forecasting (Refsgaard, 1997; Goswami et al., 2005; Todini, 2005; Bowden et al., 2012; Mockler et al., 2016; Zhang et al., 2018); we concentrate on RRMs for simulating historical behaviour of runoff and within-catchment processes. Another topic far too large to be considered in this primer relates to modular modelling systems introduced by Leavesley et al. (2002, p. 173) in responding to the question "… *what combination of process conceptualizations is most appropriate?*" (see for example, Fenicia et al. 2011; Clark et al. 2008; Clark et al. 2015; Knoben et al, 2019).

In terms of intended application, mathematical RRMs are generally either *discrete*, for modelling a specific moment in time (instantaneous, hydrograph or event-based), or *continuous*, for modelling extended periods of time. Within these two categories, RRMs come in a variety of flavours relating to the degree of simplification in space, time, and process representation. One way to view this spectrum of models is via the lens of top-down versus bottom up modelling (Klemeš, 1983; Zhang et al., 2001; Sivapalan et al., 2003). The top-down approach generally seeks to model long-term and or large-scale runoff behaviour satisfactorily, before adding further complexity to the model to represent shorter time scales or smaller spatial scales (Farmer et al., 2003; Zhang et al., 2008). Top-down models include simple empirical relationships or equations, graphical coaxial relationships, and simple conceptual models in which catchment processes are represented by simple algorithms connecting hypothetical storages representing the whole catchment. In contrast, the bottom-up approach generally seeks to scale up realistic mathematical representations of finer temporal and spatial scale catchment processes to produce an estimate of catchment runoff (Sivapalan et al., 2003). Bottom-up models are often considered *physically-based* or *process-based*. In terms of spatial representation, RRMs can be *lumped*, in which the catchment is treated as a single point in space, *semi-distributed*, in which the catchment is treated as sub-catchments that are modelled separately and with an appropriate runoff routing routine to combine the sub-catchment runoffs, or *fully–distributed*, in which the catchment is partitioned into many small units, allowing the inputs, outputs and parameters to vary spatially (see Vieux, 2005). Some example model structure diagrams are in Linsley and Crawford (1960, p. 527, Figure 1) for the conceptually semi-distributed model SWM, Abbott et al. (1986a, p. 47, Figure 1), for the complex physically-distributed model SHE, and Perrin et al. (2003, p. 277, Figure 1) for the conceptually lumped model GR4J.

Rainfall-runoff models can operate at time-steps between a minute and a year, and from small to large spatial scales. The main uses of RRMs include infilling missing or extending streamflow data, flood forecasting, estimating streamflow in ungauged catchments, urban hydrology, water resources assessment, and hydrological research. RRMs are also used in 'what-if' scenarios to investigate likely

variation in runoff due to land-use modification and or climate change, and on the impact of runoff changes on reservoir management and ecological health.

3) Key developments in rainfall-runoff modelling

A time-history of key RRM developments is presented in Figure 1 and summarised below. According to Dumitrescu and Nemec (1974) the anonymous publication in 1674 of Perrault's book, 'De l'origine des fontaines' (On the origin of springs), heralds the beginning of hydrology. Perrault's measurements of rainfall and discharge in the Seine catchment can be considered the start of rainfall-runoff modelling where annual runoff equalled annual rainfall divided by 6 (Linsley, 1967). A more detailed history of model developments can be found in Villeneuve et al. (2008). According to Dooge (1974), John Dalton (1766-1844) developed in ~1802 a water balance for England and Wales which Dooge expressed as:

$$Q = (P - E)L^2$$

where Q is runoff, P is rainfall, E is evaporation and L is the length of the main river draining the catchment.

Since the Perrault and Dalton models, there have been at least two hundred and seventy-nine RRMs described in the journal literature, plus many minor updates of previous versions. In Supplementary Table S1 we list the 279 models that we consider to be different models. Clark et al. (2011, p1) offer an interesting comment on the plethora of models. "*The current overabundance of models is symptomatic of an insufficient scientific understanding of environmental dynamics at the catchment scale, which can be attributed to difficulties in measuring and representing the heterogeneity encountered in natural systems*".

3.1) Rational method

The first formal description of a RRM, albeit a simple one, appears to be Mulvany (1851), who built on the computations of several Irish engineers. Mulvany proposed that maximum flood runoff is proportional to uniform rainfall modified by catchment area and by *"absorption and evaporation"* (Mulvany, 1851, p. 30). This approach paved the way for the discrete Rational Method which is defined as:

$$Q = CiA$$

where Q is runoff, C is an empirical coefficient, i is uniform rainfall over a specified period, and A is catchment area. According to Dooge (1974), Mulvany's important contribution was the introduction of the 'time of concentration' which Mulvany defined as "… *the time which a flood requires to attain its maximum height, during the continuance of a uniform rate of fall of rain. This may be assumed to be the time necessary for the rain, which falls on the most remote portion of the catchment, to travel to the outlet.*" (Mulvany, 1851, p. 23). Beven (2020) provides a history of the 'time of concentration' concept and highlights how water velocity, rather than the correct wave velocity (celerity), has often been used within the literature on this topic. From 1851 to 1931, several authors added an additional term (often catchment slope) to the rational equation, based mainly on field data, to account for the non-linearity of runoff because of variations in catchment area and slope in urban catchments.

Kuichling (1889) appears to be first in the United States to adopt the *time of concentration* concept into analysis (Gregory, 1907). Except for special situations in urban drainage (see Reid, 1927 and Riley,

1931 who discuss the tangent method), adopting the time of concentration concept ensures the discharge estimated using the Rational Method is the maximum value for the given situation.

The incorporation of rainfall event frequency in estimating discharge was another major advance in the application of the Rational Method (Metcalf and Eddy, 1914), which lead to the common use of intensity-duration-frequency curves. Applying the Rational Method without considering antecedent catchment conditions resulted in the frequency of peak discharge not equating to that for rainfall. This problem was identified in 1936 by Horner and Flynt (1936) but neglected until revived by Schaake et al. (1967) (see Pilgrim and Cordery, 1992, p. 9.18).

3.2) Mean annual models
In 1904, Schreiber (1904) related mean annual runoff to the ratio, $\frac{k}{\bar{P}}$, as follows:

$$\bar{R} = \bar{P}\exp\left(-\frac{k}{\bar{P}}\right)$$

where $\bar{R}$ is mean annual runoff, $\bar{P}$ is mean annual precipitation, and k is a constant. Oldekop (1911) realised that k represented *"maximum possible evaporation, only dependent on climate"*, which is another way of describing mean annual potential evapotranspiration (for details see Andréassian et al., 2016). Following Oldekop, the above equation can be written in terms of the aridity index (φ) as

$$\bar{R} = \bar{P}\exp(-\varphi)$$

where $\varphi = \frac{E_{pot}}{\bar{P}}$ and E_{pot} is potential evapotranspiration. Other researchers (see Supplementary Table S1 for details) have followed an analogous approach, the most important being Budyko (1974). As noted by Andréassian et al. (2016), Budyko-based modelling is still an active area of research and application.

3.3) Unitgraphs
The next major development was unitgraph theory, introduced by Sherman (1932) and based on the superposition principle, where a unitgraph is defined as the surface runoff hydrograph (total runoff less baseflow) produced from one unit of uniform rainfall excess (total rainfall less losses) over a catchment. Using unitgraphs to estimate runoff implies rainfall excess versus surface runoff is a linear system and can be used to estimate hydrographs resulting from variable (non-uniform) rainfall excess input. To overcome the effect of potential errors in a short period unitgraph, derived from a long period unitgraph, and to smooth out the irregularities in the computed unitgraph, Nash (1957) developed the Instantaneous Unit Hydrograph (IUH) which is defined as:

$$u = \frac{v}{k\Gamma(n)}e^{-\frac{t}{k}}\left(\frac{t}{k}\right)^{n-1}$$

where u is the ordinate of the unitgraph, v is volume of the unitgraph, n is a numerical parameter, k is a parameter with dimensions of time, $\Gamma(n)$ is the ordinate of the incomplete Gamma distribution, and t is time where the IUH is considered equivalent to a hypothetical linear reservoir. A cascade of several IUHs with the same k value is known as Nash's Linear cascade model, which can be used to estimate flood hydrographs at the outlet of a catchment from catchment rainfall excess. Nourani et al. (2009)

extended this concept to representing a catchment by a cascade of several linear storages in series and/or in parallel.

We also note two other approaches that deal with estimating surface runoff from rainfall excess namely the time-area diagram (Ross, 1921) and reservoir storage or runoff routing (Laurenson, 1959, 1964). The time-area method routes rainfall excess over a catchment to the outlet and Clark (1945) combined this with a linear reservoir to estimate a unit hydrograph. Laurenson (1964) proposed runoff routing to overcome some of the difficulties encountered when the rainfall excess–surface runoff process is non-linear; a practical application is by Mein et al. (1974).

