

A review of underlying surface parameterization methods in hydrologic models

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Abstract: Numerous topography, land-cover, land-use, and soil-type parameterization methods are required to simulate the hydrologic cycle. In this paper, using the principles of hydrologic cycle simulation, 20 methods commonly applied to runoff-yield simulation are analyzed. Additionally, parameterization methods used in 17 runoff-yield simulation methods and 15 confluence methods are discussed, including the degree of parameterization. Next, the parameterization methods are classified into four categories: not clearly expressed; calibrated; deterministic; and physical–conceptual. Furthermore, we clarify responses and contributions of different parameterization methods to hydrologic cycle simulation results. Finally, major weaknesses of simplified descriptions of complex rational and physical mechanisms in the parameterization methods of the underlying surfaces in hydrologic models are outlined, and two directions of future development are estimated, looking toward simple practicality and complex mechanization.

Keywords: hydrologic cycle simulation; watershed topography; land use and cover; watershed characteristics; parameterization

1 Introduction

The natural water circulation system is large, multi-linked, and dynamic. Studies on water circulation began with observations and experiments on precipitation, evaporation, interception, infiltration, runoff, and other singular processes (Liu *et al.*, 2014). Only since the mid-1950s has the hydrologic cycle been considered a complete system. Thus, hydrologic models have been proposed, resulting in more comprehensive studies on watershed processes and interactions.

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Watershed hydrologic simulation is based on the application of physics, mathematics, and hydrology via the generalization of the watershed system according to its input conditions (e.g., precipitation, evapotranspiration, watershed underlying surface). It requires simulation of watershed hydrologic processes, including the outflow processes at the outlets (Rui, 1997; Zhao *et al.*, 2013). Over the last century climate change and the human activities have resulted in dramatic global environmental changes, including the water circulation system, which has far-reaching impacts on the socio-economic development. Thus, water-cycle simulation is a basis for water resource evaluation, allocation, management, and decision-making in terms of flood control and mitigation, soil erosion, water resource development and utilization, environmental protection of water resources, water ecosystem restoration, road and urban planning, watershed response to human activities, etc. (Singh, 1988; Entekhabi *et al.*, 1999; Lu *et al.*, 2006; Lu *et al.*, 2010; Li *et al.*, 2015; Liang *et al.*, 2015; Xia *et al.*, 2017).

Watershed topography, land use, and land cover are closely related to water interception, infiltration, evaporation, and other factors. They directly influence outflow production and runoff at the watershed outlet. Thus, the underlying surface is particularly important to simulation (Singh, 1995). There are numerous underlying surface parameterization approaches to hydrologic cycle simulation. For example, in the soil and water assessment tool (SWAT) model, the Soil Conservation Service (SCS)-curve method is often applied to calculate runoff. Canopy interception, surface water storage, and infiltration prior to runoff production are incorporated into the initial loss. The Storm-Water Management Model (SWMM), Hydrological Informatic Modeling System (HIMS), and water and energy transfer processes (WEP) models use the Green–Ampt method and the Horton method to calculate infiltration, plant interception, depression storage, and other factors that cause precipitation loss. Similarly, parameterization methods of flow concentration differ. Whereas the Xin'anjiang, Stanford IV, HSPE, and HIMS models use the unit-hydrograph method to calculate overland flow, the TOPMODEL and distributed time-variant gain hydrological model (DTVGM) often calculate overland flow by using the method of linear reservoir. River discharge is calculated using the theory of kinematic waves, dynamic waves, diffusion waves, and the Muskingum method, which are based on the Saint–Venant equations. Different methods of flow concentration have different degrees and methods of expression regarding the underlying surface. This paper analyzes the parameterization methods of the underlying surface in hydrologic cycle simulation and investigates problems existing in parameterization of topography, land use, land cover, and soil types. It also outlines future trends.

2 Runoff yield simulation methods in hydrologic cycle modeling

Major runoff-yield simulation methods include storage-full runoff, runoff yield under excess infiltration, mixed runoff, and rainfall-runoff coefficient of correlation methods (Bao, 2006; Bao *et al.*, 2008). See Table 1.

Runoff-yield simulations in the hydrologic modeling include calculation of overland-flow and river-flood routing. Methods and equations of river-flow simulation are the Saint-Venant, kinematic wave, dynamic wave, diffusion wave, inertial wave, an algorithm for reservoir flood control, Muskingum method, the Muskingum–Cunge method, variable storage coefficient method, etc. (Zhang *et al.*, 2007).

In many studies on surface runoff in large- and medium-sized watersheds, the overland-flow stage is often ignored, and only the river flow is considered. However, in a small watershed, that stage cannot be ignored. Thus, overland-flow simulation methods include isochrones method, unit hydrograph method, linear reservoir equation, non-linear reservoir equation, and kinematic wave equation (Li, 2007).

Table 1 Classification of runoff-yield methods in hydrological models

| Runoff-yield method | Calculation method | Hydrological model |
|--|--|---|
| Rainfall-runoff coefficient of correlation | SCS, Nonlinear runoff methods | DTVGM (Xia <i>et al.</i> , 2002; Xia <i>et al.</i> , 2005a; Xia <i>et al.</i> , 2005b), HIMS (Liu <i>et al.</i> , 2006; Liu <i>et al.</i> , 2008), SWMM (Huber <i>et al.</i> , 2008), SWAT (Neitsch <i>et al.</i> , 2011; Arnold <i>et al.</i> , 1998), HEC-HMS (Feldman, 1981) |
| Storage-full runoff | Soil water storage capacity curve Topographic index | Xin'anjiang (Zhao, 1984), VIC (Liang <i>et al.</i> , 1994; Liang <i>et al.</i> , 1996), EasyDHM (Lei <i>et al.</i> , 2010a, 2010b) TOPMODEL (Beven <i>et al.</i> , 1984; Beven <i>et al.</i> , 1995), TOPKAPI (Liu <i>et al.</i> , 2002) |
| Runoff yield under excess infiltration | Soil infiltration capacity curve Green-Ampt | Shanbei model (Zhao, 1984), water tank model (Xu, 2009), EasyDHM, TOPMODEL, VIC SWAT, WEP, HIMS, SWMM, PRMS (Xu, 2009), HEC-HMS |
| Dynamic equation | Richards equation | VIC, WEP (Jia <i>et al.</i> , 2001a, 2001b), VIP (Mo <i>et al.</i> , 2004), MIKE SHE (Abbott <i>et al.</i> , 1986a, 1986b) |

