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An Overview of Rainfall-Runoff Model Types

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Abstract: This paper aims to inform the audience of the strengths and weaknesses of various rainfall-runoff models. Runoff plays an important role in the hydrological cycle by returning excess precipitation to the oceans and controlling how much water flows into water systems. Water resource managers use runoff data from models to help understand, control, and monitor the quality and quantity of water resources. Access to runoff data can be time consuming and restrictive. The goal of the USEPA's Hydrologic Micro Service (HMS) project is to develop a collection of interoperable water quantity and quality modeling components that leverage existing internet-based data sources and sensors via a web service. Each component may have multiple implementations, ranging from coarse to detailed levels of physical process modeling. Each rainfall-runoff model contains algorithms that control the calculation of runoff. Models can be categorized by the structure and spatial processing of these algorithms into empirical, conceptual, physical, lumped, semi-distributed, and distributed models. Several runoff models, including SCS Curve Number, Hydrological Simulation Program-Fortran, and Penn State's Integrated Hydrological Modeling System, are described, providing information to determine which best suits the modeling objective.

***Keywords**:* Rainfall-Runoff models; Runoff; Hydrological Cycle

1. INTRODUCTION

The hydrological cycle has many interconnected components, with runoff connecting precipitation to stream flow. Surface runoff results when some precipitation does not infiltrate into the soil and runs across the land surface into surface waters (streams, rivers, lakes or other reservoirs) (Perlman, 2016). By returning excess precipitation and controlling how much water flows into stream systems, runoff is important in balancing the hydrological cycle. Surface runoff is a central area of interest for monitoring water resources, as well as solving water quality and quantity problems such as flood forecasting and ecological and biological relationships in the water environment (Kokkonen et al., 2001). Runoff is also the main driver in contaminant transport due to excess nutrients and pesticides from agricultural lands being washed into waterways by rain events. Knowing this information helps water resource managers account for the pollution in water resources due to runoff.

Surface runoff modeling is used to understand catchment yields and responses, estimate water availability, changes over time, and forecasting (Vaze, 2012). Although there are many ways to classify models, not all models fit into a single category because they are developed for a variety of purposes (Singh, 1995). In this report we classify models as one of three general types; each type calculates the relationship between rainfall and runoff differently. The categories are empirical, conceptual, and physical, as arranged by the model structure. Researchers use different ways to classify and divide models based on spatial resolution, input/output type, model simplicity, etc. Another classification based on the spatial interpretation of the model's catchment area is described in this report. This separates models into lumped, semi-distributed, and distributed models. Choosing a rainfall-runoff model is based on the modeling purpose such as understanding and answering specific questions about the hydrological process; assessing the frequency of runoff events; or estimating runoff yield for management purposes (Vaze, 2012). Identifying the priorities of modeling and the limitations of data availability, time, and budget for models help to narrow the choices and ensure that the model is the best for the intended purpose. Modeling runoff helps gain a better understanding of hydrologic phenomena and how changes affect the hydrological cycle (Xu, 2002). Readers should use the information presented here to guide them on choosing rainfall-runoff models for their modeling or managing requirements.

Some runoff models and data are not readily available to the public, may have missing information which decreases their usefulness, and can be time consuming or cumbersome to access. To overcome this problem in accessing water resource data, web services allow researchers, managers, and the public to become more familiar with the data and better informed to make improved decisions. Improving model and data access can result in reduced duplication of efforts and save time and money. Accessing web services from data providers, downloading runoff data, shifting time-series to local time zones as needed, computing statistics, and flagging missing values are improvements needed in the modeling community. The USEPA's Hydrologic Micro Service (HMS) surface runoff component allows the user to view and compare multiple types of modeled data to make an educated decision on which data or model to use. Having multiple modeling components and various modeled datasets in one place puts ease on a water resource manager searching for data. HMS currently implements modeled runoff data from NLDAS and GLDAS and computes runoff using the curve number method.