3.4) Conceptual models

With the introduction of mainframe computers in the 1950s, Linsley and Crawford (1960) (also Crawford and Linsley, 1962) introduced the Stanford Watershed Model (SWM). There is a rich history about this development (succinctly outlined by Crawford and Burges (2004)) in which the key elements were the curiosity-driven intellectual climate at Stanford University and the computational speed of digital computers over manual methods. SWM is an example of a continuous, daily time-step, conceptual lumped model. The model conceptually represents the hydrologic processes involved in converting rainfall into runoff and consists of linked storage elements with simple algorithms defining fluxes into, and out of, those storages. Models of this form are known as *Explicit Soil Moisture Accounting* (ESMA) procedures (Todini, 2002). Although Crawford and Linsley are recognised for their major contribution to digital rainfall-runoff modelling, others followed shortly afterwards (independently or inspired by them) including Sugawara (1961), Boughton (1964) and Dawdy and O'Donnell (1965).

Following the publication of the SWM (which requires estimation of values for ~30 parameters), many similar models were developed over the next 50 years (see Supplementary Table S1). In this context, Franchini and Pacciani (1991) comment that there are two competing requirements namely the need to respect the physics of the hydrologic processes and to reduce model complexity. Over time, conceptual model development emphasised reducing the number of model parameters due to the realisation that models were over-parameterised relative to the information content of the inputs and outputs used to drive the models (Hornberger et al., 1985; Beven, 1989; Jakeman and Hornberger, 1993). Beven (1989, p. 159) suggested that *"… three to five parameters should be sufficient to reproduce most of the information in a hydrological record"*. Later, Ye et al. (1997, p. 153) suggested that *"… from humid to semiarid ephemeral catchments: that a model of about six parameters, albeit in an appropriate model structure, is sufficient to characterize the information in rainfall-discharge time series over a wide range of catchment sizes."*. Based on a detailed study of 429 catchments, Perrin et al. (2001, p. 298) concluded that *"... the number of free parameters might be restricted to between three and five in lumped rainfall-runoff models"*, a range also recommended by Wagener et al. (2004).

3.5) Fully-distributed models

A fully-distributed model uses many small independent elements to represent within catchment spatial variations in inputs, outputs and model parameters. With the increased speed and capacity of digital computers, Huggins and Monke (1968, p. 529) introduced the first fully-distributed surface runoff model, the Huggins-Monke model, based on the hypothesis that "*At every point within the watershed, a functional relationship exists between the rate of surface runoff (dependent variable) and the hydrologic parameters of topography, temperature, time from the beginning of the storm event, rainfall intensity (to the extent that it affects flow turbulence and topography), and depth of flow.*" For a distributed model this hypothesis is relaxed in that it is assumed to apply to each cell. (For a lumped

model as noted in Section 3.4, an average relationship is assumed.) When using a fully-distributed model, the number and size of grid cells in the horizontal and vertical planes must be decided, which is usually a trade-off between catchment size, the spatial resolution of available data to inform the model, and realism of process representation at different scales. Ivanov et al. (2004, p. 1) argued that detailed representation of the spatial information (topography, soils, vegetation, and meteorological forcings) was necessary because *"… model coarsening is the distortion of the simulated hydrological dynamics"*.

To avoid modelling complex heterogeneity at very small scales, but still achieve large-scale realism, Wood et al. (1988, p. 31) introduced the concept of a Representative Elementary Area (REA) as *"… a fundamental building block for catchment modeling…"*. The REA for a catchment should be large enough to average small-scale heterogeneous hydrologic responses into a homogenous response and small enough to allow different REAs to reflect larger scale spatial differences. Wood et al. (1988) suggested the size of a REA is about 1 km². An alternative concept, representative elementary watersheds (REW), was introduced by Reggiana et al. (1998) and is defined "… *as the smallest elementary unit into which we can discretise a large watershed for any given time scale of interest*" (Lee et al. 2005, p. 167). In these sub-watersheds, the conservation equations of mass, momentum, energy and entropy are averaged in space and time. Another approach to describe spatial variability of catchment features affecting RRMs follows Amerman's (1965) 'unit source area', which is commonly known as a hydrological response unit (HRU) (Beven, 2012). Here, HRU is made up of different spatial data and allows the hydrograph at the HRU outlet to be predicted from effective rainfall. We identify in Supplementary Table S1 67 fully-distributed models, of which 40 are conceptual and 27 physically based. However, few models use HRU, REA or REW as their building blocks.

3.6) Physically-based models
In 1969, Freeze and Harlan (1969) presented a blueprint for a physically-based model that represented hydrologic processes through a set of partial differential equations, interrelated by the concepts of continuity of mass and momentum with appropriate boundary conditions. They acknowledged three considerations to achieve such a model (Freeze and Harlan, 1969 p. 239):

> *"(1) Are physically-based mathematical derivations of the hydrologic processes available? Are the interrelationships between the component phenomena well enough understood? Are the developments adaptable to a simulation of the entire hydrologic cycle?*
> *(2) Is it possible to measure or estimate accurately the controlling hydrologic parameters? Are the amounts of necessary input data prohibitive?*
> *(3) Have the earlier computer limitations of storage capacity and speed of computation been overcome? Is the application of digital computers to this type of problem economically feasible?"*

While the third consideration has become less limiting over time (although Clark et al. (2017) offer some sobering comments regarding computational solutions), the first two remain highly relevant. It was not until the 1980's that a physically-based fully-distributed model, Systéme Hydrologique Européen (SHE), was operational. SHE, briefly described by Beven et al. (1980) and, more fully, by Abbott et al. (1986a, b), incorporates fundamental equations representing overland and channel flow, unsaturated and saturated sub-surface flow as well as snow-melt, interception and evapotranspiration processes. SHE was one of the first models to incorporate Richards's equation (Richards, 1931) to simulate vertical flow in the unsaturated zone. Beven et al. (1980, p. 134) point out that "*it is important to recognize that the 'laws'* [e.g. Darcy, Manning] *on which physically-based models are based may be validated by experiment, independently of the model itself. This implies that the parameters of those*

'laws' (and therefore of the model) are by definition measurable; that the predictions of the model should be capable of validation by measurements of individual processes.)" Soon after the publication of the SHE model, others followed. We identify 35 physically-based models (including coupled surface sub-surface models) in the Supplementary Table S1.

An expected outcome of developing physically based models was improved assessment of "what-if" questions through more realistic simulation of internal and external effects on catchment behaviour (Abbott et al., 1986a; Todini, 1988). However, over time the challenge of meeting the first two considerations of Freeze and Harlan (1969) became evident, which limited the practical utility of these models. Grayson et al. (1992, p. 2659) questioned whether the concept of physically based models is realistic and noted that *"Model development is often not carried out in conjunction with field programs designed to test complex models, so the link with reality is lost."* When field data are available, there remains the challenge of resolving scale differences between the data and model grid cells. Beven (1996, p. 256) reinforces these views when arguing that applications of Darcy's law and Richards' equation are not valid at spatial scales adopted in distributed models. Sivapalan (2003, p. 3165) recognised *"… that we will never have full knowledge of the heterogeneities and complexities present in specific basins, and a realistic accounting of this lack of knowledge in terms of its impact on predictions"*. While Vertessy et al. (1993, p. 669) noted there *"is little doubt that our modelling capabilities have surpassed our ability to gather meaningful field data for model parametrisation and validation"*, nevertheless, they also noted that physically-based models were still the best option for addressing many "what-if" questions.

3.7) Coupled or integrated surface-subsurface models
In 1996, O'Connell and Todini (1996, p. 14) concluded their overview of modelling hydrological systems with an encouragement to develop coupled or integrated models: "*This is an opportunity not to be missed!".* Within 10 years, nine coupled surface-subsurface models were published. However, as noted by Yu et al. (2016, p. 191), detailed results of application are, typically, not available in the final publication, leaving readers and potential users with insufficient "… *information to be certain about the data sources and simulation results, let alone replicate or reuse the model simulation from the published text, figures, and tables.*"

Fully coupled or integrated surface-subsurface models, which make up 4.3% of the data base in Table S1, solve surface and subsurface flow equations using numerical techniques in a spatially explicit manner. These models seek to represent feedbacks and interactions between surface and subsurface flow while conserving mass (Maxwell et al., 2014). Space precludes a description of a coupled model, but the interested reader can see Yu et al. (2016, p. 192-193) for a brief description of PIHM, a coupled surface-subsurface hydrologic model. These models are a continuum of the physically-distributed group but it was decided to discuss and identify these models separately (Supplementary Table S1) as there have already been two inter-model comparisons specifically for these models (Maxwell et al., 2014; Kollet et al., 2017). Readers will note that the SHE model is listed in Table S1 as a physically-distributed model. Whereas, MIKE-SHE and SHETRAN4, which are extensions of SHE, are grouped with the other 10 coupled-distributed models in Table S1 as they include three-dimensional subsurface components and a wider range of modelling capability (Beven, 2012; Ewen et al, 2000). Several of these coupled models are based on open-source code.

