Article

Impacts of Channel Network Type on the Unit Hydrograph

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Abstract: Unit hydrographs (UHs) remain widely used in hydrologic modeling to predict the stormflow that is produced at a basin outlet in response to runoff generated throughout the basin. Numerous studies have demonstrated that a basin's UH depends on its geomorphic properties, and several methods estimate synthetic UHs using such properties. However, previous studies have not examined whether the channel network type (such as dendritic, parallel, pinnate, rectangular, and trellis) impacts the UH shape. The objectives of this study were to determine: (1) whether those five network types exhibit distinct UHs, and (2) whether knowledge of the network type is sufficient to replace the actual flow path structure in UH estimation. To achieve these objectives, a UH framework is developed based on kinematic wave theory. The framework allows the impacts of the network structure on the UH to be isolated into two random variables, which facilitates comparisons between network types. The framework is applied to 10 basins of each type. The results show that the five network types exhibit distinct instantaneous UHs, but the type allows accurate UH determination only for pinnate basins.

Keywords: hydrologic response; dendritic; parallel; pinnate; rectangular; trellis

1. Introduction

A common task in hydrologic modeling is predicting the stormflow that occurs at a basin outlet in response to the runoff produced throughout the basin. Many hydrologic models, such as HEC-HMS [1] and SWAT [2], transform runoff into stormflow using a unit hydrograph (UH). The UH concept goes back to Sherman [3], who defined it as the stormflow hydrograph resulting from one unit of average excess rainfall [4]. The UH is known to depend on the basin morphology [5–7], and various methods estimate the UH from such characteristics [8]. Traditional synthetic UH methods consider only limited

aspects of the basin morphology. For example, the original SCS method uses a single dimensionless UH for all watersheds [9], but that UH is rescaled using the watershed area, mainstream length, and average slope. The original SCS method has been updated so that the dimensionless UH shape can vary based on a selected peaking factor [10,11] that estimates the UH based on the distribution of travel times to the outlet and a linear reservoir that describes the effects of storage within the watershed. Originally, the travel time distribution was based on hypothetical basin configurations, but the method in [11] has been updated to use the actual flow path configuration for the watershed of interest [12–14].

UHs have also been generated using probability density functions (PDFs); given their similar mathematical properties, the authors of [8,15] modeled the basin as a series of linear reservoirs, producing a UH with a gamma distribution. This model is usually classified as “conceptual” [15], in contrast to the earliest synthetic UH methods, which rely on some degree of subjectivity in fitting rainfall-runoff data. For instance, the authors of [16,17] list several PDFs that have been successfully used to fit the UH, including incomplete [18] and two-parameter gamma distributions [19,20], chi-squared [21], beta [22], and Weibull [23] distributions.

The Geomorphologic Instantaneous UH (GIUH) estimates the UH from the PDF of travel times to the outlet, and the PDF is estimated using Horton’s ratios, which describe the network structure. The authors of [5,24,25] proposed a similar UH based on channel links instead of [26] stream orders, and [27] extended the GIUH approach to consider the effects of hillslope travel times. The GIUH approach has also been generalized to allow a nonlinear relationship between runoff and stormflow [28]. The breadth of the GIUH approach can accommodate much variability within and between basins—for instance, partitioning a basin into units where each unit has a different parametrization [29].

UH methods have also been developed using the width function, as determined from a digital elevation model (DEM), which is the distribution of flow lengths to the outlet [30]. Thus, they explicitly consider the flow path structure for any basin of interest. They also use a spatial representation of the flow speed or flood-wave celerity along the flow paths to determine the travel times [31]. Different representations for the celerity have been proposed, including using two velocities representing hillslope and channel flows (e.g., [31–33]) or two velocities representing surface and subsurface flows [34]. Spatially distributed travel time (SDTT) or spatially distributed UH methods are similar, but they use a celerity that varies continuously in space throughout the watershed [35,36]. Some SDTT methods also relax the linearity assumption of traditional UH methods because their travel times vary in time (e.g., [37–42]).

As these previous studies demonstrate, the UH is known to depend on the channel network structure. However, it is not known whether the channel network type affects the UH. Watersheds can exhibit distinct channel network structures depending on the geomorphic conditions under which they developed, and these differences have led to the use of network types such as dendritic, parallel, pinnate, rectangular, and trellis (Figure 1). Dendritic networks are tree-like, with channels oriented in many directions and tributaries forming acute angles at confluences. This network type develops when few lithologic or topographic constraints are present [43]. Parallel networks have major channels that are aligned with each other and develop when the region has a pre-existing slope [43–47]. Pinnate networks tend to be feather-like, with a single main channel and many tributaries joining the main channel at acute angles, but the origin of this network type is unclear [43,46–48]. Rectangular networks have channels with right-angle bends and tributaries that merge at right-angles. They form when the channels exploit orthogonal jointing in the bedrock [45]. Trellis networks resemble a garden trellis with numerous short tributaries joining irregular main streams. This network type develops in fold-and-thrust belts like the Appalachian Mountains [43,48]. Additional network types have also been identified for regions with very high relief [49]. Networks can often be classified by inspection because their differences are readily apparent to the eye, but quantitative methods have also been developed to ensure objectivity [49–53]. The network type has been shown to affect the time of concentration of a watershed [54], but its impact on the UH remains unexplored.

Figure 1. An example channel network from the (a) dendritic, (b) pinnate, (c) trellis, (d) parallel, and (e) rectangular types. Black dots indicate the basin outlets.

The objectives of this study are to determine: (1) whether the dendritic, parallel, pinnate, rectangular, and trellis network types exhibit distinct UHs, and (2) whether knowledge of the type provides enough information to replace explicit consideration of a basin's structure in UH determination. To accomplish these goals, 10 basins of each type are extracted from DEMs. Each grid cell within a basin is considered to be either a hillslope or a channel, and the flood wave travel time within each cell is calculated using the kinematic wave approximation. The required cell characteristics (e.g., channel slope and width) are estimated using approximations that are applied throughout the watershed. The UH is then determined as the PDF of total travel times from each cell to the basin outlet. This approach is an extension of the SDTT method proposed by [40] and relaxes the linearity assumption of traditional UH theory because the resulting UHs can vary with the rate of runoff production. More importantly, this approach isolates the effects of the flow path network into two random variables (one for the hillslopes and one for the channels). The distributions for these random variables are compared among network types without requiring specification of large numbers of basin characteristics. The distributions are also estimated from either the actual flow paths of each basin (following existing SDTT methods), the network type (which is the simplification being explored), or from average conditions among all basins (which is similar to traditional synthetic UH methods). Thus,

the benefit of considering the network type in UH estimation can be evaluated. Finally, these different UH approaches are applied to an example storm to examine the impacts on the resulting hydrographs.