2. MODEL STRUCTURE

A model's structure determines how runoff is calculated. The three structural categories of runoff models, with strengths and weaknesses for each are displayed in Table 1. Models are listed below in order of increasing complexity, with empirical models being the simplest and physical mechanistic models the most complicated. Physical and conceptual models need thorough understanding of the physics involved in the movement of surface water in the hydrological cycle (Srinivasulu, 2008). Melsen et al. (2016) determined that model performance is mainly limited by the choice of model structure, not by parameters used in the model.

Table 1. Comparison of the basic structure for rainfall-runoff models

	Empirical	**Conceptual**	**Physical**
Method	Non-linear relationship between inputs and outputs, black box concept	Simplified equations that represent water storage in catchment	Physical laws and equations based on real hydrologic responses
Strengths	Small number of parameters needed, can be more accurate, fast run time	Easy to calibrate, simple model structure	Incorporates spatial and temporal variability, very fine scale
Weaknesses	No connection between physical catchment, input data distortion	Does not consider spatial variability within catchment	Large number of parameters and calibration needed, site specific
Best Use	In ungauged watersheds, runoff is the only output needed	When computational time or data are limited.	Have great data availability on a small scale
Examples	Curve Number, Artificial Neural Networks[a]	HSPF[b], TOPMODEL[a], HBV[a], Stanford[a]	MIKE-SHE[a], KINEROS[c], VIC[a], PRMS[d]

[a] Devi et al. (2015)
[b] Johnson et al. (2003)
[c] Woolhiser et al. (1990)
[d] Singh (1995)

Empirical models, sometimes called data-driven models, use non-linear statistical relationships between inputs and outputs as shown by the equation in Figure 1. Empirical runoff models are best used when other outputs are not needed; for example: the distribution of runoff values between upstream and downstream areas cannot be calculated with this model type. Very few parameters are needed, making data-driven models easy to use but they have no physical connection to the catchment. Simplicity of implementation, faster computational times, and cost effectiveness are reasons for empirical models to be chosen for modeling (Dawson & Wilby, 2001). Some examples of empirical models are the SCS-Curve Number used in the Soil and Water Assessment Tool (SWAT; USDA, 1986; http://swat.tamu.edu/), regression equations, and machine learning used by Artificial and Deep Neural Networks. The popular curve number method is often considered a semi-empirical model because it assumes the ratio of actual runoff to potential runoff is equal to the ratio of actual to potential retention, but there is no physical justification for this assumption.

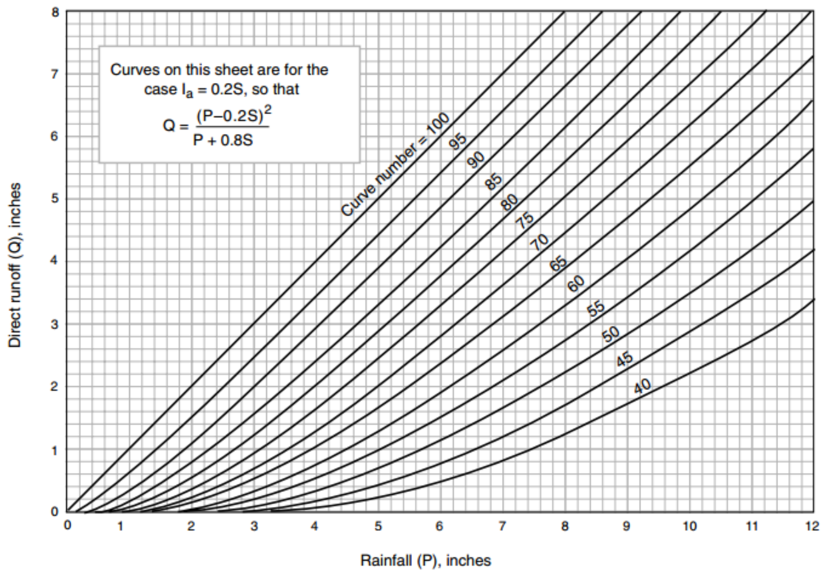

Figure 1. A visualization of the empirical Curve Number method shows the relationship between rainfall inputs and runoff outputs where I_a is initial abstraction, S is the retention parameter, P is precipitation, and Q is runoff. Image from USDA (1986)