3.8) Artificial neural network techniques
Artificial neural network (ANN) techniques were introduced to rainfall-runoff modelling in the early 1990's (Daniel, 1991). In the context of runoff estimation, ANNs use flexible data-driven approaches

to represent the complex non-linear relationships between input forcing variables and runoff that other rainfall-runoff modelling approaches find difficult to identify. Space does not permit a detailed discussion of available methods, suffice to say there are many ANNs and related applications (e.g., fuzzy logic, genetic algorithms) reported in the literature (see Abrahart et al., 2004). ANNs provide useful empirical estimates of runoff but application of these models beyond the range of data used in their development remains problematic.

3.9) Summary comment

Over time, the number of RRMs has increased (Figure 2), with surges in model development in the mid-1960s (introduction of digital computing) and the 1990s (increased availability of distributed data). Figure 2 also shows the number of published discrete and continuous RRMs models per decade, sampled by time-step of operation (sub-daily, daily, monthly, and annual). Nearly all discontinuous models use a sub-daily time-step (Table 1) to identify the shape and peak value of the resulting hydrograph. However, daily and sub-daily time-steps dominate the continuous models (Table 1). Of the 279 models in our sample, 79% were identified as continuous models and 21% as discrete models. Conceptual models make up 74% of the sample, while physically based models make up only 13%. Daily conceptually lumped models are the largest group, consisting of 22% of the sample. Supplementary Figures S1 and S2 show the timelines of continuous and discrete RRMs respectively sampled by model type (empirical, conceptual, physical or coupled) and how they address spatial variability (as lumped, semi-distributed and distributed models).

4) Model choice

As a primer this document would be incomplete without some reference to model choice including inter-comparisons. A practitioner seeking a rainfall-runoff model faces a smörgåsbord of options that have been developed over time (see Figure 2 and Supplementary Table S1). To inform this choice, numerous model inter-comparison studies, reviews and overviews have been conducted. A sub-sample for the interested reader includes: Linsley (1967); Woolhiser (1973); Fleming (1975); Weeks & Hebbert (1980); Haan et al. (1982); Linsley (1982); Klemeš, (1986a); Beven, 1987; Todini (1988); Goodrich and Woolhiser (1991); Franchini & Pacciani (1991); Wheater et al. (1993); Jakeman & Hornberger (1993); Hornberger & Boyer (1995); Xu & Singh (1998); Grayson & Blöschl (2000); Croke and Jakeman (2001); Singh & Woolhiser (2002); Boughton and Droop (2003); Reed et al. (2004); Wagener et al (2004); Boughton (2005); Duan et al. (2006); Jones et al. (2006); Villeneuve et al. (2008); Breuer et al. (2009); Chiew (2010); Blöschl et al. (2013); Maxwell et al. (2014); Kollet et al. (2017); Krysanova et al. (2017); Huang et al. (2017); Singh (2018). Although this list is long, comparisons of model performance have been limited by lack of model code, inconsistent model versions and inconsistent model implementation. The recent debates by Clark et al. (2011, 2012) and Beven et al. (2012), and by Hutton et al. (2016, 2017) and Melsen et al. (2017) highlight some of the issues, for example, hypothesis testing and definitions of reproducibility. Knoben et al (2019) recently presented the Modular Assessment of Rainfall–Runoff Models Toolbox (MARRMoT), an open-source consistent implementation of 46 conceptual hydrologic models, to facilitate future model intercomparison studies.

The large number of model options confronting a user of RRMs can be reduced by considering which models provide output of the required type for the application of interest (discrete or continuous, time-step of output), whether the required input data are available, whether the model's complexity is appropriate for the task and information content of the input data, and whether the model code is readily available. Ideally, a practitioner would then choose the best performing model with the required characteristics for the task. But practice is often different according to Addor & Melsen (2019) who highlight a strong social component to hydrologic model selection. In an analysis of abstracts from

1,529 peer-reviewed papers, published between 1991 and 2018, they investigated the use of seven hydrological models and found regional preferences in model selection. In 74% of papers considered, the model used could be predicted from the institutional affiliation of the first author, which suggests model familiarity and source code availability are stronger determinants of model selection than model performance or adequacy. Addor & Melsen (2019) found the role of model adequacy in model selection hard to identify in these publications.

The World Meteorological Organisation conducted three early inter-comparisons of conceptual models between 1968-1974, 1976-1983 and 1985-1988 (Askew, 1989). More recently, distributed models were compared in the Distributed Model Intercomparison Project Phase 1 (DMIP1, 2000-2003, Smith et al., 2004; Reed et al., 2004) and DMIP Phase 2 (beginning in 2007, Smith et al., 2012a, b, 2013). Several major conclusions of the DMIP projects identified by Smith et al. (2012a, p.3; 2012b, p. 36) were that *"Distributed models should be viewed as complements rather than replacements of lumped models in operational forecasting environments, at least for the foreseeable future"*, *"Lumped models provide a valuable integrated view of the basin outlet response",* and *"Models combining so-called conceptual rainfall-runoff mechanisms with physically-based routing schemes achieved the best overall performance"*. There were also two inter-comparisons of coupled surface-subsurface distributed models by Maxwell et al. (2014) and Kollet et al. (2017). To facilitate comparisons they progressively increased the complexity of benchmark tests via several synthetic numerical experiments with simple geometries and a small field experiment. No assessments at a catchment scale were performed.

Perrin et al. (2001) applied 19 daily conceptual lumped models with three to nine optimised parameters to 429 catchments. They concluded that *"… very simple models can achieve a level of performance almost as high as models with more parameters. These more complex models are subject to over-parameterisation, which prevents them from reaching their potential performance level"* (p. 298). This view accords with Wagener et al. (2004, p 53), who identified two questions that after 40 years of effort had not been successfully answered*, "What is the appropriate model structure for a given type of hydrological system and a particular modelling task? What is the appropriate parameter set within this structure to characterize the unique response features of a particular catchment?"* They noted that *"Simple structures (in terms of the number of free parameters) perform as well as complex ones for many purposes"*, and *"Many model structures have been developed, but only a limited number of components are used within them".* As noted in Section 3.4, the consensus number of free parameters is three to five.

Conceptual models are known to provide satisfactory estimates of streamflow at a catchment outlet but are known to often produce unrealistic internal hydrologic fluxes. For practical applications where internal catchment processes are not required, a conceptual model with a small number of parameters is the best course of action as conceptual models are known to provide satisfactory estimates of streamflow at a catchment outlet. Whereas, physics-based distributed models and coupled surface-subsurface models offer the best chance of modelling internal catchment processes (Fatichi et al., 2016), but at significant cost as field observations, data preparation and parameter calibrations are very expensive (Ampadu et al., 2013) and over-parameterisation is a risk to model accuracy.

The importance of personal judgement in applying a RRM, particularly for physically-based models, was highlighted by Holländer et al. (2009), who describe a modelling comparison study on an artificial catchment (Chicken Creek) in Germany. Catchment terrain, soil and vegetation data, three years of climate data, and initial groundwater status were provided to ten modelling groups. Discharge data were not provided. Each group applied their mainly physically based models to the catchment to estimate

three years of discharge. Holländer et al. (2009, abstract) noted *"None of the model simulations came even close to the observed water balance for the entire 3-year study period"* and that a major source of difference between model results was due to decisions made by the modellers on how they set up their models to represent the catchment. This study also highlighted how soft data about dominant processes could be used to improve model results, through better model set up, in agreement with Seibert and McDonnell (2002).

5) Other issues
There are many other issues relating to rainfall-runoff modelling that could be discussed within the framework of a primer on RRM, but space precludes their inclusion. For example (1) calibration and evaluation (Klemeš, 1986a, b; Ewen and Parkin, 1996; Parkin et al., 1996; Bathurst et al., 2004; Duan et al., 2006; Gupta et al., 2009; Vaze et al., 2010; Saft et al., 2016; Fowler et al., 2016, 2018), (2) equifinality (Beven and Freer, 2001; Savenije, 2001; Beven, 2006; Khatami et al, 2019), (3) uncertainty (Kavetski et al., 2006a, b; Nearing & Gupta, 2015; Nearing et al., 2016; Beven, 2019a); (4) consistent modelling across multiple time steps (Ficchi et al., 2019); (5) modelling framework, methodology and philosophy (Fenicia et al., 2011; Crooks et al., 2014, Clark et al., 2008, 2011, 2015; Hrachowitz and Clark, 2017); (6) plausibility and influence of internal fluxes (Guo et al., 2017; Ficchi et al., 2019; Khatami et al, 2019) ; and (7) models of everywhere (Beven, 2007; Wood et al., 2011; Beven, 2019b; Blair et al., 2019). The reference list in this primer would be incomplete if reference was not made to 'Rainfall-Runoff Modelling The Primer' in which Beven (2012) deals with the evolution of rainfall-runoff modelling including the above topics and more.