2. Materials and Methods

2.1. Hillslope Travel Time Distribution

The flood wave travel time within a hillslope cell is based on an expression derived by [55], who applied the kinematic wave approach to a sloping plane where flow enters from the upslope and is generated locally by runoff. That derivation assumes that the duration of runoff exceeds the cell's time of concentration. If this expression is combined with Manning's equation and written for a hillslope cell at location j , it becomes:

$$\tau_{h,j} = \left(\frac{n_{h,j} L_j}{\sqrt{S_j}} \right)^{0.6} E_j^{-0.4} \left[(\lambda_{flow,j} + 1)^{0.6} - (\lambda_{flow,j})^{0.6} \right], \quad (1)$$

where $\tau_{h,j}$ is the travel time for hillslope cell j , $n_{h,j}$ is Manning's roughness coefficient, L_j is the flow length in the cell, S_j is the slope, $\lambda_{flow,j}$ is the ratio of the flow entering from upslope to the flow that is produced within the plane, and E_j is the runoff rate. Although [55] calls E_j the net rainfall intensity, it is called runoff here because it could also represent the rate at which old water is released by the addition of new water (rainfall) in the cell. Whether the runoff is old or new water, it is assumed that any infiltration has already been removed, the runoff is spatially uniform, and the runoff travels on the ground surface.

The authors of [40] and [56] modified this expression for use in a SDTT method. The authors of [56] allowed the runoff to vary in time, but constrained it to be homogeneous in space, so it becomes E_i where i is an index for time. Thus, the possibility of partial area runoff production [57] is neglected. Because the runoff rate varies in time, the travel time varies in time and becomes $\tau_{h,i,j}$. In reality, $\lambda_{flow,j}$ also varies in time, but [56] made the approximation that $\lambda_{flow,j} = A_{up,j}/A$, where $A_{up,j}$ is the total area that is upslope of the grid cell and A is the area of the grid cell itself. This assumption has been made by others (e.g., [28,58]) and was evaluated in detail by [56], who found it to be a good approximation of full kinematic wave routing on hillslopes. Using these approximations, Equation (1) becomes:

$$\tau_{h,i,j} = \left(\frac{n_{h,j} L_j}{\sqrt{S_j}} \right)^{0.6} E_i^{-0.4} \left[\left(\frac{A_{up,j}}{A} + 1 \right)^{0.6} - \left(\frac{A_{up,j}}{A} \right)^{0.6} \right]. \quad (2)$$

Even though every grid cell has the same area A , L_j can vary between grid cells depending on whether flow occurs in the diagonal or cardinal directions of the DEM.

An expression can then be written for the total hillslope travel time ($T_{h,i,k}$) for flow that starts at any cell k in the basin and moves to the basin outlet:

$$T_{h,i,k} = \sum_{j \in \text{Hillslope}} \left(\frac{n_{h,j} L_j}{\sqrt{S_j}} \right)^{0.6} E_i^{-0.4} \left[\left(\frac{A_{up,j}}{A} + 1 \right)^{0.6} - \left(\frac{A_{up,j}}{A} \right)^{0.6} \right], \quad (3)$$

where the summation includes all hillslope cells on the path between cell k and the basin outlet. The total hillslope travel time is also equivalent to the time that the flood wave takes to move from point k to the channel network. Equation (3) indicates that the hillslope travel time depends on a variety of local characteristics. To simplify the model and isolate the impact of the flow path structure, three approximations are implemented. First, variation in the local flow length is neglected by replacing L_j with L , which is an effective flow length in the cell. Assuming that flow directions are equally likely to occur in all cardinal and diagonal directions, that effective length is the average of the cardinal and diagonal flow lengths of the grid cells ($L = 0.5(1 + \sqrt{2})A^{0.5}$). Second, all hillslope cells are assumed to have the same roughness n_h , which is frequently assumed when applying similar models due to data

limitations (e.g., [40,56,59]). Third, all hillslope cells are assumed to have the same effective slope S_h . In reality, most basins tend to have convex-up hillslopes due to slope-dependent transport processes such as rain splash, bioturbation, and soil creep [60–62]. However, planar hillslopes are a common assumption in many similar models (e.g., [40,59]). Using these approximations, the total hillslope travel time becomes:

$$T_{h,i,k} = E_i^{-0.4} n_h^{0.6} S_h^{-0.3} L^{-0.4} \sum_{j \in \text{Hillslope}} L \left[\left(\frac{A_{up,j}}{A} + 1 \right)^{0.6} - \left(\frac{A_{up,j}}{A} \right)^{0.6} \right]. \quad (4)$$

To simplify the notation, the constant basin properties are collected into a single hillslope coefficient $m_h \equiv n_h^{0.6} S_h^{-0.3} L^{-0.4}$. In addition, the summation in Equation (4) is defined as $A_{sh,k}$ where the subscript k is included because each location has a different path to the outlet and thus a different value for that summation. Substituting these variables into Equation (4), it becomes:

$$T_{h,i,k} = E_i^{-0.4} m_h A_{sh,k}. \quad (5)$$

One can consider $A_{sh,k}$ as the outcome (for location k) of a random variable A_{sh} . The variable A_{sh} probabilistically describes the collection of $A_{sh,k}$ values that occurs within the basin. The meaning of A_{sh} can be elucidated by considering a simplified case. If one neglects the contribution of upslope cells (i.e., $A_{up,j} = 0$ in Equation (4)), then the distribution of A_{sh} reduces to the distribution of hillslope travel distances in the basin. In the more general case, the distribution of A_{sh} is a hillslope travel distance distribution that is modified to account for upslope flow contributions.

It is assumed that the random variable A_{sh} is described by the Johnson Special Bounded (SB) distribution (this assumption is evaluated later). This distribution is related to the normal distribution, which is associated with sums [63,64], and $A_{sh,k}$ is a sum as shown in Equation (4). The Johnson SB PDF is written as:

$$f(A_{sh}) = \frac{\delta_h \lambda_h}{\sqrt{2\pi} (A_{sh} - \xi_h) (\lambda_h - A_{sh} + \xi_h)} \exp \left\{ -\frac{1}{2} \left[\gamma_h + \delta_h \ln \left(\frac{A_{sh} - \xi_h}{\lambda_h - A_{sh} + \xi_h} \right) \right]^2 \right\}, \quad (6)$$

where γ_h is a shape parameter that primarily controls the skewness, and δ_h is a second shape parameter that primarily controls the kurtosis. ξ_h and λ_h are the location and scale parameters, respectively. If the network type impacts the UH (the central hypothesis of this study), then the distribution parameters γ_h , δ_h , ξ_h , and λ_h depend on the network type. It is also expected that they depend on maximum upslope area that is observed among all hillslope cells A_{hmax} (i.e., the size of the hillslopes). These assumptions and the nature of any such dependence are examined later.

