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**PRIMER**

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# Historical development of rainfall-runoff modeling

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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 intercomparison. We also seek to clarify jargon terms for readers new to this area.

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**KEYWORDS**

model developments, model inter-comparisons, rainfall-runoff models

## 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* and *interception*), into (*infiltration*), within (lateral and vertical water movement through *unsaturated* and *saturated soil* and *groundwater*) and out of the catchment (*evaporation*, *transpiration*, and *runoff*). At small spatial and temporal scales, these processes are highly complex and exhibit heterogeneous behavior. Whereas, at larger spatial and temporal scales, process complexity generally reduces through averaging smaller scale complexities (Blöschl, Grayson, & Sivapalan, 1995; Grayson, Moore, & McMahon, 1992; Savenije, 2001; Wood, Sivapalan, Beven, & Band, 1988). 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 23 unsolved problems in hydrology (Blöschl et al., 2019). Several of these questions relate directly to rainfall-runoff modelling, while many others could influence rainfall-runoff modelling indirectly.

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 subsurface 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:

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(a) empirical ("… not suitable for spatial extension of streamflow records into ungauged catchments"), (b) 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 …"), (c) physical ("… based on the conservation of mass, momentum and energy", "… suffer from extreme data demand …") (Wagener, Wheater, & Gupta, 2004, pp. 2 and 3), and (d) distributed ("… defining parameter values for every element in the solution mesh.") (Beven, 2012, p. 40).

## 2 | RAINFALL-RUNOFF MODELS

A RRM 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 RRMs 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 modeling systems including stochastic models are not discussed. Moreover, space precludes discussion of updating RRMs for real time forecasting (Bowden, Maier, & Dandy, 2012; Goswami, O'Connor, Bhattarai, & Shamseldin, 2005; Mockler, Chan, Sapriza-Aruri, Bruen, & Wheater, 2016; Refsgaard, 1997; Todini, 2005; Zhang, Liu, Cheng, Liu, & Zhao, 2018); we concentrate on RRMs for simulating historical behavior of runoff and within-catchment processes. Another topic far too large to be considered in this primer relates to modular modeling systems introduced by Leavesley et al. (2002, p. 173) in responding to the question "… what combination of process conceptualizations is most appropriate?" (see e.g., Clark et al., 2008; Clark et al., 2015; Fenicia, Kavetski, & Savenije, 2011; Knoben, Freer, Fowler, Peel, & Woods, 2019).

In terms of intended application, mathematical RRMs are generally either *discrete*, for modeling a specific moment in time (instantaneous, hydrograph or event-based), or *continuous*, for modeling extended periods of time. Within these two categories, RRMs come in a variety of flavors 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 modeling (Klemeš, 1983; Sivapalan, Blöschl, Zhang, & Vertessy, 2003; Zhang, Dawes, & Walker, 2001). The top-down approach generally seeks to model long-term and or large-scale runoff behavior satisfactorily, before adding further complexity to the model to represent shorter time scales or smaller spatial scales (Farmer, Sivapalan, & Jothityangkoon, 2003; Zhang, Potter, Hickel, Zhang, & Shao, 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 subcatchments that are modeled separately and with an appropriate runoff routing routine to combine the subcatchment 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.

RRMs 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 MODELING

A time-history of key RRM developments is presented in Figure 1 and summarized 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 modeling where annual runoff equalled annual rainfall divided by 6 (Linsley, 1967). A more detailed history of model developments can be found in Villeneuve, Duchesne, Fortin, and Rousseau (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 279 RRMs described in the journal literature, plus many minor updates of previous versions. In Table S1 (Supporting Information) we list the 279 models that we consider to be different models. Clark et al. (2011, p. 1) 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

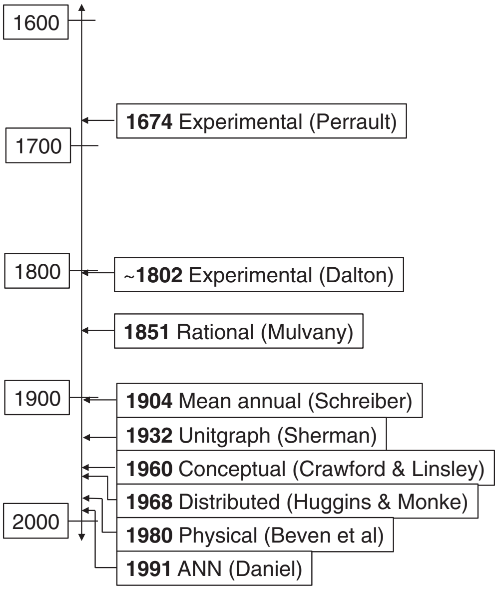

**FIGURE 1** Time-history of key developments in rainfall-runoff models

catchment slope) to the rational equation, based mainly on field data, to account for the nonlinearity 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 & 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, Geyer, and Knapp (1967) **(**see Pilgrim & 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) realized that $k$ represented “maximum possible evaporation, only dependent on climate,” which is another way of describing mean annual potential evapotranspiration (for details see Andréassian, Mander, & Pae, 2016). Following Oldekop, the above equation can be written in terms of the aridity index ($\varphi$) as