Conclusion
Over the last 350 years, hydrological modelling has developed from the broad catchment scale of Perrault based on a minimal amount of experimental data to the high resolution physically-based coupled surface subsurface spatially distributed models of today. In this primer we have taken a historical perspective to outline developments in rainfall-runoff modelling over time. Many of the plethora of models in use today can trace their lineage back to the key developments outlined above. While the development of new model types may have slowed, the refinement of existing model types continues unabated. Recent contributions to facilitate model intercomparisons and open-source code promise more informative model intercomparisons in the future and increase the ability of modellers to break free from model parochialism when selecting which model to use. Improving the performance of RRMs under changing conditions will remain an active area of research for the foreseeable future. Seeking insights for model improvement from model internal fluxes rather than solely from modelled total flow presents scope for improving model realism and attempting to constrain model equifinality. We conclude this primer with the observation, based on the literature we have surveyed and our own experience, that much progress has been made in the science of rainfall-runoff modelling since the mid-1960s but at the same time we acknowledge there remain many gaps in our knowledge as discussed by Blöschl and his 229 co-authors (2019).

References
Abbott MB, Bathurst JC, Cunge JA, O'Connell PE, Rasmussen J. An introduction to the European Hydrological System – Systéme Hydrologique Européen (SHE). 1: History and philosophy of a physically-based, distributed modelling system. *J. Hydrol.* 1986a, 87, 45-59.
Abbott MB, Bathurst JC, Cunge JA, O'Connell PE, Rasmussen J. An introduction to the European Hydrological System – Systéme Hydrologique Européen (SHE). 2: Structure of a physically-based, distributed modelling system. *J. Hydrol.* 1986b, 87, 61-77.

Abrahart RJ, Kneale PE, See LM. *Neural networks for hydrological modelling*. AA Balkema Publishers, Leiden, 2004.

Addor N, Melsen LA. Legacy, rather than adequacy, drives the selection of hydrologic models. *Water Resour. Res.* 2019, 55 (1), 378-390.

Amerman CR. The Use of Unit-Source Watershed Data for Runoff Prediction. *Water Resour. Res*. 1965, 1 (4): 499-507.

Ampadu B Chappell NA Kasei RA. Rainfall-riverflow modelling approaches: Making a choice of data-based mechanistic modelling approach for data limited catchments: a review. *Canadian Journal of Pure and Applied Sciences* 2013, 7 (3), 2571-2580.

Andréassian V, Mander Ü, Pae T. The Budyko hypothesis before Budyko: The hydrological legacy of Evald Oldekop. *J. Hydrol.* 2016, 535, 386-391.

Askew AJ. Real-time Intercomparison of hydrological models. *Int. Assoc. Hydrol. Sc. Publ*. 1989, 181, 125-132.

Bathurst JC, Ewen J, Parkin G, O'Connell PE, Cooper JD. Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses. *J. Hydrol*. 2004, 287 (1–4), 74–94.

Beven K. Towards a new paradigm in hydrology. In 'Water for the future: hydrology in perspective'. *Int. Assoc. Hydrol. Sc. Publ*. 1987, 164, 393–403.

Beven K. Changing ideas in hydrology - the case of physically-based models. *J. Hydrol.* 1989, 105, 157-172.

Beven KJ. A discussion of distributed hydrological modelling. Chapter 13A in Abbott MB, Refsgaard JC (Eds). *Distributed Hydrological Modelling*. Kluwer Academic Publishes, Dordrecht, 1996, 255-275.

Beven KJ. A manifesto for the equifinality thesis. *J. Hydrol.* 2006, 320, 18-36.

Beven KJ. Working towards integrated environmental models of everywhere: uncertainty, data, and modelling as a learning process. *Hydrol. Earth Syst. Sci.* 2007, 11 (1), 460–467.

Beven K. *Rainfall-Runoff Modelling: The Primer*. Second Edition, Wiley-Blackwell, Chichester UK, 2012.

Beven K. Towards a methodology for testing models as hypotheses in the inexact sciences. *Proc. R. Soc. A* 2019a, 475: 20180862.

Beven K. How to make advances in hydrological modelling. *Hydrol. Res*. 2019b, 50.6, 1481-1494 doi: 10.2166/nh.2019.134

Beven K. A history of the concept of time of concentration. *Hydrol. Earth Syst. Sc.* 2020, 24, 2655-2670.

Beven K, Smith P, Westerberg I, Freer J. Comment on ''Pursuing the method of multiple working hypotheses for hydrological modeling'' by Clark et al. *Water Resour. Res.* 2012, 48, W11801, doi:10.1029/2012WR012282.

Beven KJ, Warren R, Zaoui J. SHE: towards a methodology for physically-based distributed forecasting in hydrology. *Int. Assoc. Hydrol. Sc. Publ*. 1980, 129, 133-137.

Beven K, Freer J. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using GLUE methodology. *J. Hydrol.* 2001, 249, 11-29.

Blair GS, Beven K, Lamb R, Bassett R, Cauwenberghs K, Hankin B, Dean G, Hunter N, Edwards L, Nundloll V, Samreen F, Simm W, Towe R. Models of everywhere revisited: A technological perspective. *Environ. Modell. Softw.* 2019, 122, 104421, 19 pp.

Blöschl G, Grayson RB, Sivapalan M. On the Representative Elementary Area (REA) concept and its utility for distributed rainfall-runoff modelling. *Hydrol. Process.* 1995, 9, 313-330.

Blöschl G, Sivapalan M, Wagener T, Viglione A, Savenije H (Eds). *Runoff Prediction in Ungauged Basins. Synthesis across processes, places and scales*. Cambridge University Press, 2013.

Blöschl G, and 229 co-authors. Twenty-three unsolved problems in hydrology (UPH) – a community perspective. *Hydrolog. Sci. J.* 2019, 64 (10), 1141-1158.

Boughton WC. *A new simulation technique for estimating catchment yield*. ME Thesis, University of New South Wales, Sydney, 1964.

Boughton W. Catchment water balance modelling in Australia 1960–2004. *Agr. Water Manag.* 2005, 71 (2), 91-116.

Boughton W, Droop O. Continuous simulation for design flood estimation—a review. *Environ. Modell. Softw.* 2003, 18 (4), 309-318.

Bowden GJ, Maier HR, Dandy GC. Real-time deployment of artificial neural network forecasting models: Understanding the range of applicability. *Water Resour. Res.* 2012, 48, W10549, doi:10.1029/2012WR011984

Bras RL. A Brief History of Hydrology. The Robert E Horton Lecture. *Bull. Amer. Met. Soc.* 1999, 80 (6), 1151-1164.

Breuer L, Huisman JA, Willems P, Bormann H, Bronstert A, Croke BFW, Frede H-G, Gräff T, Hubrechts L, Jakeman AJ, Kite G, Lanini J, Leavesley G, Lettenmaier DP, Lindström G, Seibert J, Sivapalan M, Viney NR. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. *Adv. Water Resour.* 2009, 32, 129-146.

Budyko MI. *Climate and Life.* Translated from Russian by DH Miller, Academic, San Diego, California, 1974.

Chiew FHS. Lumped Conceptual Rainfall-Runoff Models and Simple Water Balance Methods: Overview and Applications in Ungauged and Data Limited Regions. *Geography Compass* 2010, 4(3), 206-225.

Clark CO. Storage and the unit hydrography. *T. Am. Soc. Civ. Eng.* 1945, 110, 1419-1446.

Clark MP, Slater AG, Rupp DE, Woods RA, Vrugt JA, Gupta, HV, Wagener T, Hay LE. Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models, *Water Resour. Res.*, 2008, 44, W00B02, doi.org/10.1029/2007WR006735.

Clark MP, Kavetski D, Fenicia F. Pursuing the method of multiple working hypotheses for hydrological modeling. *Water Resour. Res.* 2011, 47, W09301, doi:10.1029/2010WR009827

Clark MP, Kavetski D, Fenicia F. Reply to comment by Beven et al. on "Pursuing the method of multiple working hypotheses for hydrological modeling". *Water Resour. Res.* 2012, 48, W11802, doi:10.1029/2012WR012547.

Clark MP, Nijssen B, Lundquist JD, Kavetski D, Rupp DE, Woods. RA, Freer JE, Gutmann ED, Wood AR, Bekke LD, Arnold JR, Gochis DJ, Rasmussen RM. A unified approach for process-based hydrologic modeling: 1. Modeling concept. *Water Resour. Res.* 2015, 51, 2498–2514, doi:10.1002/2015WR017198.