2.2. Channel Travel Time Distribution

A similar approach is used for the travel time distribution for the channels. The flood wave travel time in a channel cell is based on an expression derived by [65], who considered a wide rectangular channel with flow entering from both upstream and laterally under the kinematic wave approximation. If the equation in [65] is applied to a channel cell at location j , it can be written as:

$$\tau_{c,j} = L_j \left(\frac{n_{c,j}}{\sqrt{S_j}} \right)^{0.6} W_j^{0.4} \left[\frac{Q_{down,j}^{0.6} - Q_{up,j}^{0.6}}{Q_{down,j} - Q_{up,j}} \right], \quad (7)$$

where $\tau_{c,j}$ is the travel time in the channel cell j , L_j is the length of the channel in the cell, $n_{c,j}$ is Manning's roughness coefficient, W_j is the channel width, $Q_{down,j}$ is the flow at the downstream end of the cell, and $Q_{up,j}$ is the flow that is contributed to the cell from upstream. It is unlikely that the entire upstream area simultaneously contributes flow to a channel cell for storms with realistic durations (unlike hillslopes, which drain relatively small areas). Following [66], it is assumed that

only a constant fraction r of the upstream area contributes flow simultaneously. Thus, $Q_{up,j} = rE_i A_{up,j}$ and $Q_{down,j} = rE_i (A_{up,j} + A)$ if runoff is spatially homogeneous. In reality, r is expected to vary in time during a storm [38]. An expression can then be written for the total channel travel time from a cell k in the basin to the outlet $T_{c,i,k}$:

$$T_{c,i,k} = \sum_{j \in \text{Channel}} L_j \left(\frac{n_{c,j}}{\sqrt{S_j}} \right)^{0.6} \left(\frac{W_j}{rE_i} \right)^{0.4} \left[\frac{(A_{up,j} + A)^{0.6}}{A} - A_{up,j}^{0.6} \right], \quad (8)$$

where the summation includes all channel cells on the path between cell k and the outlet.

Several approximations are implemented to isolate the effect of the network structure. Local variations in cell flow lengths are again neglected by replacing L_j with L , and all channel cells are assumed to have the same roughness n_c . In addition, the channel slope is assumed to depend on the contributing area according to a power function $S_j = b(A_{up,j} + A)^{-\theta}$ where b and θ are constants that can vary among basins [67–71]. The coefficient b is related to the vertical relief of the basin, while θ describes the concavity of the longitudinal profiles of the channels. The slope-area relationship describes the average slope at a given contributing area, but much variation typically occurs around this average value [70,72,73]. In addition, deviations from a power function can also occur [74]. Such complexities are neglected here. Finally, the channel width is also assumed to depend on the contributing area according to a power function $W_j = d(A_{up,j} + A)^e$ where d and e are constants that can vary between basins. Such a dependence has been observed empirically [68,75–77] and has been used in other models [38]. Using these simplifications in Equation (8), one obtains:

$$T_{c,i,k} = E_i^{-0.4} n_c^{0.6} r^{-0.4} b^{-0.3} d^{0.4} A^{0.3\theta+0.4e-0.4} \sum_{j \in \text{Channel}} L \left(\frac{A_{up,j}}{A} + 1 \right)^{0.3\theta+0.4e} \left[\left(\frac{A_{up,j}}{A} + 1 \right)^{0.6} - \left(\frac{A_{up,j}}{A} \right)^{0.6} \right]. \quad (9)$$

To simplify the notation, the constants in front of the summation are collected into a single channel coefficient $m_c \equiv r^{-0.4} n_c^{0.6} b^{-0.3} d^{0.4} A^{0.3\theta+0.4e-0.4}$, and the summation in Equation (9) is defined as $A_{sc,k}$. Using these definitions, Equation (9) can be written:

$$T_{c,i,k} = E_i^{-0.4} m_c A_{sc,k}. \quad (10)$$

The variable $A_{sc,k}$ is viewed as the outcome for location k of a random variable A_{sc} . If upstream flows were neglected (i.e., $A_{up,j} = 0$ in Equation (9)), then the distribution of A_{sc} would describe the distribution of channel travel distances within the basin, which is essentially the basin's width function. Thus, the distribution of A_{sc} can be viewed as a modified width function that accounts for upstream flow.

It is assumed that A_{sc} is described by the Johnson SB distribution, which can be written as:

$$f(A_{sc}) = \frac{\delta_c \lambda_c}{\sqrt{2\pi}(A_{sc} - \xi_c)(\lambda_c - A_{sc} + \xi_c)} \exp \left\{ -\frac{1}{2} \left[\gamma_c + \delta_c \ln \left(\frac{A_{sc} - \xi_c}{\lambda_c - A_{sc} + \xi_c} \right) \right]^2 \right\}, \quad (11)$$

where γ_c and δ_c are the shape parameters, ξ_c is the location parameter, and λ_c is the scale parameter. If the network type affects the UH, then the parameters γ_c , δ_c , ξ_c , and λ_c depend on the network type. These parameters are also expected to depend on the maximum upstream area for any channel cell $A_{\max}$ (i.e., the size of the basin). The choice of distribution and any dependence of the parameters on the network type will be evaluated later.

2.3. Total Travel Time Distribution

The total travel time from an arbitrary point k to the outlet ($T_{i,k}$) is the sum of the hillslope and channel travel times from that point, so one can write:

$$T_{i,k} = T_{h,i,k} + T_{c,i,k} = E_i^{-0.4} (m_h A_{sh,k} + m_c A_{sc,k}). \quad (12)$$

To simplify the notation, the time-invariant portion of the overall travel time is defined as $X_k \equiv m_h A_{sh,k} + m_c A_{sc,k}$. The PDF for X can be determined by a convolution assuming that $m_h A_{sh,k}$ and $m_c A_{sc,k}$ are independent. The hillslope size is typically similar irrespective of the hillslope's position in the basin [78], so the hillslope and channel travel times from a point to the outlet are expected to be independent [4]. Because an analytical solution for this convolution is not known, the convolution is performed numerically:

$$f_X(n\Delta X) = \sum_{l=0}^n f_{m_h A_{sh,k}}(l\Delta X) f_{m_c A_{sc,k}}(n\Delta X - l\Delta X), \quad (13)$$

where n is the number of discrete increments of X used in the numerical evaluation, ΔX is the size of the increment, and l is an index for those increments. Finally, the instantaneous UH (IUH) associated with runoff rate E_i can be found from the PDF of T_i , which is:

$$f_{T_i}(T_i) = E_i^{0.4} f_X(E_i^{0.4} T_i). \quad (14)$$

The IUH varies in time because E_i varies in time. The UH $U_i(t)$ for runoff rate E_i can then be calculated as [40]:

$$U_i(t) = \frac{1}{\Delta t} \int_{t-\Delta t}^t f_{T_i}(T_i) dT_i, \quad (15)$$

where Δt is the runoff time step. Stormflow hydrographs can then be calculated by a convolution of the runoff values and the associated UHs, as described by [41].