Conceptual models interpret runoff processes by connecting simplified components in the overall hydrological process. They are based on reservoir storages and simplified equations of the physical hydrological process, which provide a conceptual idea of the behaviors in a catchment (see Figure 2) (Devi et al., 2015; Vaze, 2012). These models need a range of parameters and meteorological input data. Conceptual models have gained popularity in the modeling community because they are easy to use and calibrate. Lack of physical meaning in governing equations and parameters is also a limitation. Conceptual models are best used when computation time is limited and catchment characteristics are not analyzed in detail. The Topography based Hydrological Model (TOPMODEL; https://idea.isnew.info/r.topmodel.html), Hydrologiska Byråns Vattenbalansavdelning (HBV; http://www.geo.uzh.ch/en/units/h2k/Services/HBV-Model.html), and Hydrological Simulation Program-Fortran (HSPF; https://www.epa.gov/exposure-assessment-models/hspf) are some examples of conceptual models, often called semi-physical models because they are based on a water balance equation.

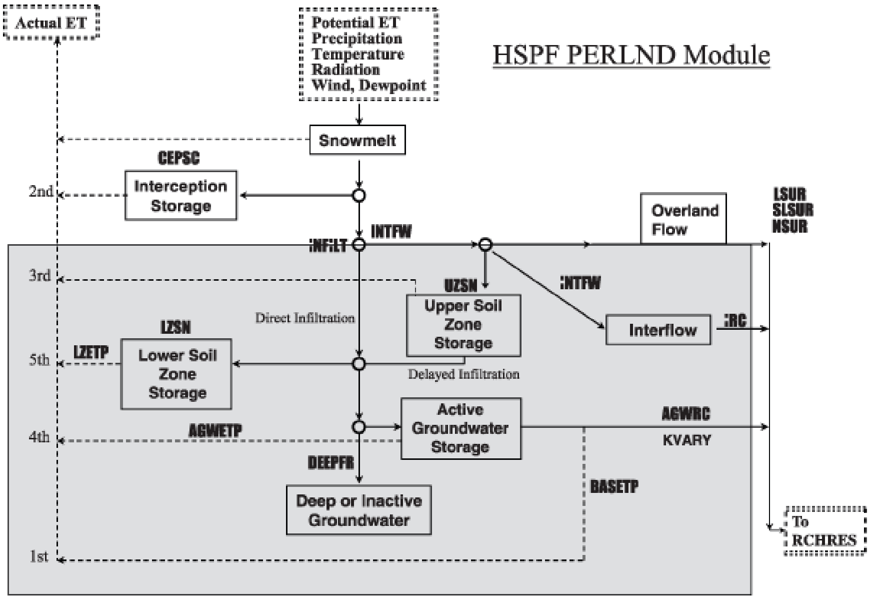

Figure 2. The conceptual model HSPF schematic shows the Pervious Land segment module (PERLND) as an assembly of multiple storage processes following the water balance equation. Image from Atkins et al.(2005)