Clark MP, Bierkens MFP, Samaniego L, Woods RA, Uijlenhoet R, Bennett KE, Pauwels VRN, Cai X, Wood AW, Peters-Lidard CD. The evolution of process-based hydrologic models: historical challenges and the collective quest for physical realism. *Hydrol. Earth Syst. Sc.* 2017, 21, 3427-3440.

Clarke RT. A review of some mathematical models used in hydrology, with observations on their calibration and use. *J. Hydrol.* 1973, 19, 1-20.

Crawford NH, Burges SJ. History of the Stanford Watershed Model. *Water Resour. Impact* 2004, 6(2), 3-5.

Crawford NH, Linsley RK. *The synthesis of continuous streamflow hydrographs on a digital computer*. Report 12, Dept. of Civil Eng., Stanford University, 1962.

Croke BF, Jakeman AJ. Predictions in catchment hydrology: an Australian perspective. *Mar. Freshwater Res.* 2001, 52, 65-79.

Crooks SM, Kay AL, Davies HN, Bell VA. From Catchment to National Scale Rainfall-Runoff Modelling: Demonstration of a Hydrological Modelling Framework. *Hydrology* 2014, 1, 63-88.

Daniel TM. Neural Networks – applications in hydrology and water resources engineering. *Proc. Inter. Hydrology and Water Symposium.* Inst. Engrs. Australia, National Conf. Publ. 1991, 91/22., 3, 797-902.

Dawdy DR, O'Donnell T. Mathematical models of catchment behaviour. *J. Hydraul. Div. ASCE* 1965, 91 (HY4), 123-137.

Dooge JCI. The development of hydrological concepts in Britain and Ireland between 1674 and 1874. *Hydrol. Sci. J.* 1974,19 (3), 279-302.

Duan Q, Schaake J, Andréassian V, Franks S, Goteti G, Gupta HV, Gusev YM, Habets F, Hall A, Hay L, Hogue T, Huang M, Leavesley G, Liang X, Nasonova ON, Noilhan J, Oudin L. Sorooshian S, Wagener T, Wood EF. Model Parameter Estimation Experiment (MOPEX): An overview of science strategy and major results from the second and third workshops. *J. Hydrol.* 2006, 320 (1-2), 3-17, doi: 10.1016/j.jhydrol.2005.07.031.

Dumitrescu S, Nemec J. Hydrology: a look back and a look forward. In *UNESCO. Three centuries of scientific hydrology: key papers submitted on the occasion of the celebration of the Tercentenary of Scientific Hydrology*. Paris, 9–12 September 1974: a contribution to the International Hydrological Decade. UNESCO, Paris, 1974, 16–22.

Ewen J, Parkin G. Validation of catchment models for predicting land-use and climate change impacts. 1. Method. *J. Hydrol.* 1996, 175, 583-594.

Ewen J, Parkin G, O'Connell PE. SHETRAN: a coupled surface/subsurface modelling system for 3D water flow and sediment and solute transport in river basins. *J. Hydrol. Eng. ASCE* 2000, 5 (3), 250-258.

Farmer D, Sivapalan M, Jothityangkoon C. Climate, soil and vegetation controls upon the variability of water balance in temperate and semi-arid landscapes: downward approach to hydrological prediction. *Water Resour. Res.* 2003, 39 (2), 1035. doi:10.1029/2001WR000328.

Fatichi S, Vivoni ER, Ogden FL, Ivanov VY, Mirus B, Gochis D, Downer CW, Camporese M, Davison JH, Ebel B, Jones N, Kim J, Mascoro G, Niswonger R, Restrepo P, Rigon R, Shen C, Sulis M, Tarboton D. An overview of current applications, challenges, and future trends in distributed process-based models in hydrology. *J. Hydrol.* 2016, 537, 45-60.

Fenicia F, Kavetski D, Savenije HG. Elements of a flexible approach for conceptual hydrological modeling: 1. Motivation and theoretical development. *Water Resour. Res*. 2011, 47, doi:10.1029/2010WR010174

Ficchi Q, Perrin C, Andréassian V. Hydrological modelling at multiple sub-daily time steps: Model improvement via flux-matching. *J. Hydrol.* 2019, 575, 1308-1327.

Fleming G. *Computer Simulation Techniques in Hydrology*. Environmental Science Series, Elsevier, New York 1975.

Fowler KJA, Peel MC, Western AW, Zhang L, Peterson TJ. Simulating runoff under changing climatic conditions: revisiting an apparent deficiency of conceptual rainfall-runoff models. *Water Resour. Res.*, 2016, 52, 1820–1846.

Fowler K, Coxon G, Freer J, Peel MC, Wagener T, Western A, Woods R, Zhang L. Simulating runoff under changing climatic conditions: a framework for model improvement. *Water Resour. Res.*, 2018, 54, 9812-9832.

Franchini M, Pacciani M. Comparative analysis of several conceptual rainfall-runoff models. *J. Hydrol.* 1991, 122, 161-219.

Freeze RA, Harlan RL. Blueprint for a physically-based digital simulated hydrologic response model. *J. Hydrol.* 1969, 9, 237–258.

Goodrich DC, Woolhiser DA. Catchment hydrology. *Rev. Geophys* 1991, 29(S1), 202-209.

Goswami M, O'Connor KM, Bhattarai KP, Shamseldin AY. Assessing the performance of eight real-time updating models and procedures for the Brosna River. *Hydrol. Earth Syst. Sc.* 2005, 9 (4), 394-411.

Grayson R, Blöschl G. *Spatial patterns in catchment hydrology*. Cambridge University Press, UK 2000.

Grayson RB, Moore ID, McMahon TA. Physically based hydrologic modeling 2. Is the concept realistic. *Water Resour. Res.* 1992, 26 (10), 2659-2666.

Gregory CE. Rainfall and runoff in storm-water sewers. *T. Am. Soc. Civ. Eng.* 1907, 58, 458-510.

Guo D, Westra S, Maier HR. Impact of evapotranspiration process representation on runoff projections from conceptual rainfall-runoff models. *Water Resour. Res.*, 2017, 53, 435-454.

Gupta HV, Kling H, Yilmaz KK, Martinez GF. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *J. Hydrol.* 2009, 377, 80-91.

Haan CT, Johnson HP, Brakensiek DL, (Eds). *Hydrologic modelling of small watersheds*. American Society of Agricultural Engineers, St. Joseph, Michigan 1982.

Holländer HM, Blume T, Bormann H, Buytaert W, Chirico GB, Exbrayat J-F, Gustafsson D, Hölzel H, Kraft P, Stamm C, Stoll S, Blöschl G, Flühler H. Comparative prediction of discharge from an artificial catchment (Chicken Creek) using sparse data. *Hydrol. Earth Syst. Sc.* 2009, 13, 2069-2094.

Hornberger GM, Beven KJ, Cosby BJ, Sappington DE. Shenandoah watershed study: calibration of a topography-based variable contributing area hydrological model to a small forested catchment. *Water Resour. Res.* 1985, 21 (12), 1841-1850.

Hornberger GM, Boyer EW. Recent advances in watershed modelling. *Rev. Geophys. Suppl.* 1995, 33, 949-957.

Horner WW, Flynt FL. Relation between rainfall and runoff from small urban areas. *T. Am. Soc. Civ. Eng.* 1936, 101, 140-183.

Hrachowitz M, Clark MP. The complementary merits of competing modelling philosophies in hydrology, *Hydrol. Earth Syst. Sc.* 2017, 21, 3953-3973.

Huang S, Kumar R, Flörke M, Yang T, Hundecha Y, Kraft P, Gao C, Gelfan A, Liersch S, Lobanova A, Strauch M, van Ogtrop F, Reinhardt J, Haberlandt U, Krysanova V. Evaluation of an ensemble of regional hydrological models in 12 large-scale river basins worldwide. *Climatic Change* 2017, 141, 381-397.

Huggins LF, Monke EJ. A mathematical model for simulating the hydrologic response of a watershed. *Water Resour. Res.* 1968, 4, 529-539.

Hutton C, Wagener T, Freer J, Han D, Duffy C, Arheimer B. Most computational hydrology is not reproducible, so is it really science? *Water Resour. Res.*, 2016, 52, 7548–7555, doi:10.1002/2016WR019285.

Hutton C, Wagener T, Freer J, Han D, Duffy C, Arheimer B. Reply to comment by Melsen et al. on "Most computational hydrology is not reproducible, so is it really science?". *Water Resour. Res.*, 2017, 53, 2570–2571, doi:10.1002/2017WR020476.