In summary, this modeling approach isolates the effect of the drainage network structure into the random variables A_{sh} and A_{sc} , which are modifications of the travel distance distributions that also account for the effects of upstream flow on the travel times. For a given basin, the PDFs for A_{sh} and A_{sc} can be calculated without prior specification of most basin characteristics (L , θ , and e are required). Thus, within the presented framework, they allow the most direct and general assessment of impact of the network structure on the IUH (with as few confounding effects as possible). We have hypothesized that the parameters that determine the PDFs for A_{sh} and A_{sc} can be found based on the network type as well as A_{hmax} and A_{max} . The distributions of A_{sh} and A_{sc} can be transformed into a time-varying IUH using the following basin properties as inputs: n_h , S_h , n_c , r , b , d , θ , and e .

2.4. Application

The presented UH framework is applied to 10 basins from each of the five network types. Based on inspection of satellite photos and available imperviousness data (see Supplementary Materials), all the basins have little human development and no obvious human alteration of the channel network. Nearly all the basins were originally processed by [53]. They chose each outlet to ensure that the associated basin exhibits a single network type (i.e., the outlets do not correspond to stream gauge locations). In their collection, however, Buckeye Run, WV (dendritic) and Stony Run, WV (trellis) are sub-basins within other included basins. Furthermore, Hill Creek, UT (parallel) does not strongly exhibit parallel characteristics. Thus, these three basins were replaced with Rockcastle Creek, KY (dendritic), Penn's Creek, PA (trellis), and Mancos River Tributary, CO (parallel). The new basins were selected from regions where the networks had been previously classified with a quantitative method [54]. The new basins were processed in the manner used by [53] for the other basins. Specifically, the TauDEM

toolbox for ArcGIS was used to fill pits, determine flow directions (according to the D8 algorithm), and calculate upslope/upstream areas and slopes [79–81]. The computed travel time can be infinite in a cell if the local slope is zero. Thus, any zero slope was replaced by the lesser of (1) the resolution of the calculated slope (which is estimated as 1 m divided by the DEM grid cell length) or (2) 0.8 times the minimum nonzero slope present in the processed DEM.

A cell is considered to contain a channel if the contributing area exceeds a selected threshold. Montgomery [82] divided the slope-area plot into five geomorphic zones (hillslopes, valley heads, colluvial channels, bedrock channels, and alluvial channels), and we evaluated two thresholds based on these zones. The first threshold separates the valley heads and colluvial channels, and the second distinguishes the colluvial and bedrock channels. The presented results use the second threshold because it avoids producing unrealistic adjacent, parallel channels at small contributing areas (the results when the first threshold is used are discussed later).

Basic characteristics for the 50 basins are summarized in Table 1. Additional general properties of the basins are provided in the Supplementary Materials. The pinnate basins tend to be larger than the other types with an average area of 1014 km². The parallel and rectangular basins are the smallest with average areas of 217 km² and 254 km², respectively. The DEM resolution depends on the DEM source. It is coarsest (on average 76.4 m) for pinnate basins in Ukraine and Moldova, for which the Shuttle Radar Topography Mission (SRTM) provided data at a resolution of 3 arc seconds. The other network types have an average resolution of 27 m. The channel threshold area (which also determines A_{hmax}) is largest for pinnate basins (on average 688,560 m²) and smallest for dendritic and parallel basins (on average 53,720 m² and 76,850 m², respectively).

Table 1. Basin areas and channel threshold areas for the 50 analyzed basins. The thresholds are identified between the colluvial and bedrock channel segments in the slope-area plots.

	Basin Name	Basin Area (km ²)	Channel Threshold Area (m ²)	Basin Name	Basin Area (km ²)	Channel Threshold Area (m ²)
Dendritic	Bluestone, WV	324	33,300	Rockcastle, KY	314	53,400
	Buffalo, WV	419	56,000	Tenmile, PA	512	95,500
	Captina, OH	460	29,200	Turkey, SC	625	63,000
	Cedar, GA	219	115,500	Tygarts, KY	291	79,100
	Little Saluda, SC	565	102,900	Wheeling, WV	739	36,500
Parallel	Albert, WY	439	57,400	Piceance 1, CO	156	70,600
	Black Sulphur, CO	266	73,300	Piceance 2, CO	74	47,600
	Duck, CO	142	80,300	Sheep, WY	487	215,100
	Greasewood, CO	61	65,200	Willow, UT	350	55,400
	Mancos River, CO	113	133,100	Yellow, CO	85	110,000
Pinnate	Dniester 1, UKR	2114	1,037,900	Dniester 6, UKR	761	1,045,100
	Dniester 2, UKR	1356	488,500	Nistru 1, MDA	697	639,400
	Dniester 3, UKR	1005	707,800	Nistru 2, MDA	589	758,400
	Dniester 4, UKR	1573	540,300	Nistru 4, MDA	723	614,600
	Dniester 5, UKR	967	706,700	Nistru 5, MDA	350	983,800
Rectangular	Boquet, NY	241	108,500	Salmon, NY	495	146,200
	Boreas, NY	218	250,500	Schroon, NY	239	172,300
	Cold, NY	218	104,300	Summer, NY	147	88,900
	Hudson, NY	198	239,700	Walker, NY	133	198,400
	Saint Regis, NY	344	124,600	W. St. Regis, NY	304	116,100
Trellis	Aughwick, PA	823	141,700	Juniata, PA	539	62,700
	Cacapon, WV	865	125,100	Middle, PA	219	166,300
	Chestuee, TN	339	54,300	Penns, PA	480	956,900
	Evitts, MD	240	168,600	Peters, WV	609	59,600
	Jackson, VA	251	116,300	Sleepy, WV	294	51,500

3. Results

3.1. Distributions of A_{sh} and A_{sc}

In order to calculate A_{sc} values within any basin, values must be selected for the flow length in each DEM cell L , the width-area exponent e , and the slope-area exponent θ . L was set based on the

DEM resolution of each basin under consideration, and e was assigned a typical value of 0.5 for all basins [82]. Because θ might depend in part on the network type, it was calculated from the slope-area plot of each basin. The value of θ for each basin is provided in the Supplementary Materials. θ has averages of 0.37, 0.43, 0.35, 0.38, and 0.39 for the dendritic, parallel, pinnate, rectangular, and trellis types, respectively.