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

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

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

where $u$ is the ordinate of the unitgraph, $\upsilon$ 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, Singh, and Delafrouz (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 nonlinear; a practical application is by Mein, Laurenson, and McMahon (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 recognized for their major contribution to digital rainfall-runoff modeling, 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 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 emphasized reducing the number of model parameters due to the realization that models were over-parameterised relative to the information content of the inputs and outputs used to drive the models (Beven, 1989; Hornberger, Beven, Cosby, & Sappington, 1985; Jakeman & 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 modeling 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 $\text{km}^2$. An alternative concept, representative elementary watersheds (REW), was introduced by Reggiani, Sivapalan, and Hassasizadeh (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, Sivapalan, & Zebe, 2005, p. 167). In these subwatersheds, 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 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 & 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 1980s that a physically based fully distributed model, Systéme Hydrologique Européen (SHE), was operational. SHE, briefly described by Beven, Warren, and Zaoui (1980) and, more fully, by Abbott et al. (1986a); Abbott, Bathurst, Cunge, O'Connell, and Rasmussen (1986), incorporates fundamental equations representing overland and channel flow, unsaturated and saturated subsurface 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 subsurface models) in 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 behavior (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) recognized “… 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 modeling 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, pp. 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 (Table S1) as there have already been two intermodel comparisons specifically for these models (Kollet et al., 2017; Maxwell et al., 2014). 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 modeling capability (Beven, 2012; Ewen, Parkin, & O'Connell, 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 modeling in the early 1990s (Daniel, 1991). In the context of runoff estimation, ANNs use flexible data-driven approaches to represent the complex nonlinear relationships between input forcing variables and runoff that other rainfall-runoff modeling 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, Kneale, & See, 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 (subdaily, daily, monthly, and annual). Nearly all discontinuous models use a subdaily time-step (Table 1) to identify the shape and peak value of the resulting hydrograph. However, daily and subdaily 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. 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 RRM faces a smörgåsbord of options that have been developed over time (see Figure 2 and Table S1). To inform this choice, numerous model inter-comparison studies, reviews and overviews have been conducted. A subsample for the interested reader includes: Linsley (1967); Woolhiser (1973); Fleming (1975); Weeks and Hebbert (1980); Haan, Johnson, and Brakensiek (1982); Linsley (1982); Klemeš (1986a); Beven, 1987; Todini (1988); Goodrich and Woolhiser (1991); Franchini and Pacciani (1991); Wheater, Jakeman, and Beven (1993); Jakeman and Hornberger (1993); Hornberger and Boyer (1995); Xu and Singh (1988); Grayson and Blöschl (2000); Croke and Jakeman (2001); Singh and Woolhiser (2002); Boughton and Droop (2003); Reed et al. (2004); Wagener et al. (2004); Boughton (2005); Duan et al. (2006); Jones, Chiew, Boughton, and Zhang (2006); Villeneuve et al. (2008); Breuer

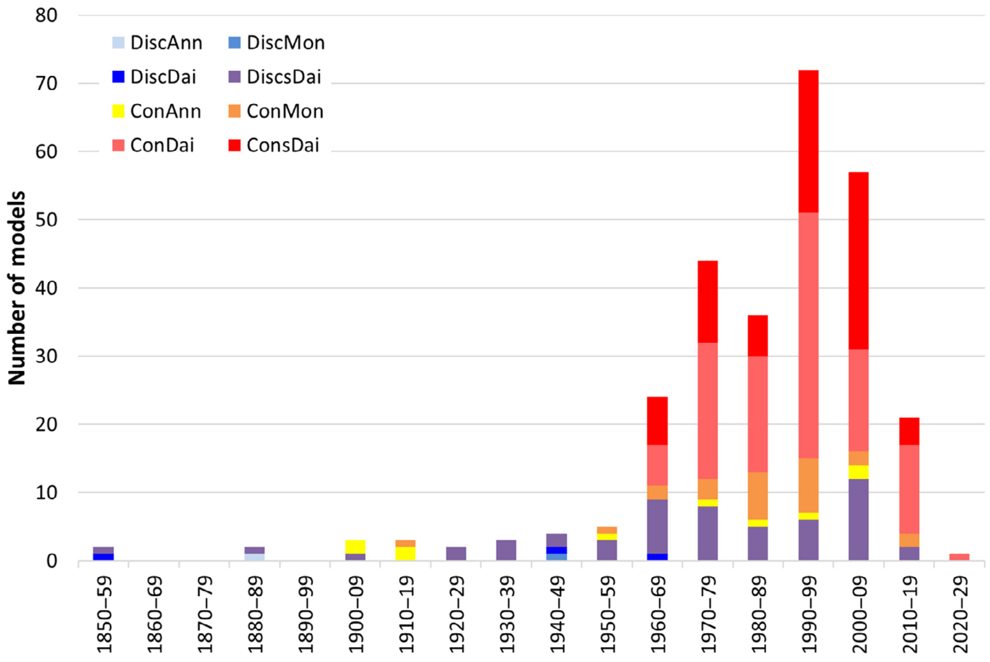

**FIGURE 2** Number of discrete and continuous rainfall-runoff models per decade sampled by time-step (279 models). Ann: annual; Con: continuous; Dai; daily; Disc: discrete; Mon: monthly; sDai: subdaily