Note: SWAT: Soil and Water Assessment Tool; SCS: Soil Conservation Service curve method; SWMM: Storm-Water Management Model; HIMS: Hydrological Informatic Modeling System; WEP: Water and Energy transfer Processes models; HSPF: Hydrological Simulation Program-Fortran; DTVGM: Distributed Time-Variant Gain hydrological Model; HEC-HMS: Hydrologic Engineering Center Hydrologic Model System; VIC: Variable Infiltration Capacity; EasyDHM: Easy Distributed Hydrological Model; TOPMODEL: Topography based Hydrological Model; TOPKAPI: Topographic Kinematic Approximation and Integration; PRMS: Precipitation-Runoff Modeling System; VIP model: Vegetation Interface Processes; MIKE SHE: MIKE Système Hydrologique Européen; SWMIV: Stanford Watershed Model IV; HBV: Hydrologiska Byråns Vattenbalansavdelning Model

Commonly used methods of overland- and river-flow simulations in hydrologic models are shown in Table 2.

Table 2 Classification of confluence methods in hydrological models

| Confluence process | Calculation method | Hydrological model |
|--------------------|-------------------------------------|---|
| Overland flow | Unit hydrograph method | Xin'anjiang model, SWMIV, HSPF, HEC-1, TOPMODEL, VIC-3L, HIMS, SWAT |
| | Isochrones method | Xin'anjiang model, HIMS |
| | Linear reservoir equation | Xin'anjiang model, TOPMODEL, DTVGM |
| | Non-linear reservoir equation | SWMM, TOPKAPI |
| River flow | Kinematic wave equation | HEC-1, TOPKAPI, DTVGM, WEP-L (Jia <i>et al.</i> , 2006), EasyDHM |
| routing | Dynamic wave equation | SHE, VIC-3L (Yuan <i>et al.</i> , 2004), PRWS, WEP-L |
| | Muskingum method | Xin'anjiang model, HBV, HEC-1, SWAT, HIMS, EasyDHM |
| | Variable storage coefficient method | SWAT, EasyDHM |

Note: SWAT: Soil and Water Assessment Tool; SCS: Soil Conservation Service curve method; SWMM: Storm-Water Management Model; HIMS: Hydrological Informatic Modeling System; WEP: Water and Energy transfer Processes models; HSPF: Hydrological Simulation Program-Fortran; DTVGM: Distributed Time-Variant Gain Hydrological Model; HEC-HMS: Hydrologic Engineering Center Hydrologic Model System; VIC: Variable Infiltration Capacity; EasyDHM: Easy Distributed Hydrological Model; TOPMODEL: Topography based Hydrological Model; TOPKAPI: Topographic Kinematic Approximation and Integration; PRMS: Precipitation-Runoff Modeling System; VIP model: Vegetation Interface Processes; MIKE SHE: MIKE Système Hydrologique Européen; SWMIV: Stanford Watershed Model IV; HBV: Hydrologiska Byråns Vattenbalansavdelning Model

The purpose of the model application and time scales are related. Usually an hour or even a minute time scale is required for flood forecasting. However, in water-resource management, a daily scale is used, and a monthly scale meets most requirements for climate change and other environmental impact assessments. Because different time scales lead to different requirements regarding the level of detail of the description of the runoff-yield, even within the same model, a different time scale causes different methods to be selected for simulation. Therefore, the data requirement of the model also differs.

3 Parameterization methods of underlying watershed in rainfall–runoff

Parameterization methods in rainfall–runoff process simulation are discussed in relation to four aspects: the interception by vegetation and depression storage; the rainfall–runoff correlation method; the storage–full runoff method; and the runoff yield under excess infiltration method.

3.1 Interception by vegetation and depression storage

There are numerous hydrological simulation methods that consider interception by vegetation and depression storage.

3.1.1 Interception by vegetation

In hydrologic simulation, it is necessary to consider interception, which depends on the type and density of vegetation cover, season, precipitation characteristics, and other factors. In practice, empirical models have usually been applied, such as the Horton model (1935, 1940), LKP model, Meriam model, and others. Horton proposed a series of empirical equations for different plants and used a relatively wide range of empirical formula (see Table 3) with empirical values of parameters S_v and C .

3.1.2 Depression storage

On plains and slope zones, owing to relatively large numbers of hollows, depression storage is relatively large, significantly changing the watershed response. In 1979, Ullah and Dickinson (1979a; 1979b) proposed a relationship between the depression volume, V (cm^3), and the surface slope, s , (see Table 3). In 1979, Linsley *et al.* (1975), based on characteristics of the surface depressions, derived a relationship between depression storage volume, V , and depression storage capacity S (see Table 3). During runoff-process simulation, the impact of different terrain on the depression storage is relatively large.

3.2 Rainfall–runoff correlation method

The SCS runoff curve method and the non-linear Time-Variant Runoff Gain method are discussed.

3.2.1 SCS runoff curve method

The SCS runoff curve method is a kind of empirical relationship, which is based on measured data and through statistical analyses and summary. To calculate surface runoff, the SCS-curve method, the canopy interception of rainfall, surface water storage, and infiltration are integrated into initial loss. Therefore, it is not necessary to separately calculate canopy interception of rainfall (SCS, 1993).

The empirical formula of surface runoff and interception by the SCS-curve method can be seen in Table 3. The influence of land use and land cover on the runoff process is mainly reflected by a *CN* value. The greater the *CN* value, the smaller watershed interception and the larger surface runoff. SCS model developers have provided a detailed reference table with given *CN* values. However, owing to large errors in runoff, the determination of *CN* values is still a bottleneck of the SCS curve application in practice (Mishra *et al.*, 2003).