Before comparing the distributions of A_{sh} and A_{sc} between network types, it is necessary to examine whether the Johnson SB distribution is appropriate. Twenty-four theoretical distributions were identified as candidates to describe A_{sh} and A_{sc} based on their general properties (e.g., the existence of a lower bound). The parameters of each distribution were estimated for each basin using Easyfit version 5.6, which selects the parameter estimation method (method of moments, L-moments, maximum likelihood, or least squares) according to the distribution type. The fit of each distribution was then measured using the Kolmogorov-Smirnov (K-S) statistic, which is the maximum deviation between the sample cumulative distribution function (CDF) (i.e., determined directly from the DEMs) and the theoretical CDF [83,84]. The K-S statistic is not compared to a critical value in a hypothesis test because the observations of A_{sh} and A_{sc} are not independent due to the nested structure of the drainage networks. Thus, they violate the assumptions required to perform such a test [83,85]. Because the candidate distributions have different numbers of parameters, the Akaike Information Criterion (AIC), as formulated by [86], was also used to assess the fit of each distribution while accounting for the number of parameters and possible overfitting.

The K-S statistics for the four best-fitting distributions for A_{sh} and A_{sc} are plotted for all basins in Figure 2. The four best-fitting distributions for A_{sh} are the generalized extreme value, three-parameter Weibull, four-parameter generalized gamma, and Johnson SB (Figure 2a). Overall, the Johnson SB distribution fits the observations of A_{sh} best with an average K-S statistic of 0.014. Among the considered distributions, it also produces the lowest average K-S statistic for each type except rectangular. Furthermore, the Johnson SB distribution produces the best AIC values for 31 of the 50 basins. The Weibull distribution produces the best AIC values for the remaining basins. Overall, these results suggest that the Johnson SB distribution is the best choice for representing A_{sh} and that the use of a four-parameter distribution is warranted.

The four best-fitting distributions for A_{sc} are the generalized extreme value, PERT, four-parameter generalized gamma, and Johnson SB distributions (Figure 2b). On average, the Johnson SB distribution fits the observed CDFs of A_{sc} best with an average K-S statistic of 0.023. The Johnson SB distribution also exhibits the best average performance for each network type. The Johnson SB distribution produces the best AIC values for 26 of the 50 basins (the four-parameter generalized gamma distribution produces the best AIC values for many of the remaining basins). Overall, these results suggest that the Johnson SB distribution is also the best choice for representing A_{sc} .

Figure 3 compares the distributions of A_{sh} and A_{sc} for an example basin of each type. The A_{sh} distributions always have positive skewness, but the degree of peakedness and skewness varies between the network types. Specifically, the rectangular and trellis basins have more apparent peaks and skewness than the other types. In all cases, the Johnson SB distribution fits the histograms well. The A_{sc} distributions also differ substantially between the five basins. Notably, the A_{sc} distribution has negative skewness for the dendritic and parallel basins. It is nearly symmetrical for the trellis basin and has positive skewness for the pinnate and rectangular basins. The Johnson SB distribution fits histograms well, but it misses local fluctuations in some of the histograms.

Figure 2. Kolmogorov-Smirnov (K-S) statistics for the four best fitting distributions for (a) A_{sh} and (b) A_{sc} . DEN denotes dendritic, PAR denotes parallel, PIN denotes pinnate, REC denotes rectangular, and TRE denotes trellis.

Figure 4 plots the calibrated Johnson SB distribution parameters for A_{sh} against A_{hmax} for all 50 basins. The shape parameters δ_h and γ_h and the location parameter ξ_h appear to be independent of A_{hmax} and relatively constant within each type. However, differences are observed in the parameter values for different types. For example, rectangular and trellis basins tend to have higher δ_h and γ_h values than the other network types. Higher δ_h values produce more peaked distributions, and higher γ_h values produce greater skewness. Thus, these results confirm that the differences observed earlier for the example basins are typical for the network types. The scale parameter λ_h depends on A_{hmax} (Figure 4), and this dependence appears to differ between types. Most notably, the pinnate and trellis basins have steeper relationships than the other types. The relationships can be approximated by power functions (a power function is preferable to a linear function because it always passes through the origin as expected for both A_{sh} and A_{sc}). The dependence of the A_{sh} distribution parameters on network type is interesting because the type is based on the channel network structure not the hillslope flow paths. These results suggest a connection between the flow path structure on the hillslopes and the channels.

Figure 3. Histograms and fitted Johnson SB distributions for A_{sh} (a–e) and A_{sc} (f–j) for an example basin of each type. The basins are the same as those in Figure 1.

Figure 4. Parameters (a) δ_h , (b) γ_h , (c) ξ_h , and (d) λ_h of the Johnson SB distribution for A_{sh} plotted against the maximum hillslope area A_{hmax} . The symbols show the calibrated parameter values for each basin. The horizontal lines in (a–c) show the average parameter value for each network type. The lines in (d) show power functions fitted to the λ_h values for each network type.

Figure 5 plots the Johnson SB parameters for A_{sc} against A_{max} . The shape parameters δ_c and γ_c and the location parameter ξ_c appear to be independent of A_{max} . δ_c does not appear to differ between the network types, but the skewness-related parameter γ_c appears to differ. Dendritic and parallel basins have negative γ_c values, while pinnate basins have positive γ_c values (which is consistent with the example basins in Figure 3). The scale parameter λ_c varies with A_{max} , and the observed relationships can be approximated with power functions. The power functions may differ between certain network types. Specifically, the power function for pinnate basins is much higher than the power function for rectangular basins.

Figure 5. Parameters (a) δ_c , (b) γ_c , (c) ξ_c , and (d) λ_c of the Johnson SB distribution for A_{sc} plotted against the maximum upstream area A_{max} . The symbols show the calibrated parameter values for each basin. The horizontal lines in (b–c) show the average parameter value for each network type. The lines in (d) show power functions fitted to the λ_c values for each network type.