Physical models are based on the understandings of the physics related to hydrological processes (Vaze, 2012). Physically-based equations govern the model to represent multiple parts of real hydrologic responses in the catchment. The general physics laws and principles used include water balance equations, conservation of mass and energy, momentum, and kinematics. The greatest strength of a physical model is the connection between model parameters and physical catchment characteristics which make it more realistic. Spatial and temporal variations within the catchment are incorporated into physical models. Most physical models give a three-dimensional view of the water exchange within the soil, surface, and air, as shown in Figure 3. They are best used when precise data are available, physical properties of the hydrological processes are accurately understood, and applied on fine scales due to computational time. The large amounts of data required to run them limit their usage (Uhlenbrook et al., 2004). Some examples of physical models include Visualizing Ecosystem Land Management Assessments (VELMA; https://www.epa.gov/water-research/visualizing-ecosystem-land-management-assessments-velma-model-20), MIKE System Hydrologique European (MIKE SHE; https://www.mikepoweredbydhi.com/products/mike-she), Penn State Integrated Hydrologic Modeling System (PIHM; http://www.pihm.psu.edu/), and the Kinematic Runoff and Erosion Model (KINEROS; http://www.tucson.ars.ag.gov/kineros/) (Singh, 1995).

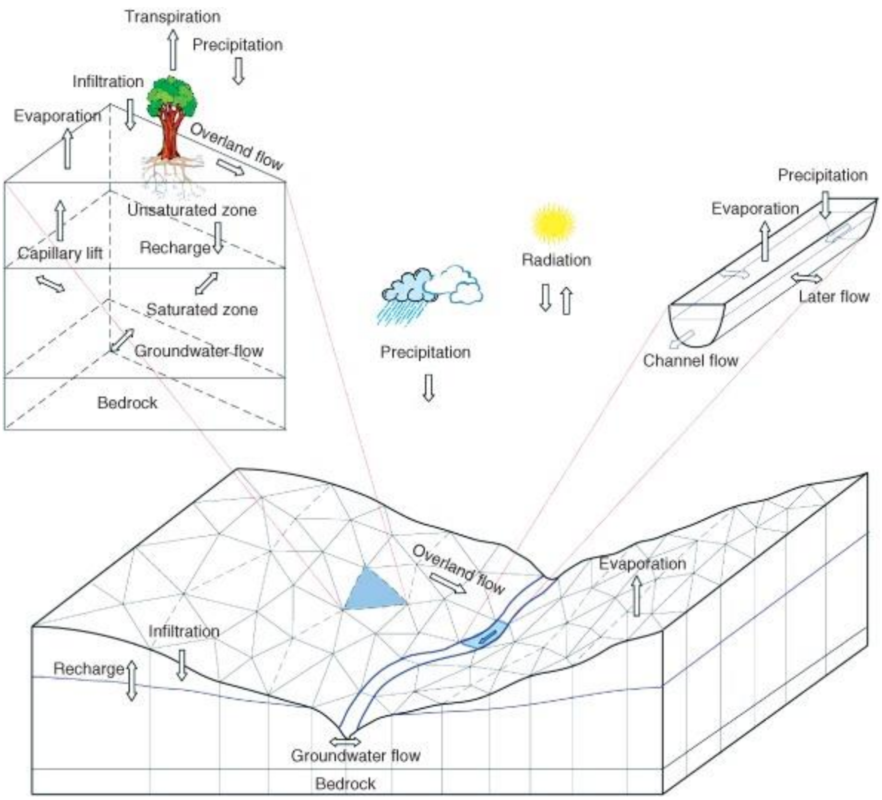

Figure 3. The model structure of the physically-based Penn State Integrated Hydrologic Modeling System (PIHM). It shows physical movement of water through each Triangular Irregular Network via overland flow, evapotranspiration, infiltration, recharge, and groundwater. Image from Qu (2004).

3. SPATIAL PROCESS

The spatial processes in runoff models provide a means of representing the catchment for modeling. They are based on input data and how runoff is generated and routed over the catchment. The spatial structure of catchment processes in rainfall-runoff models can be categorized as lumped, semi-distributed, and fully distributed (see Table 2). Lumped models do not consider spatial variability within the catchment; semi-distributed models reflect some spatial variability; and fully distributed models process spatial variability by grid cells. Semi-distributed models take spatial variability into consideration at smaller scales than lumped models, but do not calculate runoff at every grid cell. Spatial interpretation in a lumped model, a semi-distributed model, and a distributed model are shown in Figure 4.