3.2.2 Non-linear Time-Variant Runoff Gain method

Hydrologic non-linear Time-Variant Gain Model (TVGM) was developed by Xia *et al.* (2002a, 2002b) as a simple and effective method for non-linear hydrologic systems. Main equations related to watershed runoff can be seen in Table 3. The monthly-scale DTVGM model uses *N* from the Bagrov model for classification of main land use types (Wang, 2005).

3.3 Storage-full runoff

The watershed storage curve method and the topographic index method are commonly used in storage-full runoff methods.

3.3.1 Watershed storage curve method

Runoff processes in a watershed are spatially not uniform. Before the entire watershed reaches full-storage runoff, partial areas already exist with full storage and runoff. Generally, the watershed water storage capacity curve characterizes uneven spatial distribution of soil water deficits. The watershed water storage curve equation is given in Table 3. During hydrologic simulation, the input parameters often use the watershed-average storage capacity, *WM*, and the water storage capacity distribution exponential curve, *b*. The value of *WM* is related to the watershed drought condition, and the constant, *b*, reflects the unevenness of the watershed water storage capacity (Zhao *et al.*, 1963). The watershed water storage curve method does not express the influence of terrain, land use, land cover, or soil on runoff. However, the *b* parameter implicitly shows the effects of the underlying surface.

3.3.2 Topographic index

Beven *et al.* (1984) proposed TOPMODEL, in which the topographic index, $\ln(\alpha / \tan\beta)$, is used to reflect hydrologic phenomena in a watershed, determine the size of the original area through water content, and determine water content via the topography index. The relationship between topographic index and water content is derived in accordance with the steady-state theory, assuming that the dynamic of groundwater levels changes in a watershed.

3.4 Runoff yield under excess infiltration method

There are two infiltration methods: the infiltration curve method and the infiltration formula.

3.4.1 Infiltration curve method

1) Infiltration capacity curve

Infiltration laws in a watershed are represented by an infiltration curve. The main principles and formulas of the soil infiltration capacity curve are shown in Table 3. When calculating the runoff infiltration curve, to improve the accuracy and reduce the effects of spatial and temporal non-uniform distribution of rainfall intensity on runoff, rainfall duration should

Table 3 Summary of runoff formation methods

| Runoff formation method | Main principle | Formula | Parameters | Parameter determination | Remarks |
|--|--|--|------------|---|---|
| Interception by vegetation | Horton empirical equation (Xu, 2009) | $I_n = S_v + CP_c$ | S, C | Empirical values | I_n is retention loss; S_v is vegetation in the canopy cover area; P_c is rainfall in the vegetation cover area |
| Depression storage | The size and distribution of depressions and amount of precipitation in watershed are related (Ullah <i>et al.</i> , 1979; Linsley <i>et al.</i> , 1975) | $V = a \exp(-bs)$ $V = (I - f) \exp(-kPe)$ | S, k | Calculated from measured data and formula | V is depression volume; S is depression storage; I is rain intensity; f is infiltration rate; Pe is net rainfall; a, b, k are constants |
| SCS runoff curve method | Based on the measured data, through statistical analysis and summing up empirical relationships (Mishra <i>et al.</i> , 2003) | $Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$ $S = 25.4 \left(\frac{1000}{CN} - 10 \right)$ | CN | Obtained from tables | Q_{surf} is daily surface runoff; R_{day} is daily precipitation; I_a is initial loss; S is interception; CN is curve number method |
| Non-linear Time-Variant Runoff Gain method | The systematic relationship between rainfall and runoff is nonlinear, its important contribution is the change in the runoff caused by differences in the soil moisture (i.e. soil water content) in the runoff process (Xia, 2002a) | $R(t) = G(t)X(t)$ $G(t) = g_1 + g_2API(t)$ | N | Empirical value | $R(t)$ is effective net rainfall; $X(t)$ is rainfall; $G(t)$ is system gain, has ideal linear relationship with soil wetness; g_1 , and g_2 are runoff model parameters; N is effectiveness parameter |

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| Runoff formation method | Main principle | Formula | Parameters | Parameter determination | Remarks |
|--|--------------------------------|--|---------------------------|--|--|
| Storage-full runoff | Watershed storage curve method | $\alpha = 1 - \left(1 - \frac{WM'}{WM} \right)^b$ $WM = \frac{WM'M}{1 + b}$ | WM, b | Calculated by the formula | WM' is value of water storage capacity of each point of aeration zone; WM/M is the maximum value; a is the relative value of the drainage area; WM is the average storage capacity of the whole basin; b is constant |
| | Topographic index | $Q_b = AT_0 \exp(-\lambda^*) \exp(-\bar{z} / S_{zm})$ $\lambda^* = \frac{1}{A} \int_A \ln \left(\frac{\alpha_i}{\tan \beta_i} \right) dA$ ^[24,25] | A, \bar{z}, T_0, S_{zm} | Calculated from the measured data and by the formula | Q_b is soil flow; T_0 is saturated hydraulic conductivity; A is basin area; \bar{z} is average depth of surface water; S_{zm} is the maximum water depth in the unsaturated zone |
| | Richards equation | $\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[K_x(\theta) \frac{\partial \phi}{\partial x} \right] + \frac{\partial}{\partial y} \left[K_y(\theta) \frac{\partial \phi}{\partial y} \right] + \frac{\partial}{\partial z} \left[K_z(\theta) \frac{\partial \phi}{\partial z} \right]$ | K | Calculated by the formula | θ is water content; t is time; K is permeability coefficient; ϕ is total water potential of unsaturated zone; x, y and z represent the direction of axes |
| Runoff yield under excessive infiltration method | Infiltration curve method | $F_P(t) = a + bt - ae^{-\beta t}$ $a = \frac{1}{\beta} (f_0 - f_c) \quad b = f_c$ | B, f_0, f_c | Obtained by experiment | $F_P(t)$ is the amount of cumulative water infiltration under time t ; β is coefficient; f_0 is initial infiltration rate; f_c is stable infiltration rate |