Ivanov VY Vivoni ER Bras RL Entekhabi D. Catchment hydrologic response with a fully distributed triangulated irregular network model. *Water Resour. Res.*, 2004, 40, W11102, doi:10.1029/2004WR003218

Jakeman AJ, Hornberger GM. How much complexity is warranted in a rainfall-runoff model? *Water Resour. Res.* 1993, 29 (8), 2637-2649.

Jones RN, Chiew FHS, Boughton WC, Zhang L. Estimating the sensitivity of mean annual runoff to climate change using selected hydrological models. *Adv. Water Resour.* 2006, 29, 1419-1429.

Kavetski D, Kuczera G, Franks SW. Bayesian analysis of input uncertainty in hydrological modeling: 1. Theory. *Water Resour. Res., 2006a*, 42(3), W03407. doi:10.1029/2005WR004368.

Kavetski D, Kuczera G, Franks SW. Bayesian analysis of input uncertainty in hydrological modeling: 2. Application. *Water Resour. Res.,* 2006b, 42(3), W03408. doi:10.1029/2005WR004376.

Khatami S, Peel MC, Peterson TJ, Western AW. Equifinality and Flux Mapping: a new approach to model evaluation and process representation under uncertainty. *Water Resour. Res.* 2019, 55, 8922-8941.

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

Klemeš V. Operational testing of hydrological simulation models. *Hydrolog. Sci. J.* 1986a, 31 (1), 12-24.

Klemeš V. Dilettantism in hydrology: transition or destiny? *Water Resour. Res.* 1986b, 22 (9), 177S-188S.

Knoben WJM, Freer JE, Fowler KJA, Peel MC, Woods RA. Modular Assessment of Rainfall-Runoff Models Toolbox (MARRMoT) v1.2: an open-source, extendable framework providing implementations of 46 conceptual hydrologic models as continuous state-space formulations. *GeoSci. Model Dev.* 2019, 12, 2463-2480.

Kollet S, Sulis M, Maxwell RM, Paniconi C, Putti M, Bertoldi G, Coon ET, Cordano E, Andrizzo S, Kikinzon E, Mouche E, Mugler C, Park Y-J, Refsgaard JC, Stisen S, Sudicky E. The integrated hydrologic model intercomparison project, IH-MIP2: A second set of benchmark results to diagnose integrated hydrology and feedbacks, *Water Resour. Res*. 2017, 53, 867–890, doi:10.1002/2016WR019191.

Krysanova V, Vetter T, Eisner S, Huang S, Pechlivanidis I, Strauch M, Gelfan A, Kumar R, Aich V, Arheimer B, Chamorro A, van Griensven A, Kundu D, Lobanova A, Mishra V, Plötner S, Reinhardt J, Seidou O, Wang X, Wortmann M, Zeng X, Hattermann FF. Intercomparison of regional-scale hydrological models and climate change impacts projected for 12 large river basins worldwide—a synthesis, *Environ. Res. Lett.* 2017, 12, 105002.

Kuichling E. The relation between the rainfall and discharge of sewers in populous districts. *T. Am. Soc. Civ. Eng.* 1889, XX (1), 1-56.

Laurenson EM. Storage Analysis and Flood Routing in Long River Reaches. *J. Geophys. Res.* 1959, 64, 2423-2431.

Laurenson EM. A catchment storage model for runoff routing. *J. Hydrol.* 1964, 2, 141-163.

Leavesley GH, Markstrom SL, Restrepo PJ, Viger RJ. A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling. *Hydrol. Process*. 2002, 16, 173-187.

Lee H, Sivapalan M, Zebe E. Representative elementary watershed (REW) approach, a new blueprint for distributed hydrological modelling at the catchment scale: development of closure relations. Predictions in Ungauged Basins: Approaches for Canada's Cold Region. *Int. Assoc. Hydrol. Sc.* 2005, 166-218.

Linsley RK. The relation between rainfall and runoff. *J. Hydrol.* 1967, 5, 297-311.

Linsley RK. Rainfall-runoff models – an overview. In Singh VP (ed) *Rainfall-Runoff Relationship*, Water Resources Publications Littleton, CO, USA 1982.

Linsley RK, Crawford NH. Computation of a synthesis streamflow record on a digital computer. *Int. Assoc. Hydrol. Sc. Publ.*, 1960, 51, 526-538.

Maxwell RM, Putti M, Meyerhoff S, Delfs J-O, Ferguson IM, Ivanov V, Kim J, Kolditz O, Kollet SJ, Kumar M, Lopez S, Niu J, Panico C, Park Y-J, Phanikumar MS, Shen C, Sudicky EA, Sulis M. Surface-subsurface model intercomparison: A first set of benchmark results to diagnose integrated hydrology and feedbacks. *Water Resour. Res.* 2014, 50, 1531–1549, doi:10.1002/2013WR013725.

Mein RG, Laurenson EM, McMahon TA. Simple non-linear model for flood estimation. *Jour. Hydraul. Div., ASCE* 1974, 100 (HY11), 1507-1518.

Melsen LA, Torfs PJJF, Uijlenhoet R, Teuling AJ. Comment on ''Most computational hydrology is not reproducible, so is it really science?'' by Hutton et al., *Water Resour. Res.*, 2017, 53, 2568–2569, doi:10.1002/2016WR020208.

Metcalf L, Eddy HP. *American Sewerage Practice, Volume I: Design of Sewers*. McGraw-Hill, New York 1914.

Mockler EM, Chan KP, Sapriza-Aruri G, Bruen M, Wheater HS. Assessing the relative importance of parameter and forcing uncertainty and their interactions in conceptual hydrological model simulations. *Adv. Water Resour.* 2016*,* 97, 299-313.

Mulvany TJ, 1851. On the use of self-registering rain and flood gauges in making observations on the relations of rainfall and of flood discharges in a given catchment. *T. Inst. Civil Engrs. Ire.* 1851, 4 (2), 18-33.

Nash JE. The form of the Instantaneous Unit Hydrograph. *Int. Assoc. Hydrol. Sc.* 1957 Publ. 45 (3), 114-121.

Nearing GS, Gupta HV. The quantity and quality of information in hydrologic models. *Water Resour. Res.*, 2015, 51(1), 524-538.

Nearing GS, Tian Y, Gupta HV, Clark MP, Harrison KW, Weijs SV. A philosophical basis for hydrological uncertainty. *Hydrol. Sci. J.*, 2016, 61(9), 1666-1678.

Nourani V, Singh VP, Delafrouz H. Three geomorphological rainfall-runoff models based on the linear reservoir concept. *Catena* 2009, 76, 206–214.

O'Connell PE, Todini E. Modelling of rainfall, flow and mass transport in hydrological systems: an overview. *J. Hydrol.* 1996, 175, 3-16.

Oldekop EM. Evaporation from the surface of river basins (in Russian), Collection of the works of students of the Meteorological Observatory, 1911, University of Tartu, Band 4, p. 209.

Parkin G, O'Donnell G, Ewen J, Bathurst JC, O'Connell PE, Lavabre J. Validation of catchment models for predicting land-use and climate change impacts. 2. Case study for a Mediterranean catchment. *J. Hydrol.* 1996*,* 175 (1–4), 595–613.

Perrin C, Michel C, Andréassian V. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. *J. Hydrol.* 2001, 242, 275-301.

Perrin C, Michel C, Andréassian V. Improvement of a parsimonious model for streamflow simulation. *J. Hydrol.* 2003, 279, 275–289.

Peters-Lidard CD, Hossain F, Leung LR, McDowell N, Rodell M, Tapiador FJ, Turk FJ, Wood A. 100 Years of Progress in Hydrology. Chapter 25 in *AMS Meteorological Monographs*. 2019, 59, 50 pp, doi: 10.1175/AMSMonographs-D-18-0019.1.

Pilgrim DH, Cordery I. Flood runoff. Chapter 9 in Maidment DR. *Handbook of Hydrology*, McGraw-Hill, Inc., New York 1992.

Reed S, Koran V, Smith M, Zhang Z, Moreda F, Seo D-J, and DMIP participants. Overall distributed model intercomparison project results. *J. Hydrol.* 2004, 298, 27–60.

Refsgaard JC. Validation and intercomparison of different updating procedures for real-time forecasting. *Nordic Hydrol.* 1997, 28, 65-84.

Reggiani P, Sivapalan M, Hassasizadeh SM. A unifying framework for watershed thermodynamics: balance equations for mass, momentum, energy and entropy, and the second law of thermodynamics. *Adv. Water Resour.* 1998, 22 (4), 367-398.

Reid J. The estimation of storm-water discharge. *J. Inst. Munic. Engineers* 1927, 53, 997–1021.

Richards LA. Capillary conduction of liquids through porous mediums. *Physics* 1931, 1, 318-333.

Riley DW. Notes on calculating the flow of surface water in sewers. *J. Inst. Munic. County Eng.* 1931, 58, 1483.