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

| Time-step | Emp | CL | CD | CsD | PL | PD | PsD | ID | SL | SsD | WL | Subtotal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Continuous models | | | | | | | | | | | | |
| 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 |
| Subdaily | 0 | 17 | 16 | 18 | 2 | 11 | 1 | 8 | 2 | 0 | 1 | 76 |
| Subtotal | 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 |
| Subdaily | 9 | 13 | 8 | 13 | 1 | 2 | 0 | 4 | 0 | 4 | 0 | 54 |
| Subtotal | 12 | 13 | 8 | 14 | 1 | 2 | 0 | 4 | 0 | 4 | 1 | 59 |

Abbreviations: CD, conceptual and distributed; CL, conceptual and lumped; CsD, conceptual and semi-distributed; Emp, empirical; ID, physical coupled surface and subsurface distributed; PD, physical and distributed; PL, physical and lumped; PsD, physical and semi-distributed; SL, systems and lumped; SsD, systems and semi-distributed; WL, water balance and lumped.

et al. (2009); Chiew (2010); Blöschl, Sivapalan, Wagener, Viglione, and Savenije (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); Clark, Kavetski, and Fenicia (2012) and Beven, Smith, Westerberg, and Freer (2012), and by Hutton et al. (2016, 2017) and Melsen, Torfs, Uijlenhoet, and Teuling (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 and 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 and Melsen (2019) found the role of model adequacy in model selection hard to identify in these publications.

The World Meteorological Organization 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., 2012, b, 2013). Several major conclusions of the DMIP projects identified by Smith et al. (2012, p. 3; 2012, 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 optimized 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 modeling internal catchment processes (Fatichi et al., 2016), but at significant cost as field observations, data preparation and parameter calibrations are very expensive (Ampadu, Chappell, & Kasei, 2013) and over-parameterisation is a risk to model accuracy.

The importance of personal judgment in applying a RRM, particularly for physically based models, was highlighted by Holländer et al. (2009), who describe a modeling comparison study on an artificial catchment (Chicken Creek) in Germany. Catchment terrain, soil and vegetation data, 3 years of climate data, and initial groundwater status were provided to 10 modeling groups. Discharge data were not provided. Each group applied their mainly physically based models to the catchment to estimate 3 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 modelers 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 modeling that could be discussed within the framework of a primer on RRM, but space precludes their inclusion. For example (a) calibration and evaluation (Bathurst, Ewen, Parkin, O'Connell, & Cooper, 2004; Duan et al., 2006; Ewen & Parkin, 1996; Fowler et al., 2018; Fowler, Peel, Western, Zhang, & Peterson, 2016; Gupta, Kling, Yilmaz, & Martinez, 2009; Klemeš, 1986a, 1986b; Parkin et al., 1996; Saft, Peel, Western, Perraud, & Zhang, 2016; Vaze et al., 2010), (b) equifinality (Beven, 2006; Beven & Freer, 2001; Khatami, Peel, Peterson, & Western, 2019; Savenije, 2001), (c) uncertainty (Beven, 2019a; Kavetski, Kuczera, & Franks, 2006a, 2006b; Nearing et al., 2016; Nearing & Gupta, 2015); (d) consistent modeling across multiple time steps (Ficchi, Perrin, & Andréassian, 2019); (e) modeling framework, methodology and philosophy (Clark et al., 2008, 2011, 2015; Crooks, Kay, Davies, & Bell, 2014; Fenicia et al., 2011; Hrachowitz & Clark, 2017); (f) plausibility and influence of internal fluxes (Ficchi et al., 2019; Guo, Westra, & Maier, 2017; Khatami et al., 2019); and (g) models of everywhere (Beven, 2007; Beven, 2019b; Blair et al., 2019; Wood et al., 2011). 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 modeling including the above topics and more.

## 6 | CONCLUSION

Over the last 350 years, hydrological modeling 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 modeling 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 modelers 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 modeled 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 modeling since the mid-1960s but at the same time we acknowledge there remain many gaps in our knowledge as discussed by Blöschl et al. (2019).

### CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

### AUTHOR CONTRIBUTIONS

**Murray Peel:** Conceptualization; formal analysis; investigation; visualization; writing-original draft; writing-review and editing. **Thomas McMahon:** Conceptualization; data curation; formal analysis; investigation; visualization; writing-original draft; writing-review and editing.

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### RELATED WIREs ARTICLE

Toward a theoretical framework for integrated modeling of hydrological change

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## SUPPORTING INFORMATION

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

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