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| Runoff formation method | Main principle | Formula | Parameters | Parameter determination | Remarks |
|--|---|---|----------------------|--|--|
| Initial and final loss method | It is a simplified method of infiltration curve method with actual infiltration simplified to two stages of initial and final loss, respectively (USACE, 2000, 2001) | $P_{at} = \begin{cases} 0 & \sum P_i < I_a \\ P_t - f_c & \sum P_i > I_a, P_t > f_c \\ 0 & \sum P_i > I_a, P_t < f_c \end{cases}$ | I_a, f_c | Calculated from the measured data and by the formula | P_{at} is net rainfall; P_t is average rainfall in period $t-t+\Delta t$; I_a is initial loss of rainfall; f_c is the maximum potential rate of rainfall loss in basin |
| Profit and loss constant method | Assuming that initial loss is a variable that changes with the lapse of time and development of rainfall. After a long period without rainfall, the initial loss gradually returns to its initial value | $I_{at} = I_a - P_t + V_t$ | I_a, f_c, v_c | Calculated from the measured data and formula | I_a is initial loss in time t ; I_a is initial loss; P_t is amount of rainfall in time t ; V_t is recovery of initial loss in time t |
| Green & Ampt (physical conceptual formula) | Assuming that during the infiltration process the wetting front always has a distinct boundary surface between the wet and dry soil, the wetting pre-front has the initial moisture content, and there is a fixed suction at the wetting front (Green <i>et al.</i> , 1911) | $f_t = K \left[\frac{1 + (\phi - \theta_f) S_f}{F_t} \right]$ | K, S, θ, ϕ | Can be determined by a specific experiment, also the reference value can be used | f_t is rainfall loss in t time; K is saturated hydraulic conductivity; F_t is volume of soil water shortage; S_f is cumulative rainfall loss in time t ; $(\phi - \theta)$ is wet soil thickness |
| Horton (empirical formula) | Assuming that the infiltration rate is not only a function of time, but also related to the state of soil water content. When soil water content is large, the infiltration capacity is low and permeability increases (Horton, 1935, 1940) | $f_p = f_c + (f_0 - f_c)e^{-kt}$ | K, f_c | Empirical values, determined by specific experiment | f_p is infiltration capacity; f_0 is initial infiltration capacity; f_c is rate of stable infiltration; k is empirical parameter; t is infiltration period |

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| Runoff formation method | Main principle | Formula | Parameters | Parameter determination | Remarks |
|------------------------------------|--|---|------------------|---|--|
| Kostiakov (empirical formula) | Assuming that during the infiltration process the infiltration capacity f_p is inversely proportional to the cumulative infiltration F_p , α is the constant of proportionality | $f_p = \sqrt{\frac{\alpha}{t} - t^3}$ | α | Empirical value | f_p is infiltration capacity; α is empirical parameter; t is infiltration period |
| Philip (empirical formula) | Assuming that during the infiltration process (f_p-f_c) and ($F_p-f_c t$) are inversely proportional, α is the constant of proportionality (Philip, 1954) | $f_p = \sqrt{\frac{\alpha}{t} - t^2} + f_c$ | α, f_c | Empirical values, determined by specific experiment | f_p is infiltration capacity; f_c is rate of stable infiltration; α is empirical parameter; t is infiltration period |
| Hotan (empirical formula) | Based on the infiltration empirical formula of the storage volume concept | $f_p = GI \cdot \alpha \cdot SA^{1.4} + f_c$ | α, f_c | Determined according to the soil type and crop conditions | f_p is infiltration capacity; SA is water shortage in surface soil; GI is crop growth index; α is ground porosity index; t is infiltration period |
| Smith (empirical formula) | Assuming that the infiltration rate is limited by the rainfall intensity, then the pressure of the water head of the soil surface begins to tend to zero and in tp time surface water is generated or runoff begins to appear- this moment is taken as the beginning of the infiltration capacity (Smith <i>et al.</i> , 1978) | $f_p = f_\infty + A(t-t_0)^{-\alpha}$ | A, t_0, α | Empirical values | f_p is infiltration capacity; f_∞ is equal to theoretically saturated conductivity; A, t_0, α are parameters related to soil type, initial soil water content and rainfall intensity, respectively |
| Smith-Parlange (empirical formula) | Richards equation, can be applied to calculate water accumulation time and infiltration capacity (Zhan <i>et al.</i> , 2000) | $\int_0^{t_p} t di = \frac{B(\theta)}{i_p - K_s} \approx \frac{s^2/2}{i_p - K_s}$ | i_p, s | Obtained according to soil properties or by infiltration test | i_p is rain intensity during water accumulation period; s is the degree of absorption defined by Philip; K_s is degree of saturated hydraulic conductivity |

not be large (e.g., minutes), and the watershed area should be divided into smaller units per the distribution of rainfall stations. However, to determine the infiltration capacity curve, runoff data and field experiments are required to obtain, which in practice is difficult to achieve.

2) Simplified infiltration capacity curve

The initial and final loss method is a simplified infiltration curve, where the actual infiltration process is simplified and split into two stages: initial and final. The initial loss before runoff produced is represented by the watershed average depth of water. The final loss is represented by average infiltration rate, f_c . Skaggs and Khaleel (1982) gave reference values of f_c for different soil types. Under conditions of data scarcity, the initial rate of infiltration can be set to reference values.

The profit and loss constant method is similar to the initial and final loss method. The profit and loss method assumes that the initial loss is a kind of variable changing with the development of time and rainfall. After long-term lack of rainfall, the initial loss will gradually return to the initial value. Thus, in addition to the two parameters (i.e., initial loss I_a and subsequent infiltration rate f_c), the recovery rate v_c is required.

3.4.2 Infiltration formula

Infiltration formulas can be divided into two types: physical conceptual and the experimental. Among the commonly used physical conceptual infiltration formula, the Green–Ampt formula is popular. Experimental infiltration formulas are more diversified and include the Horton, Kostiaikov, Philip, Hotan, Smith, and Smith–Parlange formulas. The main formulas and their parameters are shown in Table 3. From the table can be seen, empirical infiltration formulas for runoff are often calculated to determine the experimental parameters.