To determine whether the differences in the distribution parameters for A_{sh} and A_{sc} are statistically significant, an analysis of variance (ANOVA) was employed for the parameters that are independent of A_{hmax} and A_{max} . Specifically, a one-way ANOVA method was used for unadjusted pairwise comparisons between network types [87] with a 90% confidence interval (p -value = 0.1). Similarly, an analysis of covariance (ANCOVA) was used to determine whether the coefficients and exponents of the power functions are significantly different between types [88]. For λ_h , the power function is:

$$\lambda_h = \lambda_{hcoef} A_{hmax}^{\lambda_{hexp}}, \quad (16)$$

where $\lambda_{h\text{coef}}$ and $\lambda_{h\text{exp}}$ are the fitted coefficient and exponent, respectively. The power function for λ_c is the same but uses the coefficient $\lambda_{c\text{coef}}$ and exponent $\lambda_{c\text{exp}}$. The ANCOVA analysis was performed by first taking the logarithms of the variables involved and examining whether the intercepts and slopes of the resulting linear relationships are different.

For A_{sh} , all 10 pairs of network types have at least one parameter that is significantly different (Table 2). Thus, the differences that were identified visually in Figure 4 are consistent enough between types to be significant. For A_{sc} , eight out of 10 pairs of network types have at least one parameter that is significantly different (Table 2). Most commonly, the different parameter is γ_c , which is associated with skewness. In contrast, never differs between types. Fewer parameters are significantly different for A_{sc} than A_{sh} because the parameters for A_{sc} tend to be more variable within a given network type. Overall, these results confirm that the distributions for A_{sh} and A_{sc} are different between the five network types.

Table 2. Distribution parameters that exhibit significant differences between the network types based on the analysis of variance (ANOVA) and analysis of covariance (ANCOVA) tests. For each pairing of network types, the top row reports parameters for A_{sh} , and the bottom row reports parameters for A_{sc} .

Network Type	Parallel	Pinnate	Rectangular	Trellis
Dendritic	γ_h ξ_c	$\delta_h, \xi_h, \lambda_{h\text{coef}}, \lambda_{h\text{exp}}$ $\gamma_c, \xi_c, \lambda_{c\text{coef}}$	$\delta_h, \gamma_h, \xi_h$ $\gamma_c, \xi_c, \lambda_{c\text{coef}}$	$\delta_h, \gamma_h, \xi_h$ γ_c, ξ_c
Parallel		ξ_h γ_c	$\delta_h, \gamma_h, \xi_h$ γ_c	$\delta_h, \gamma_h, \xi_h, \lambda_{h\text{coef}}, \lambda_{h\text{exp}}$ -
Pinnate			δ_h, γ_h γ_c	$\delta_h, \gamma_h, \xi_h, \lambda_{h\text{coef}}, \lambda_{h\text{exp}}$ γ_c
Rectangular				$\xi_h, \lambda_{h\text{coef}}, \lambda_{h\text{exp}}$ -

Table 3 provides the average values of δ_h , γ_h , and ξ_h for each network type (and average values for all basins combined). It also provides the coefficient and exponent of the power function that estimates λ_h from $A_{h\text{max}}$ for each type (and a fitted power function for all basins combined). Equivalent information is provided for γ_c , ξ_c , and λ_c , but only an overall average value is provided for δ_c because this parameter does not vary significantly between types.

Table 3. Estimated parameters of the Johnson SB distribution for A_{sh} (left) and A_{sc} (right).

Type	δ_h	γ_h	ξ_h	$\lambda_{h\text{coef}}$	$\lambda_{h\text{exp}}$	δ_c	γ_c	ξ_c	$\lambda_{c\text{coef}}$	$\lambda_{c\text{exp}}$
Dendritic	0.991	0.654	−1.8	16	0.204	-	−0.533	−1339	398	0.579
Parallel	1.036	0.881	−3.9	76	0.081	-	−0.288	−556	1256	0.381
Pinnate	1.069	0.711	−13.7	15	0.255	-	0.352	−479	4579	0.244
Rectangular	1.300	1.300	−14.0	258	0.006	-	−0.011	−341	5687	0.088
Trellis	1.296	1.567	−11.2	14	0.256	-	−0.081	−533	1203	0.414
All	1.138	1.023	−8.9	3	0.373	0.982	−0.112	−649	668	0.504

We next evaluate the reliability of estimating the distributions for A_{sh} and A_{sc} from the network type (as well as $A_{h\text{max}}$ and A_{max}). To make this assessment, the K-S statistic is calculated when the distributions for A_{sh} and A_{sc} are estimated by three methods. In Method 1, the distribution parameters are determined directly from the A_{sh} and A_{sc} distributions for each basin (i.e., using the values shown in Figures 4 and 5). In Method 2, they are estimated from the network type (using the values for each type in Table 3). In Method 3, they are estimated without consideration of the network type (using the values for all basins combined in Table 3).

Comparing Methods 3 and 2 for A_{sh} , 44 of the 50 basins have improved accuracy (lower K-S statistics) when the network type is included (Figure 6a). The average K-S statistic across all basins

is 0.095 for Method 3 and 0.037 for Method 2. The improvement occurs for all types but is smallest for trellis networks. Thus, considering the network type provides much better estimates of the A_{sh} distribution than neglecting the network type. Comparing Methods 2 and 1 for A_{sh} , the K-S statistics are relatively similar (the average K-S statistic is 0.014 for Method 1). However, Method 1 provides better K-S statistics for trellis basins. Thus, the network type provides adequate information for estimating the distribution of A_{sh} for most types, but explicit consideration of the individual basins is needed for trellis networks.

Figure 6. Kolmogorov-Smirnov (K-S) statistics for the Johnson SB distribution for (a) A_{sh} and (b) A_{sc} when the distribution parameters are estimated separately for each network (Method 1), based on network type (Method 2), and neglecting network type (Method 3).

For A_{sc} , 31 of the 50 basins have improved accuracy (lower K-S statistics) when the network type is included (comparing Methods 3 and 2), but the overall improvement is small (Figure 6b). The average K-S statistic is 0.231 for Method 3 and 0.190 for Method 2. The improvement is greatest for parallel and pinnate basins. Using Method 2 for parallel basins, the K-S value is reduced by a third, while the

value is halved for pinnate basins. For dendritic basins, almost no improvement is observed. Dendritic basins are expected to exhibit the highest degree of variability in their network structures because they develop without strong topographic or lithologic constraints. The K-S statistics for Method 1 are typically much lower than those of Method 2 (the average K-S statistic for Method 1 is 0.023). The only case where the distribution of A_{sc} can be accurately estimated from the network type instead of the individual network is pinnate.