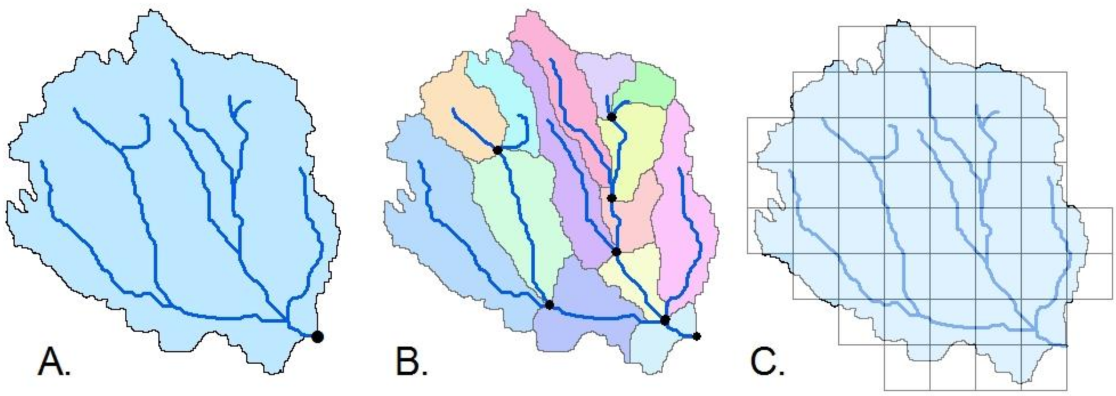

Figure 4. Visualization of the spatial structure in runoff models. A: Lumped model, B: Semi-Distributed model by sub-catchment, C: Distributed model by grid cell. Runoff is calculated for each sub-catchment at the pour point represented by the black dots in Figure 4B. Distributed models calculate

runoff for each grid cell, while lumped models calculate one runoff value for the entire catchment at the river outlet point represented by the black dot in Figure 4A. Image created using ArcGIS software (ESRI, 2015).

Table 2. Comparison of the spatial structures in rainfall-runoff models

	Lumped	**Semi-Distributed**	**Distributed**
Method	Spatial variability is disregarded; entire catchment is modeled as one unit	Series of lumped and distributed parameters	Spatial variability is accounted for
Inputs	All averaged data by catchment	Both averaged and specific data by sub-catchment	All specific data by cell
Strengths	Fast computational time, good at simulating average conditions	Represents important features in catchment	Physically related to hydrological processes
Weaknesses	A lot of assumptions, loss of spatial resolution, not ideal for large areas	Averages data into sub-catchment areas, loss of spatial resolution	Data intense, long computational time
Examples	Empirical and conceptual models, machine learning	Conceptual and some physical models, TOPMODEL[a], SWAT[b]	Physically distributed models, MIKESHE[c], VELMA[d]

[a] Devi et al. (2015)
[b] Beven (2012)
[c] Singh (1995)
[d] McKane et al. (2014)

Lumped models treat the catchment area as a single homogenous unit. Spatial variability of catchment parameters is disregarded in lumped models (Moradkhani & Sorooshian, 2008; Singh, 1995). By assuming homogeneity over the catchment, lumped models lose spatial resolution of the input data; for example, using the mean soil storage and uniform precipitation amounts. A lumped model is designed to simulate total runoff and streamflow at the outlet point, not specific flows within a catchment (shown in Figure 4A). For this reason, lumped models adequately simulate average runoff conditions with fast computational times. Lumped models include a lot of assumptions about the hydrological process and tend to over- or underestimate runoff values (UCAR, 2010). Empirical and conceptual models are usually run spatially as lumped.