Vegetation interception during the runoff formation of hydrologic cycle simulation considers land use and land cover effects on the water cycle. For depression storage, it considers the influence of topography. Rainfall–runoff yield correlation methods experimentally derive or use semi-quantitative rainfall–runoff relationships to characterize the influence of the underlying surfaces. During runoff yield under excess infiltration methods, the soil in the underlying surface is described by empirical parameters of the infiltration formula, whereas topography, land use, and land cover are implicit influencing factors expressed indirectly.

In summary, hydrological cycle simulation considers the impact of land use and land cover on the water cycle during vegetation interception and the runoff yield process. It also considers the effect of terrain on the water cycle during the filling process and the influence of terrain on the water cycle during the storage process. The rainfall–runoff correlation characterizes the influence of the underlying surface via an empirical relationship or semi-quantitative relationship obtained by experiment. The influence of terrain and land use is described primarily using empirical parameters. The runoff yield under excess infiltration of soil in the underlying surface is usually described using empirical parameters of the infiltration formula with the infiltration curve method, whereas terrain and land use cover are implicitly influencing factors and are not directly expressed.

In the future, runoff mechanisms will be controlled by the water-balance principle in the watershed. Thus, it is necessary to further strengthen the quantitative study on the runoff mechanism for several reasons. First, hydrological processes are always modeled on different scales, including the spatial scale (i.e., slope, basin, region) and the time scale (i.e., minute, hour, month, year, multi-year). Second, the underlying surface of the watershed has

strong individuality, and there are many factors influencing the underlying surface during runoff, including land use, land cover, topography, soil characteristics, and the initial water content of the watershed. These main factors are considered in the current hydrologic cycle model. However, the complexity of physical mechanisms and the diversity of underlying surfaces make it difficult to describe accurately. Finally, intense human activities significantly exert impact on the underlying surface, making it more diversified and complex. Simultaneously, many constructions and hydraulic structures destroy the natural flow.

4 Parameterization methods of underlying watershed surfaces in the confluence process simulation

This section presents the simulation of overland-flow confluence and stream-flow routing. These two processes are usually simulated separately during hydrological cycle modeling.

4.1 Simulation of overland-flow confluence process

Empirical surface-flow confluence process modeling is based on the linear superposition theory, and most methods include the isochronous streamline method, the unit hydrograph method (e.g., time unit, instantaneous unit, geomorphic unit), the linear reservoir method, and other simplified methods (Zhan *et al.*, 2000).

4.1.1 Isochrone method

The isochrone method simplifies the physical process of overland flow and gives relatively satisfactory results in distributed hydrologic models. The main principles and formulas of the method are shown in Table 4. The confluence speed of overland flow is the key factor in the isochrone method, usually based on measured data and experiments. Therefore, effects of underlying watershed surfaces are not clearly expressed and are implied in the empirical parameters of the isochrones.

4.1.2 Unit hydrograph method

The unit hydrograph method is an empirical simulation method in which a watershed is considered without considering the unevenness of the net rainfall and the underlying surfaces. This corresponds to the ratio and superposition conditions. The main formulas of the unit hydrograph, the instantaneous unit, and the geomorphologic unit are given in Table 4.

Based on a series of linear reservoirs, J. E. Nash *et al.* (1957, 1960) used spatial characteristics, improved the unit-line method, and proposed the instantaneous hydrograph concept. However, in the Nash instantaneous unit hydrograph, certain empirical parameter determinations remain, and the unit hydrograph cannot be solely based on underlying watershed surface information.

In 1979, Rodriguez-Iturbel proposed the concept of Geomorphic Instantaneous Unit Hydrograph (GIUH), which linked probability theory, the method of underlying surface information, and the unit-line method. V. K. Gupta (1980) extended this theory and proposed a geomorphic instantaneous unit hydrograph formula expressed by topographic and hydraulic parameters. Using the GIUH is an effective way of determining flow confluence in areas having no information.

The Nash instantaneous unit hydrograph method and the GIUH are based on characterization of the physical mechanism of the influence of watershed topography on runoff. How-

ever, it is based on the hypothesis of an entire river watershed. Thus, it cannot provide a spatial description and simulation of the flow confluence process and is unable to handle the case of a large watershed with uneven precipitation distribution.

4.2 Stream-flow routing

Stream-flow routing is based on the equation of flow continuity and the equation of energy conservation with the Saint–Venant equation as the theoretical basis. This equation system is based on the physical stream-flow confluence mechanism and considers river slope and roughness. This equation system belongs to the first-order hyperbolic quasilinear partial differential equations, which can be solved by the numerical solution. However, the solution is complicated and does not necessarily provide satisfactory results.

4.2.1 Simplified momentum equation

The dynamic equations of the Saint–Venant system can be simplified by neglecting certain items. Thus, different types of flood waves (e.g., kinematic, dynamic, diffusion, inertial etc.) can be obtained. Presently, commonly used kinematic waves, dynamic waves, and diffusion waves, neglecting the inertial term in the dynamic equation and adding the flood wave term described in the equation is the dynamic wave. The inertial piece in the momentum formula in the diffusion wave is neglected. Each momentum fluctuation equation is a dynamic wave in the momentum formula (Govindaraju *et al.*, 1990; Singh, 1994).

Compared to other methods of calculation, a relatively lower flow confluence geomorphologic information input is required to use the kinematic wave method, which is relatively simple. Therefore, it is commonly applied to overland-flow yield and distributed hydrologic model calculations (Orlandini *et al.*, 1999). Saint–Venant equation and the simplified momentum equation inputs mainly require measured river-section data.

4.2.2 Other empirical equations

The simplified momentum equation simplifies the continuity equation of the Saint–Venant equation system into the following river-section water-balance equation:

$$\frac{I_1 + I_2}{\Delta t} - \frac{Q_1 + Q_2}{\Delta t} = V_2 - V_1 \quad (1)$$

where I_1 and I_2 are the initial and final inflow discharges, respectively; Q_1 and Q_2 are the initial and final outflow discharges, respectively; V_1 and V_2 are the initial and final river channel storage capacities, respectively; Δt is the time interval.