Ross CN. The calculation of flood discharges by the use of a time contour plan. *T. Inst. Eng. Aust.* 1921, 2, 85-92.

Savenije HHG. Equifinality, a blessing in disguise? *Hydrol. Process.* 2001, 15, 2835-2838.

Saft M, Peel MC, Western AW, Perraud J-M, Zhang L. Bias in streamflow projections due to climate-induced shifts in catchment response. *Geophys. Res. Lett.* 2016, 43, 1574-1581.

Schaake JG, Geyer JC, Knapp JW. Experimental examination of the Rational Method. *J. Hydraul. Eng. ASCE* 1967, 93, 353-370.

Schreiber P. Über die Beziehungen zwischen dem Niederschlag und der Wasserführung der Flüsse in Mitteleuropa. *Z. Meteorol.* 1904, 21(10), 441-452.

Seibert J, McDonnell JJ. On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration. *Water Resour. Res.* 2002, 38 (11) doi:10.1029/2001WR000978

Sherman LK. Streamflow from Rainfall by the Unit-graph Method. *Eng. News-Rec.* 1932, 108 (14), 501-505.

Singh VP, Woolhiser DA. Mathematical modelling of watershed hydrology. *J. Hydrol. Eng. ASCE* 2002, 7 (4), 270-292.

Singh, VP. Hydrologic modeling: progress and future directions. *Geosci. Lett.* 2018, 5, 15.

Sivapalan, M. Prediction in ungauged basins: a grand challenge for theoretical hydrology. *Hydrol. Process.* 2003, 17, 3163-3170.

Sivapalan M, Blöschl G, Zhang L, Vertessy R. Downward approach to hydrological prediction. *Hydrol. Process.* 2003, 17, 2101-2111.

Smith MB, Seo D-J, Koren VI, Reed SM, Zhang Z, Duan Q, Moreda F, Cong S. The distributed model intercomparison project (DMIP): motivation and experiment design. *J. Hydrol.* 2004, 298, 4–26.

Smith MB, Koren V, Reed S, Zhang Z, Zhang Y, Moreda F, Cui Z, Mizukami N, Anderson EA, Cosgrove BA. The distributed model intercomparison project – Phase 2: Motivation and design of the Oklahoma experiments. *J. Hydrol.* 2012a, 418-419, 3-16.

Smith MB, Koren V, Zhang Z, Zhang Y, Reed SM, Cui Z, Moreda F, Cosgrove BA, Mizukami N, Anderson EA, DMIP 2 participants. Results from the DMIP 2 Oklahoma experiments. *J. Hydrol.* 2012b, 418-419, 17-48.

Smith M, Koren V, Zhang Z, Moreda F, Cui Z, Cosgrove B, Mizukami N, Kitzmiller D, Ding F, Reed S, Anderson E, Schaake J, Zhang Y, Andreassian V, Perrin C, Coron L, Valéry A, Khakbar B, Sorooshian S, Behrangi A, Imam B, Hsu K-L, Todini E, Coccia G, Mazzetti C, Andres EO, Francés F, Orozco I, Hartman R, Henkel A, Fickenscher P, Staggs S. The distributed model intercomparison project – Phase 2: Experiment design and summary results of the western basin experiments. *J. Hydrol.* 2013, 507, 300-329.

Sugawara M. On the analysis of runoff structure about several Japanese Rivers. *Japanese J. Geophys.,* 1961, 2(4), 1-76.

Todini E. Rainfall-runoff modelling: past, present and future. *J. Hydrol.* 1988, 100, 341-352.

Todini E. The ARNO model. Chapter 16 in VP Singh and DK Frevert, *Mathematical Models of Large Watershed Hydrology.* Water Resources Publications 2002.

Todini E. Rainfall-runoff Models for Real-time Forecasting. Chapter 123 in Anderson MG (Ed) *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd 2005.

Vaze J, Post DA, Chiew FHS, Perraud J-M, Viney NR, Teng J. Climate non-stationarity – validity of calibrated rainfall-runoff models for use in climate change studies. *J. Hydrol.* 2010, 394, 447-457.

Vertessy RA, Hatton TJ, O'Shaughnessy PJ, Jayasuriya MDA. Predicting water yield from a mountain ash forest catchment using a terrain analysis based catchment model. *J. Hydrol.* 1993, 150, 665-700.

Vieux BE. *Distributed Hydrologic Modeling Using GIS*, Water Science and Technology Series. 38. Kluwer, Norwell, MA, 2005, 293 pp

Villeneuve J-P, Duchesne S, Fortin J-P, Rousseau AN. De l'hydrologie du bassin à la gestion intégrée par bassin versant (The evolution from watershed hydrological science to integrated watershed management) River Basins – From Hydrological Science to Water Management. *Int. Assoc. Hydrol. Sc. Publ*. 2008, 323, 1-40.

Wagener T, Wheater HS, Gupta HV. *Rainfall-Runoff Modelling in Gauged and Ungauged Catchments*. Imperial College Press, London 2004.

Weeks WD, Hebbert RHB. A comparison of rainfall-runoff models. *Nordic Hydrol.* 1980, 11, 7-24.

Wheater HS, Jakeman AJ, Beven KJ. Progress and directions in rainfall-runoff modelling. In: Jakeman AJ, Beck MB, McAleer MJ (Eds.), *Modelling Change in Environmental Systems*. John Wiley and Sons, Chichester, 1993, pp. 101–132.

Wood EF, Sivapalan M, Beven K, Band L. Effects of spatial variability and scale with implications to hydrologic modeling. *J. Hydrol.* 1988, 102, 29-47.

Wood EF, Roundy JK, Troy TJ, Van Beek LPH, Bierkens MFP, Blyth E, de Roo A, Döll P, Ek M, Famiglietti J, Gochis D, van de Giesen N, Houser P, Jaffé PR, Kollet S, Lehner B, Lettenmaier DP, Peters-Lidard C, Sivapalan M, Sheffield J, Wade A, Whitehead P. Hyperresolution global land surface modeling: meeting a grand challenge for monitoring Earth's terrestrial water. *Water Resour. Res.*, 2011, 47 (5), W05301. doi:10.1029/2010WR010090.

Woolhiser DA. Hydrologic and Watershed Modeling – State of the Art. *T. Am. Soc. Agr. Eng.* 1973, 16 (3), 553-559.

Xu C-Y, Singh VP. A Review on Monthly Water Balance Models for Water Resources Investigations. *Water Resour. Manag.* 1988, 12, 31-50.

Ye W, Bates BC, Viney NR, Sivapalan M, Jakeman AJ. Performance of conceptual rainfall-runoff models in low-yielding ephemeral catchments. *Water Resour. Res.* 1997, 33 (1), 153-166.

Yu X, Duffy CJ, Rousseau AN, Bhatt G, Alvarez AP, Charron D. Open science in practice: Learning integrated modeling of coupled surface subsurface flow processes from scratch. Earth and Space Science, 2016, 3: 190–206, doi:10.1002/2015EA000155

Zhang L, Dawes WR, Walker GR. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resour. Res.* 2001, 37 (3), 701-708.

Zhang L, Potter N, Hickel K, Zhang Y, Shao Q. Water balance modeling over variable time scales based on the Budyko framework – Model development and testing. *J. Hydrol.* 2008, 360, 117– 131.

Zhang X, Liu P, Cheng L, Liu Z, Zhao Y. A back-fitting algorithm to improve real-time flood forecasting. *J. Hydrol.* 2018, 562, 140-150.