3.2. IUHs

Four cases are used to compare the IUHs between network types and between different estimation methods. Case 1 explicitly considers the individual cell slopes and the actual flow paths for each basin (i.e., the travel times are based on Equations (3) and (8)). This method is equivalent to a pre-existing nonlinear SDTT method [41] and is considered the best estimate of the IUH for each basin. Case 2 replaces the individual cell slopes with S_h (for hillslopes) and the slope-area relationship (for channels), and it replaces the actual distributions of A_{sh} and A_{sc} with a theoretical distribution that is calibrated for each basin (i.e., the travel times are based on Equations (4) and (9)). The case continues to use the distribution parameters that were obtained from each individual basin. This case evaluates the assumptions that allow the network structure to be isolated in the variables A_{sh} and A_{sc} . Case 3 instead estimates the distribution parameters based on the network type. This is a synthetic UH method that uses the network type to infer the flow path configuration. Case 4 estimates the parameters of the theoretical distributions irrespective of the network type. This case is analogous to traditional synthetic UH methods that neglect consideration of an individual basin's network structure.

For this comparison, most of the parameters were set to constant values for all 50 basins (Table 4). This approach reduces confounding effects under the assumption that these parameters are independent of the network type. The selected roughness for the hillslopes n_h corresponds to short-grass prairie [89], and the roughness for channels n_c corresponds to a low-slope stream with weeds and stones or a mountain stream with cobbles and boulders [90]. The fraction of area contributing flow r falls within the range for humid to arid climates (0.2 to 0.5) [66]. The width-area coefficient d is a typical value [82]. The b value varies between basins and might be associated with the network type, so it is estimated from the slope-area plot from each basin's DEM. For Cases 2 through 4, S_h was estimated as the average hillslope slope from the DEM of each basin because it might also depend on the network type. For consistency, A was set based on the DEM resolution of each basin under consideration. The values of b , S_h , and A for each basin are provided in the Supplementary Materials.

Table 4. Model parameters used in the development of the instantaneous unit hydrographs. Parameters that vary are determined from the digital elevation model for each basin.

Parameter	Value	Units
Channel roughness (n_c)	0.05	s/m ^{1/3}
Hillslope roughness (n_h)	0.15	s/m ^{1/3}
Grid cell area (A)	Varies	m ²
Slope of hillslopes (S_h)	Varies	m/m
Slope-area factor (b)	Varies	m ^{-2θ}
Slope-area exponent (θ)	Varies	-
Channel width factor (d)	0.02	m ^{1-2e}
Channel width exponent (e)	0.5	-
Fraction of area contributing (r)	0.3	m ² /m ²
Runoff rate (E_i)	25.4	mm/h

The IUHs from Case 1 exhibit notable differences between the example basins of each type (Figure 7). The IUH for the dendritic basin is negatively skewed, the IUH for the pinnate basin is positively skewed, and the IUHs for the other basins are approximately symmetrical. Comparing Figure 7 to the right column in Figure 3, one sees that the IUH shapes are almost identical to the

distributions of A_{sc} for the same basins. The A_{sc} distributions play a much larger role than the A_{sh} distributions in determining the IUHs because 80% or more of the total travel time occurs in the channels.

Figure 7. Instantaneous unit hydrographs (IUHs) estimated by the four methods described in the legend for an example basin of the (a) dendritic, (b) parallel, (c) pinnate, (d) rectangular, and (e) trellis types. The basins are the same as those in Figure 1.

When the slopes are approximated and the theoretical distribution is used (Case 2), the IUHs remain similar to Case 1, but the local fluctuations in the IUHs are lost (Figure 7). For the pinnate and trellis basins, the IUHs for Case 2 also shift to the right. The travel times depend nonlinearly on slope, so using the average slope for a given contributing area is not equivalent to using the distribution of slopes for that contributing area. When the network type is used to estimate the IUH (Case 3), the IUH for the pinnate basin remains very close to Case 2 while the other basins deviate more. This result is consistent with the earlier results that showed the distributions of A_{sc} are best estimated from the network type for the pinnate case. Case 4, which neglects the network type, has approximately zero skewness and is a poor match for the IUHs from Case 1 for all basins shown.

Four metrics are used to quantify the difference in performance between the network-type-based method (Case 3) and the case that neglects the type (Case 4) for all 50 basins (Figure 8). The first metric is the Root Mean Squared Error (RMSE) [91,92] where Case 1 is considered the observed IUH (Figure 8a). The second metric is the Nash-Sutcliffe Coefficient of Efficiency (NSCE) [93]. Because larger NSCE values indicate better performance (in contrast with the other metrics), Figure 8b instead shows 1-NSCE so that lower values indicate better performance. The third metric is the absolute error in the IUH peak value (Figure 8c), and the fourth metric is the absolute error in the time of the IUH peak (Figure 8d).

Figure 8. Performance metrics when the instantaneous unit hydrographs are estimated by either including or neglecting the network type as indicated in the legend. Column heights indicate the average performance and black bars indicate the range of performance for each case.

By most measures, considering the network type provides little improvement in the estimated IUH. For time to peak, however, considering the type improves the average performance for all types and reduces the range in performance for all types except trellis. This improvement occurs because the network type helps determine the skewness of the IUH as seen in Figure 7. Considering the type also provides an improvement in performance by all measures for parallel and pinnate basins. However, by most measures, pinnate has lower errors when the type is considered than the other network types. This result occurs because the pinnate type is an adequate substitute for the individual flow path network when estimating the distributions of A_{sh} and A_{sc} .

The RMSEs for Case 3 were also calculated when the assumed parameter values were varied from those in Table 4 (not shown). Overall, the RMSE decreases when the hillslope roughness n_h increases, the channel roughness n_c increases, the width-area coefficient d increases, the slope-area coefficient b decreases, the fraction of area contributing flow r decreases, the runoff E_i decreases, and the linear reservoir constant K increases. It remains almost unchanged as the average hillslope slope S_h changes. These results are explained in depth by [94,95].