Dynamic equation can be simplified to the water amount tank storage equation in the river section, which is substituted by an approximate relation among I , Q , and V . The outflow process is calculated on the basis of inflow, and different approximations give different methods of calculation. Among the most commonly used are the reservoir–flood routing method (Zhang *et al.*, 2002; Rui, 2004), the Muskingum method (Mccarthy, 1938), the Muskingum–Cunge method (Cunge, 1969; Bajracharya *et al.*, 1997), and the variable storage coefficient method. Their main formulas are given in Table 4.

In the Muskingum method, parameters K and X must be determined first. K is the average propagation time in the river section. Its value depends on the river-section length and wave speed. Parameter X represents the relative impact of inflow and outflow on the storage capacity, and its range is $[0, 1]$. K and X are determined experimentally.

Table 4 Summary of flow concentration methods

| Flow concentration method | Main principle | Formula | Parameters | Parameter determination | Remarks | |
|---------------------------|-------------------------|---|--|-------------------------|--|--|
| Overland flow | Isochronous line | Assuming that flow lines in the basin are isochronous, considering that water droplets on the same line flow to the outlet section at the same time, the distribution of isochronous flow lines are obtained using the flow concentration speed (Zhan <i>et al.</i> , 2000) | $Q_t = \frac{1}{\Delta t} \sum_{j=k_1}^{k_2} r_{d,j} \Delta A_{t-j+1}$ | c | The value of flow velocity near the peak is main basis for determining the value of convergence speed c | Q is outflow at the end of the period; r_d is net precipitation; ΔA_i is the area of the i -th isochronous flow block; Δt is the unit time period length; t is flow timing; k_1, k_2 are cumulative boundaries |
| | Time interval unit line | Considering basin as a system, assuming that the system is linear and time-invariant, that is runoff generated by net rain can be calculated by linear operation (Zhan <i>et al.</i> , 2000) | $Q_{d,t} = \sum_{j=k_1}^{k_2} r_{d,j} q_{t-j+1}$ | r_d, q | Analysis, trial- and error method, least squares method, graphic method etc. | Q_d is the direct runoff at the end of the drainage section of the basin; r_d is the net rainfall in a time period; q is the flow rate at the end of the unit line time period |
| | Instantaneous unit line | One unit of instantaneous inflow is regulated by a series of n equivalent reservoirs, whose outflow is IUH (Nash, 1957, 1960) | $u(t) = \frac{1}{K\Gamma(N)} \left(\frac{t}{K}\right)^{N-1} e^{-t/K}$ | N, K | Matrix method for reference, but also based on topographic information to obtain N value, and then optimization method to obtain K value can be used | N is the number of linear cascade reservoirs; K is the water flow propagation time in the linear reservoir |

(To be continued on the next page)

(Continued)

| Flow concentration method | Main principle | Formula | Parameters | Parameter determination | Remarks |
|-------------------------------|--|---|---------------|-----------------------------------|---|
| GIUH | Assuming that instantaneous injection of net rainfall evenly distributed in basin is composed of multiple water dots, and assuming a weak correlation between the water particles. Therefore, the instantaneous unit hydrograph of the basin is the probability density function of water particle detention time (Rodriguez <i>et al.</i> , 1979; Gupta <i>et al.</i> , 1980) | $\begin{aligned} Q(t) &= I_0 f_B(t) \quad t > 0 \\ f_B(t) &= \frac{dF_B(t)}{d(t)} \\ &= \sum_{s \in S} f_{x_1} * f_{x_2} * \dots * f_{x_k}(t) p(s) \end{aligned}$ | Flow velocity | Calculated by the formula | I_0 is the net precipitation; f_x is the probability density function of the retention time; $p(s)$ is the path probability; * is convolution multiplication |
| SCS unit line model | SCS model unit line of the net rain period is variable; therefore, it is not possible to give the dimensionless ordinate values of unit line. Thus, transformation of that dimensionless unit line must be very accurate | $\begin{aligned} q_p &= \frac{0.208FR}{t_p} \quad t_p = \frac{2}{3}t_c \quad t_c = \frac{5}{3}L \\ L &= \frac{I^{0.8}(S + 25.4)^{0.7}}{7069y^{0.5}} \quad D = 0.133t_c \end{aligned}$ | q_p, L, D | Obtained according to the formula | q_p is unit line flood peak flow; L is flood peak lag; D is the length of unit line time interval |
| Linear reservoir equation | Flow water balance equation and storage equation (Zhang <i>et al.</i> , 2002; Rui, 2004) | $K \frac{dQ}{dt} + Q = I$ | K | Hydrological analysis | K is storage constant (mean basin concentration time) |
| Non-linear reservoir equation | Flow water balance equation and storage equation (Zhang <i>et al.</i> , 2002; Rui, 2004) | $nkQ^{n-1} \frac{dQ}{dt} + Q = I$ | n, k | Hydrological analysis | n, k are constants |

(To be continued on the next page)

| (Continued) | | | | | |
|---------------------------|---|--|------------|---|--|
| Flow concentration method | Main principle | Formula | Parameters | Parameter determination | Remarks |
| Saint-Venant equations | Composed of continuity equation and momentum equation, the law of conservation of mass and the law of conservation of momentum are the basic laws | $\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$ | n, C, K | Obtained from tables | x is distance along river; Z is water level; v is average flow velocity at cross-section; n is Manning's roughness coefficient; C is Chezy coefficient; K is flow modulus (specific discharge) |
| | | $-\frac{\partial Z}{\partial x} = S_f + \frac{1}{g} \frac{\partial v}{\partial t} + \frac{v}{g} \frac{\partial v}{\partial x}$ | | | |
| River flow routing | Kinematic wave equation | $\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial x} = 0 \quad c_k = \eta v$ | η | Obtained in accordance with the formula, according to the measured data | η is wave velocity coefficient |
| | Diffusion wave equation | $\frac{\partial Q}{\partial t} + c \frac{\partial Q}{\partial x} = \mu \frac{\partial^2 Q}{\partial x^2}$ | C, η | Obtained by the formula, according to the measured data | C is wave velocity; η is diffusion coefficient |
| | Simplified dynamic equation | | | | |
| Dynamic wave equation | None of the momentum equations can be ignored (Singh, 1994; Orlandini <i>et al.</i> , 1999) | $\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$ | n, C, K | Obtained from tables | n is Manning's coefficient of roughness; C is Chezy coefficient; K is flow modulus |
| | | $v \frac{\partial v}{\partial x} + \frac{\partial v}{\partial t} + g \frac{\partial y}{\partial x} = g \left(i_0 - \frac{v^2}{C^2 R} \right)$ | | | |