Table 1 Distribution of 279 rainfall-runoff models by type and time-step

Continuous models											
Time-step	Emp	CL	CD	CsD	PL	PD	PsD	ID	SL	SsD	WL	Sub-total
Annual	2	0	0	0	0	0	0	0	0	0	8	10
Monthly	0	22	0	1	0	0	0	0	1	0	2	26
Daily	1	60	16	21	1	2	3	0	4	0	0	108
Sub-daily	0	17	16	18	2	11	1	8	2	0	1	76
Sub-total	3	99	32	40	3	13	4	8	7	0	11	220
Discrete models											
Annual	1	0	0	0	0	0	0	0	0	0	0	1
Monthly	0	0	0	0	0	0	0	0	0	0	1	1
Daily	2	0	0	1	0	0	0	0	0	0	0	3
Sub-daily	9	13	8	13	1	2	0	4	0	4	0	54
Sub-total	12	13	8	14	1	2	0	4	0	4	1	59

Emp: empirical; CL: conceptual and lumped; CD: conceptual and distributed; CsD: conceptual and semi-distributed; PL: physical and lumped; PD: physical and distributed; PsD: physical and semi-distributed; ID: physical coupled surface and sub-surface distributed; SL: systems and lumped; SsD: systems and semi-distributed; WL: water balance and lumped.
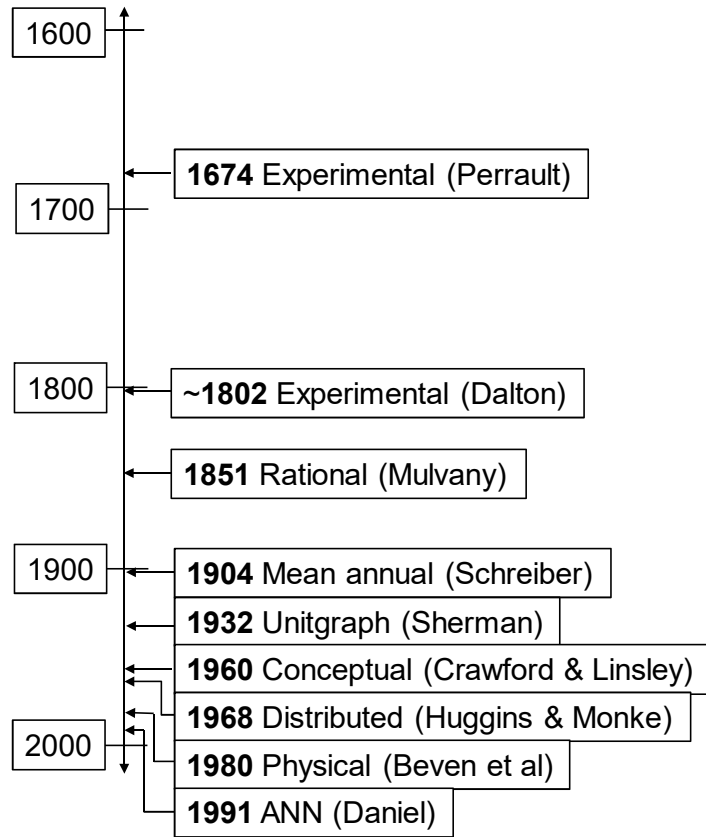
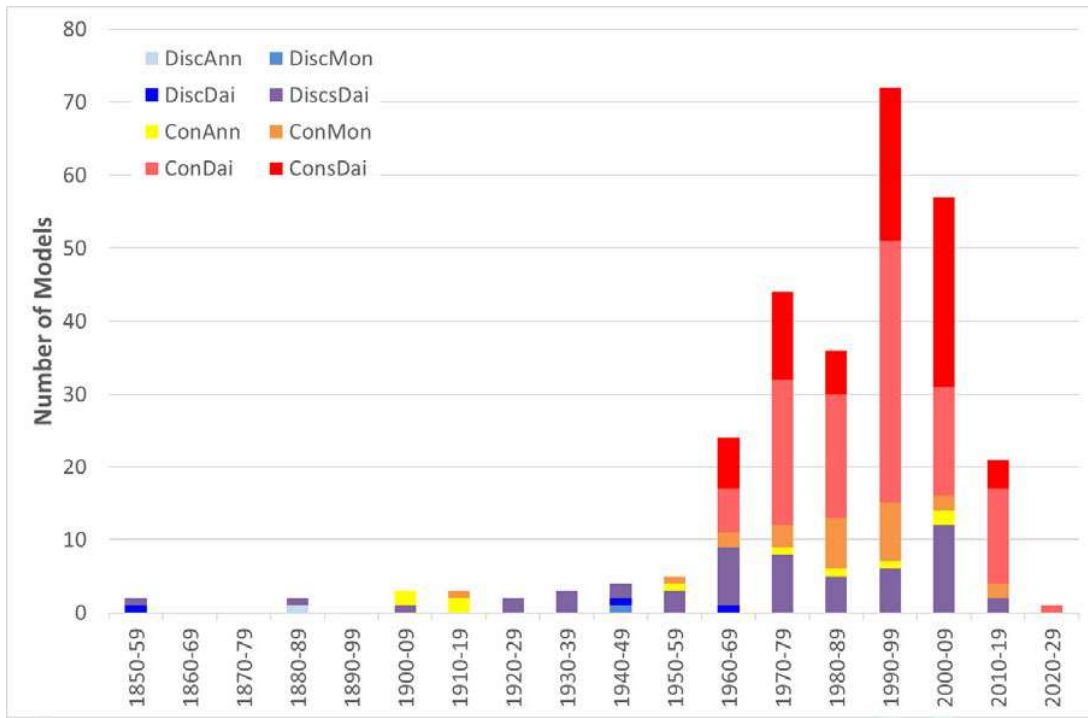**Figure 1** Time-history of key developments in rainfall-runoff models

Figure 2 Number of discrete and continuous rainfall-runoff models per decade sampled by time-step (279 models). (Disc: discrete; Con: continuous; sDai: sub-daily; Dai; daily; Mon: monthly; Ann: annual)
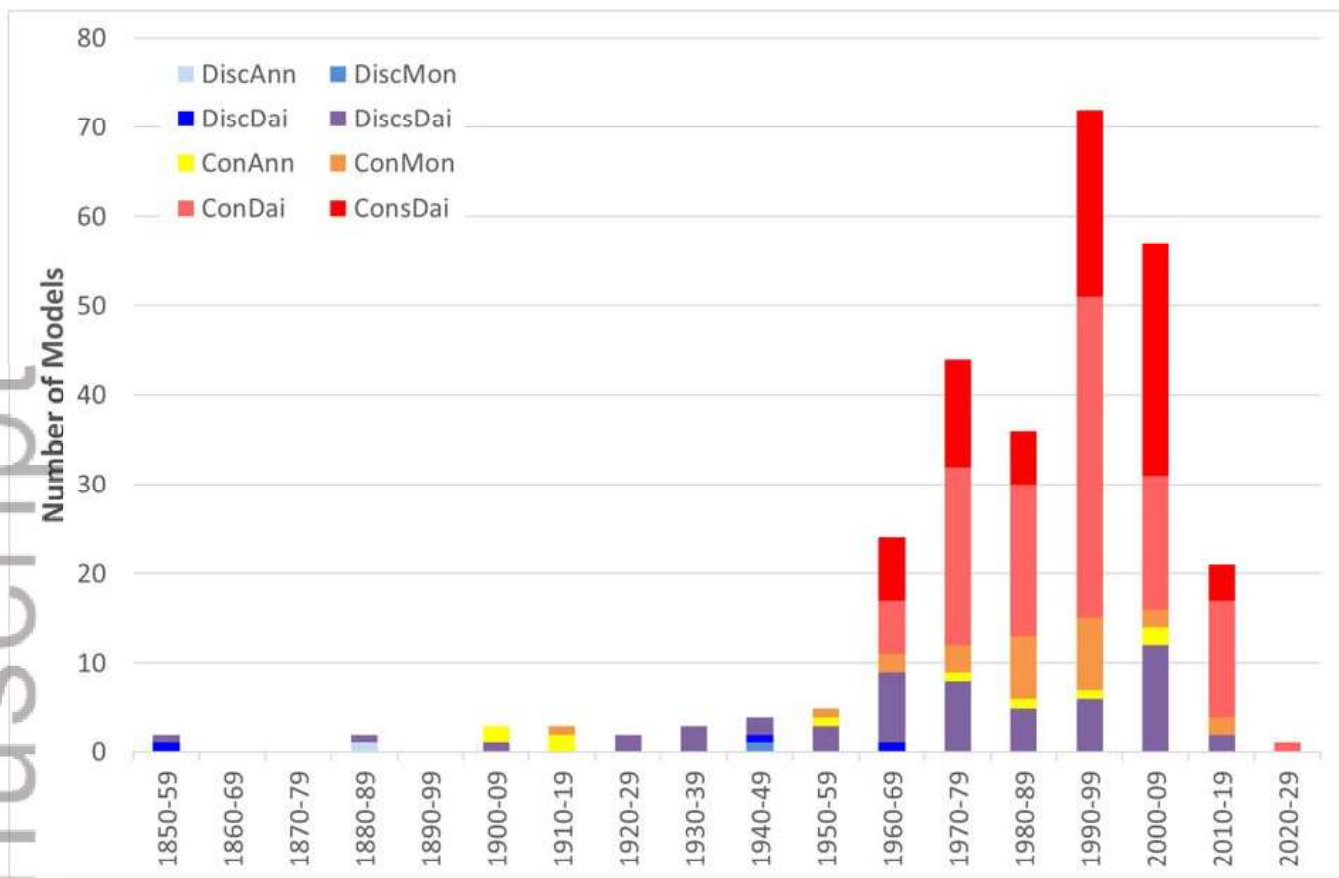
Figure 2 Number of discrete and continuous rainfall-runoff models per decade sampled by time-step (279 models). (Disc: discrete; Con: continuous; sDai: sub-daily; Dai; daily; Mon: monthly; Ann: annual)

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