3.3. Hydrographs

In this section, we consider whether the differences in the IUHs that were observed in the previous section produce meaningful differences in the response to a storm. Specifically, a 6-h SCS Type II storm with a total depth of 12.7 mm and an 18-min time step (5% of the storm duration) was applied to the example basins. For simplicity, all rainfall was assumed to become runoff (no losses were considered). The hydrologic response was then generated using the four IUH methods (i.e., Cases 1–4). To facilitate comparison between basins, the resulting discharge hydrographs were normalized by each basin's area to produce hydrographs for specific discharge q (Figure 9). Overall, the hydrographs exhibit visual differences between the five basins, which suggests that the differences in the A_{sh} and A_{sc} distributions (and IUHs) between the network types can produce differences in the generated hydrographs. The results also suggest that the different IUH methods can produce visibly different hydrographs, including differences in the timing and magnitude of the peak value. If Case 1 is again considered the most accurate case, the IUH method that uses the network type (Case 3) usually provides a better approximation than the method that neglects any consideration of network structure (Case 4). However, the use of the actual flow paths (Case 2) provides a noteworthy improvement in the hydrograph over Case 3 in all cases except pinnate. Overall, these results are consistent with the IUH results presented earlier and demonstrate that the IUH differences produce meaningful differences in the storm hydrographs.

Figure 9. (a) Rainfall intensity for a 6-h SCS Type II storm and the resulting specific discharge hydrographs for an example basin of the (b) dendritic, (c) pinnate, (d) trellis, (e) parallel, and (f) rectangular types when the IUH is determined using the four methods described in the legend. The basins are the same as those in Figure 1.

4. Discussion and Conclusions

This study considered whether the dendritic, parallel, pinnate, rectangular, and trellis networks exhibit distinct UHs and whether knowledge of the network type provides sufficient information about the network structure for synthetic UH determination. Flood wave travel times were calculated based on a kinematic wave approach, and approximations were implemented to isolate the effects of the network structure into two random variables (A_{sh} and A_{sc}). The distribution of A_{sh} is similar to the distribution of hillslope travel lengths, but it accounts for the effects of upslope flow contributions on the travel time. The distribution of A_{sc} is similar to the width function, but it also includes the effects of upstream flow.

The distributions of A_{sh} are significantly different between the five network types. Because the types are determined from the channel network structure, this result suggests that the flow path structure on the hillslopes (which determines A_{sh}) is somehow associated with the channel network type. It is possible that the flow path structure on the hillslopes depends on the channel network configuration into which they flow or perhaps that the dominant hillslope processes are associated with the network types and control the hillslope flow paths.

The distributions of A_{sc} are also significantly different between the five network types. Most notably, the parameter that controls the skewness of the A_{sc} distribution differs between types. Dendritic and parallel basins have negative skewness (i.e., many large A_{sc} values), which is associated with abundant locations in the basin that are distant from the outlet (see examples in Figure 1). In contrast, pinnate basins have positive skewness (i.e., few large A_{sc} values), which is associated with fewer locations in the basin that are far from the outlet (see Figure 1). The other network types tend to have more symmetrical distributions for A_{sc} . The differences in the A_{sc} distributions are also observed in the associated IUHs. Overall, the results suggest that dendritic, parallel, pinnate, rectangular, and trellis networks have distinct UHs as hypothesized.

Using the network type produces better estimates of the A_{sh} distributions for individual basins than neglecting the type. For all types aside from trellis, the network type provides sufficient information to determine the A_{sh} distributions. For trellis, considering the type provides only modest improvements over neglecting it. Using the network type also produces better estimates of the A_{sc} distributions for individual basins than neglecting it. However, for all types except pinnate, knowledge of the type does not provide sufficient information to accurately estimate the A_{sc} distributions.

The proposed synthetic UH method, which estimates the distributions of A_{sh} and A_{sc} based on the network type, provides better estimates of the IUH time to peak than a method that neglects the type. This improvement occurs because the time to peak is affected by the skewness of the A_{sh} and A_{sc} distributions, which is different among the types. However, other measures of performance such as RMSE and NSCE usually show little improvement when network type is considered. The exceptions are parallel and pinnate, which show noteworthy improvement in all measures when the type is considered. By most measures, pinnate networks have lower errors than the other types.

Although not discussed in detail in this paper, the analyses were repeated for a medium and small sub-basin within each of the 50 large basins [95]. Those results suggest that the distinctions between the network types become less clear at small scales, so the value of the network type in UH determination decreases. We also repeated the analysis when the IUH is coupled with a linear reservoir similar to the Clark method. After applying the linear reservoir, all UHs became positively skewed. The distinctions between network types remained but became smaller. Finally, we repeated the analysis using a smaller area threshold for identifying the channel cells and found that the same qualitative conclusions hold.

Overall, the results suggest that considering network type provides some benefits over neglecting it. Thus, considering the network type may help hydrologists better understand the hydrologic behavior of a particular basin in comparison to other basins that have different network types. The distinctive hydrologic response a given network type may also help explain the geomorphic evolution of that network type. However, knowledge of the type is an adequate substitute for the actual flow path configuration only for pinnate basins. Thus, the results do not support the hypothesis that the network

type can provide sufficient information about the flow path structure for synthetic UH determination, except for pinnate networks. For pinnate networks, the typical network structure may provide enough information to make a detailed consideration of an individual network's structure unnecessary.

This research could be extended along several paths. First, the effects of misclassifying a network on the synthetic UH performance could be investigated because it might be difficult to classify some networks in practice. Second, the effect of the DEM resolution on the results could be studied. It is expected that finer resolutions would better characterize each network and thus may provide clearer differences between network types. Third, further examination of the hillslope travel time distributions is warranted. For example, it might be possible to relate the dominant hillslope processes to the travel time distributions on the hillslopes. The hillslope travel times are expected to become more important when smaller basins are modeled. Fourth, the assumption that a constant fraction of upstream area simultaneously contributes flow to channels could be further analyzed. A relationship between this fraction and the overall basin size could be considered. Similarly, the effects of other simplifying assumptions (the constant hillslope slope, the constant area threshold to distinguish hillslopes and channels, the power law slope-area relationship for the channels, etc.) could be examined because they might impact the results. Fifth, the assumption that runoff occurs uniformly across the basin and that the flow occurs on the ground surface could be relaxed to consider partial area runoff production and the distinction of old and new water. This change may affect the resulting hydrographs. Sixth, the impacts on urbanization on the hydrologic response of different network types could be examined. It is expected that impervious areas would change both the pattern of runoff production and the roughness, and the introduction of gutter and pipe systems might reduce the differences between the network types. Finally, the IUHs from the proposed method were evaluated by comparing to a pre-existing SDTT model that explicitly represents the slopes and flow paths within the basin. For pinnate basins where a network-type-based synthetic UH may be viable, future research should compare the results from the synthetic UH to observed hydrographs. Comparisons should also be made to UHs inferred from streamflow data. Such comparisons would also allow for testing other assumptions in the UH method, including the use of kinematic wave theory.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/12/3/669/s1>, Table S1: Summary of geomorphic properties for the 50 analyzed basins, Table S2: Summary of general properties for the 50 analyzed basins.

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