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(Continued)

| Flow concentration method | Main principle | Formula | Parameters | Parameter determination | Remarks |
|-------------------------------------|--|---|------------|---|---|
| Reservoir flood routing method | Water balance equation and tank storage equation (Zhang <i>et al.</i> , 2002) | $V_2 + \frac{\Delta t}{2} Q_2 = \frac{\Delta t}{2} (I_1 + I_2) + V_1 - \frac{\Delta t}{2} Q_1$ | I, Q, V | Graphic method, trial-and-error method | I is inflow rate; Q is outflow; V is channel storage |
| Muskingum method | Water balance equation and tank storage equation (Mccarthy, 1938) | $Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_1$ $C_0 = \frac{0.5\Delta t - KX}{0.5\Delta t + K(1-X)}$ $C_1 = \frac{0.5\Delta t + KX}{0.5\Delta t + K(1-X)}$ $C_2 = \frac{-0.5\Delta t + K(1-X)}{0.5\Delta t + K(1-X)}$ | K, X | Parameters can be described using the hydraulic and topographic characteristics. Parameters can also be determined using the least squares method, the graphic method, the matrix method etc. | K is storage constant; X is constant, has different explanations, its scope and interpretation are interdependent |
| Muskingum-Cunge method | Muskingum-Cunge method is an improvement of the Muskingum method, the biggest difference is in the determination of parameters K and x , in the Muskingum-Cunge method the parameters are determined on the basis of the water flow data (Bajracharya <i>et al.</i> , 1938; Cunge, 1969) | $Q_2 = C_0 I_1 + C_1 I_2 + C_2 Q_1 + C_3 Q_{lat}$ $C_0, C_1, \text{ and } C_2 \text{ are the same as above}$ $C_3 = \frac{\Delta t}{0.5\Delta t + K(1-X)}$ $K = \frac{\Delta x}{c} \quad X = \frac{1}{2} \left(1 - \frac{Q}{c\Delta x BS_0}\right)$ | K, X | Determined by the measured water flow data | c is wave speed; Q_{lat} is lateral inflow; B is water surface width; S_0 is slope of river bed |
| Variable storage coefficient method | It is an improvement of the Muskingum method, when taking into account the river flood wave propagation time and the length and slope of the river reach, K values of different river reaches should be different | $K = \frac{L}{V_c} \quad V_c = \frac{5V}{3}$ $V = \frac{R^{2/3} \sqrt{i}}{n}$ | n, R | Obtained from tables, calculated by the formula | n is the Manning's coefficient; R is the hydraulic radius |

Empirical relationship replaced dynamic equation

The Muskingum–Cunge method's biggest difference from the Muskingum method is how it determines parameters K and X . In the Muskingum–Cunge method, these parameters are calculated from the time-step length, the river-bed slope, and the flood-wave velocity. The calculation formulas are given in Table 4. To some extent, the Muskingum–Cunge method reflects the influence of watershed topography and spatial characteristics of the river network on the flow-yield process.

Topography has a relatively large impact on flow concentration, and it is also a factor that is most studied. In small watersheds, land cover and other factors affect the runoff processes via hydraulic roughness and other properties. Current studies focus on areas with measured data or those where empirical relationships can be established.

Overland flow simulation is based on the confluence process, based on the water-balance principle and hydrodynamic theory. For example, the isochrone method assumes that there is a line that reaches the outlet of a basin at the same time, obtaining its distribution based on the confluence speed. The unit line and SCS unit line are based on the measured data of the basin to reverse the flow process. The instantaneous unit line is based on the function of the connection reservoirs to simulate the confluence process. Furthermore, the instantaneous unit line of the geomorphology is based on the flow. The probability density of residence time is simulated in the confluence process. Topography greatly influences the confluence process, and it is the most influential factor. For small watersheds, the surface cover surface characteristics affect the runoff process via hydraulic characteristics, such as roughness. Current research focuses on using measured data to establish empirical relations.

Confluence methods are based on flow and energy equations to simulate the course of the river flow. The equations are simplified, depending on assumptions and precision requirements. These methods ensure a clear response to the mechanism of the underlying river channel surface. However, for practical applications, they have shortcomings, including the randomness of the underlying surface, including the assumption of the existence of premises and the actual inconsistency. In the hydrologic cycle simulation, river discharge calculations require generalization and simplification of slope and river channel, partially or completely ignoring the spatial variability of hydraulic characteristics. It uses uniform parameters to correct model operations, which significantly limits the descriptive abilities and the spatial precision of the confluence methods.

5 Classification of the parameterization methods

Watershed rainfall–runoff simulation parameterization methods can be divided into four categories, depending on the degree of topographical parameterization. The first includes methods not clearly indicated by the effects of terrain and land use on rainfall–runoff processes. The second uses empirical parameters to express the influence of terrain, land use, and land cover in runoff yield and outflow concentration, which are calibrated with parameter data. The third is the deterministic parameters category, which is based on the empirical relationship between terrain, land use, land cover and runoff yield and concentration process, the expressed parameters can be obtained by looking up tables or simple calculation. The fourth is the physical conceptual category, in which the relationships among topography, land cover, land use, and rainfall–runoff parameterization are established by physical mechanisms.

Owing to the parameterization of the watershed topography, land use, land cover, and soil type in the rainfall–runoff simulation of underlying surface methods, the degree of the parametric description the physical mechanism can be classified as shown in Tables 5 and 6.