Semi-distributed models are variations of lumped models, with features of distributed models. They can consist of a series of lumped parameters applied in a quasi-spatially distributed manner. For example, semi-distributed models can have data that are separated within a catchment but homogenous within a sub-area (Figure 4B) (Beven, 2012). Sub-areas represent important features in a catchment including soil type, drainage time, and vegetation zone, which combines the advantages of lumped and distributed models (Pechlivanidis et al., 2011). Semi-distributed models consider spatial variability and land use characteristics without an overwhelming model structure (Kokkonen et al., 2001). The benefits of a semi-distributed model are fast computational time and the ability to use less data and fewer parameters than a distributed model (Pechlivanidis et al., 2011). SWAT and TOPMODEL are two examples of semi-distributed models.

Distributed runoff models are the most complex because they account for spatial heterogeneity in inputs and parameters. Fully distributed models separate the model process by small elements or grid cells. Each small element (or cell) has a distinct hydrological response and is calculated separately, but incorporates interactions with bordering cells (Rinsema, 2014). By calculating runoff for every grid cell, the model provides detailed runoff information at various points within the catchment (see Figure 4C). This comprehensive information, helps to understand pollutant and sediment transport within a watershed along with capturing spatial and temporal variability of the hydrological process (Knapp, 1991). Distributed models are data-intensive, with all input data distributed spatially and temporally. Inputs needed for a typical distributed model are Digital Elevation Models (DEM); land use imagery from satellites; gridded precipitation; soil characteristics and how they change over time; topography; and watershed characteristics such as dimensions and boundaries. Drawbacks of distributed models are their demands for distributed data and calibrated parameters for every grid cell. MIKE-SHE and PIHM are examples of spatially distributed runoff models.

4. UNCERTAINITY

A runoff model is a simplification of a physical process; therefore, all models are uncertain to some degree. Rainfall-runoff model uncertainty can come from the observed data, natural uncertainties, parameter estimation, calibration, or model assumptions. Input data are a major source of uncertainty for rainfall-runoff models because they rely heavily on input data and physically based parameters (Pechlivanidis et al., 2011). As a result of the imbalance of model parameters and observed measurements, the equifinality problem creates different optimal parameter sets that lead to good model performances without having parameters with physical numerical meaning (Lee et al., 2012). The challenging aspect of validating models with observed data is that observed discharge data cannot be directly compared to modeled runoff values because modeled runoff does consider subsurface interactions and discharge data does not give information about spatial distribution of runoff within the catchment (Fekete, 2002). Results of rainfall-runoff model comparisons may be contradictory and hard to interpret because models differ in so many aspects (Andréassian et al., 2004). Models are usually created to answer specific questions and thus cannot be compared in a general way.

5. DISCUSSION

Surface runoff, a major process in the hydrological cycle, connects precipitation to surface reservoirs. Changes in vegetation, soil moisture, meteorological components, and surface conditions alter runoff (Chahine, 1992). Some models are better at considering these changes by computing runoff in a distributed spatial process. Simulations of surface runoff can help water resource managers understand how changes in the environment affect runoff and the hydrological cycle. Our classification of rainfall-runoff models by model structure and spatial processes shows different types of rainfall-runoff models and ways in which we distinguish models. The structure of a rainfall-runoff model is determined by the complexity of governing equations used for calculating runoff. Spatial processes in models are determined by how the catchment is interpreted: as lumped, semi-distributed, or fully distributed. Many models contain more than one element from each category and cover the spectrum between categories (Rinsema, 2014). Rainfall-runoff models must be chosen according to the project objective, data availability, size of the study, output needed, and simplicity desired. Physically distributed models give the most detailed information about the rainfall-runoff process which is useful in successfully managing water systems. Data availability may also limit the model selection. For this reason, simpler models are widely used because fine-scale catchment characteristics are unknown or too expensive to investigate (Rinsema, 2014). Each model type has limitations that may make it unsuitable for a specific project. Reviewing data requirements, physical meaning, user friendliness, and spatial resolution are all necessary to determine which model type should be selected.

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