Table 5 Classification of parameterization in runoff–yield processes

| Category | | Runoff-yield method |
|--|--------------------------|--|
| Rainfall-runoff coefficient of correlation | Deterministic parameters | SCS runoff curve method |
| | | Non-linear Time-Variant Runoff Gain method |
| Storage-full runoff | Calibrated parameters | Soil water capacity demand curve method |
| | Deterministic parameters | Topographic index |
| | Physical conceptual | Richards equation |
| Runoff yield under excess infiltration | Not clearly expressed | Infiltration curve method |
| | | Initial and final loss method |
| | Physical conceptual | Green & Ampt (physical concept formula) |
| | Calibrated parameters | Profit and loss constant method |
| | | Horton (empirical formula) |
| | | Kostiakov (empirical formula) |
| | | Philip (empirical formula) |
| | | Hotan (empirical formula) |
| | | Smith (empirical formula) |
| | | Smith-Parlange (empirical formula) |

Table 6 The classification of flow concentration parameterization methods

| Flow concentration method | | | Category |
|-----------------------------|---|-------------------------------------|--------------------------|
| Overland flow concentration | Isochronous line | | Calibrated parameters |
| | | | |
| | Unit hydrograph | Time interval unit line | Not clearly expressed |
| | | Instantaneous unit line (J.E. Nash) | Calibrated parameters |
| | | GIUH | Physical conceptual |
| | | SCS runoff curve | Deterministic parameters |
| | | | Calibrated parameters |
| River flow routing | Linear reservoir equation | | Calibrated parameters |
| | Non-linear reservoir equation | | |
| | Saint-Venant equations | | Calibrated parameters |
| | | | |
| | | | |
| | Simplified dynamic equation | Kinematic wave equation | Deterministic parameters |
| | | Diffusion wave equation | |
| | | Dynamic wave equation | |
| | Other empirical equations replacing dynamic equations | Reservoir flood routing method | Calibrated parameters |
| | | Muskingum method | |
| | | Muskingum-Cunge method | |
| | | Variable storage coefficient method | |

6 Extant problems of parameterization methods and future trends

Because of the diversity and spatial variability of the underlying surface, the scale effect of the hydrological process (Wood *et al.*, 1988) and the intense human activities (Kuk-Hyun *et*

al., 2014; Tang *et al.*, 2015; Liu *et al.*, 2016; Zhang *et al.*, 2016), we observe complexity of the underlying surface in the hydrological cycle. Thus, in a typical watershed hydrologic cycle model, toward the underlying watershed surface topography, land use, land cover, and soil type in the rainfall-runoff process, the degree of description of the physical mechanism empirical parameters prevail. Most of the empirical parameters are obtained via calibrated parameters. The class of deterministic parameters is usually established on parameter tables or empirical relationships. In the physical-conceptual category, there are certain physical equations to express their response. However, with the development of technology, the problem of solving complex equations becomes simpler. Additionally, the more complex equations complicate the hypotheses and parameters, making them often difficult to satisfy, owing to the lack of observational data.

Models are simulations of objective reality or abstract processes. Thus, the hydrologic model is an abstraction of the complex natural hydrologic cycle in a watershed. On the one hand, the application of the hydrologic cycle model aims to explore the laws of nature, approximating the process using various experiments and mathematical equations. Over time, it more accurately describes the natural water cycle. With advances in physics and mathematics, this type of model becomes more complex and provides more accurate characterizations of natural mechanisms. Categories of physical concepts and deterministic parameters represent the second trend. Parameterization methods include physical mechanisms. However, these methods are relatively limited. On the other hand, future research will have more space for exploration. Models have been built to solve real problems, but simplified simulations have little effect on the accuracy of a modeled process. Even so, the simplest calculation that uses minimum data leads to a better and more thorough understanding of phenomena. Such models are simpler and more practical. The above-mentioned methods, including those not clearly expressed, calibrated parameters, and deterministic parameters, represent the first trend, in which the parametric approach provides a simplified empirical relationship to represent the underlying surface in the watershed hydrologic cycle.

As for the relationship between the two aforementioned trends, the processes described as the first trend are more detailed. Thus, the equations will become more complex, and the uncertainty of the model will increase. However, exploration of its mechanism can provide a development paradigm for the second trend and more accurately solve the problem of its application.

7 Discussion

Hydrologic cycle simulation is widely used in studies of environmental changes. Watershed topography, land use, land cover, soil type, and other underlying surfaces are closely connected to precipitation, infiltration, and evaporation. They have direct impacts on the rainfall-runoff processes, whereas the flow yield directly affects the flow at the watershed outlet. Thus, topography, land use, and land cover are particularly important in hydrologic simulation.

There are numerous parameterization methods for the underlying surfaces regarding hydrologic models. In this paper, the following simulated aspects of the underlying surfaces in the hydrologic cycle simulation are reviewed.

(1) Rainfall-runoff process simulation methods commonly used in hydrologic cycle simulation are classified. Then, the parameterization of the terrain, land use, land cover, and

soil types are explored. The role of that mechanism is portrayed.

(2) The parameterization methods of the underlying surface in the physical mechanism of the rainfall–runoff process are divided into four categories: the not-clearly expressed; calibrated parameters; deterministic parameters; and physical–conceptual. Currently, the most commonly used parameterization methods are calibrated parameters category, which describe the physical mechanism of topography, land use and land cover and soil types in runoff yield and concentration in watershed underlying surface. These are followed by the deterministic parameters category, generally determined by a parameter table or empirical relationship. In the case of physical conceptual category parameterization methods, physical equations represent the response relationships, however, their application faces difficulties, owing to the lack of data supporting the boundary conditions.

(3) Returning to the natural model, with different requirements requiring parametric approaches, parameterization methods describe the physical mechanism and characteristics of the rainfall–runoff process in the watershed as detailed as possible. They also develop a more complex mechanism. Simultaneously, exploration of the mechanism provides a systematic paradigm for describing the main principles needed to meet the demand for a practical development via a simple method.

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