River routing tool using vector-type river network for water resource applications in the contiguous USA

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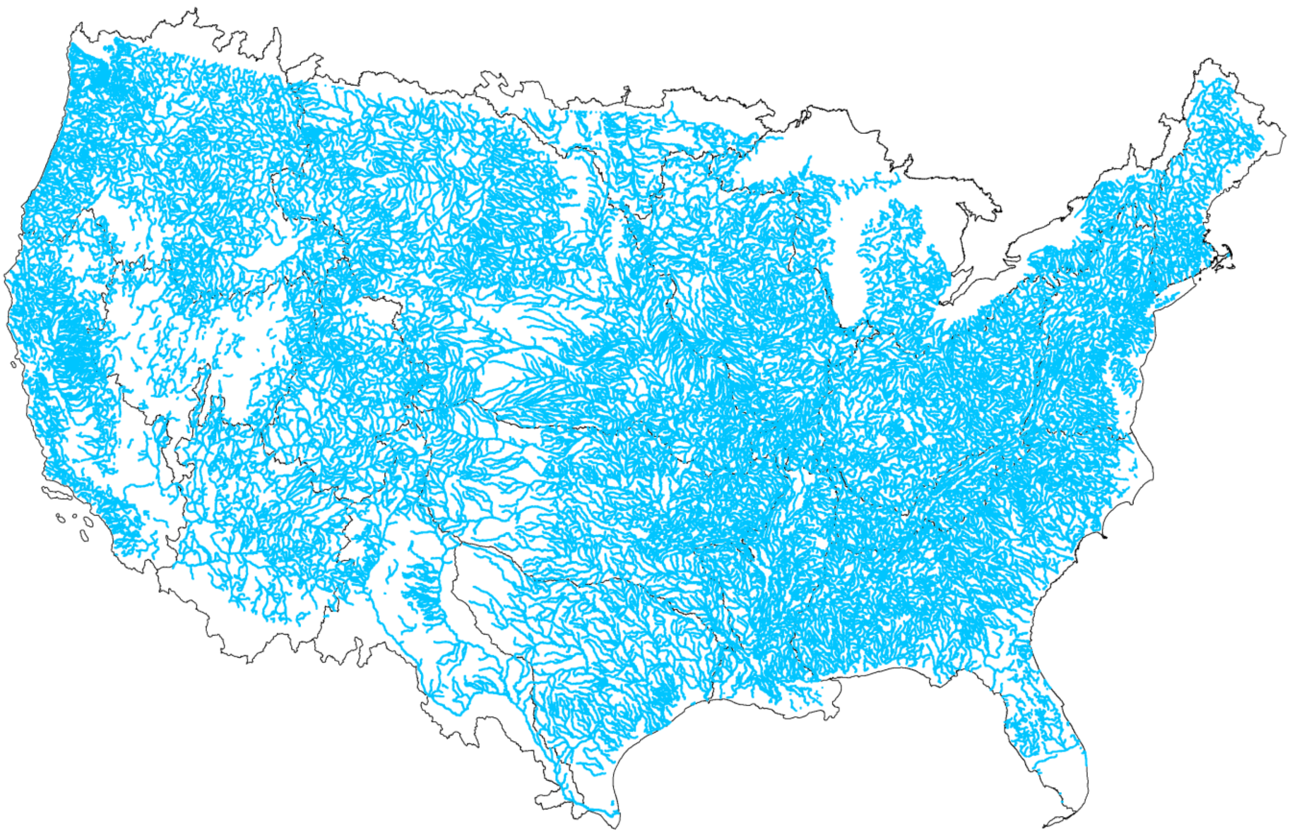

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Abstract

This technical note describes the applications of river routing tools that work at various spatial scales from headwater basin to continental-scale river system. The routing tool is used to post-process runoff simulated by distributed hydrologic models and land surface models. The routing tool utilizes the USGS Geospatial Fabric (GF) dataset which contains basin polygons defined as catchment Hydrologic Response Units (cHRU) and associated river segment information over the contiguous United States. We have augmented the GF to supplement all the parameters required for the routing tool, and these data are provided in the NetCDF file used as input to the routing tool. In this document, the capabilities of the routing scheme are illustrated at three different sized river basins and compared with the gridded routing scheme used in the Variable Infiltration Capacity (VIC) model. Further refinement of the tools is discussed; including parallel computing based on independent river basin and improved spatial estimates of hydraulic geometry.

1 Introduction

This technical note describes a tool to produce spatially distributed streamflow estimates using runoff output from macro-scale hydrologic models or land surface models. Those models simulate runoff depth for model elements (e.g., grid box or any other hydrologic response units) over the model domain. The tool we describe here post-processes the runoff depth output to produce streamflow at every point in the river network across the continental United States (CONUS).

There is a wide spectrum of complexity of river routing schemes applied at both local and continental scales. At the local scale, US Army Corps of Engineer (USACE) developed stand-alone river modeling system called Hydrologic Engineering Center-River Analysis System (HEC-RAS; Brunner 2001). HEC-RAS offers various hydraulic routing schemes from use of full one-dimensional (1D) Saint-Venant equations for unsteady flow simulation to simple uniform flow simulation. HEC-RAS has been popular among civil engineers for river channel design, and floodplain analysis over a small part of river network with surveyed river geometry and physical properties. At the continental scale, unit-hydrograph approaches have been used (e.g., Nijssen et al. 1997; Lohmann et al. 1998; Goteti et al. 2008), though many of recent large scale river models use full dynamic flow equations (e.g., Miguez-Macho and Fan 2012; Paiva et al. 2013), simplified Saint-Venant equations (e.g., Arora and Boer 1999; Lucas-Picher et al. 2003; Koren et al. 2004; Yamazaki et al. 2011; Li et al. 2013) or hydrologic routing (e.g., David et al. 2011).

Regardless of the routing schemes, a key issue for large scale river model is the derivation of river network. There are many past researches that focused on development of automated river network derivation for large scale river flow analysis (e.g., Fekete et al. 2001; Olivera et al. 2002; Davies and Bell 2009; Yamazaki et al. 2009), many of them developed and evaluated the methods to upscale fine resolution flow direction grid to coarser grid. Recently, more river routing models utilize the vector type river network data for large scale river modeling (Goteti et al. 2008; David et al. 2011; Paiva et al.

2011; Lehner and Grill 2013; Paiva et al. 2013; Yamazaki et al. 2013). Figure 1 illustrates difference between grid type river network and vector type river network.

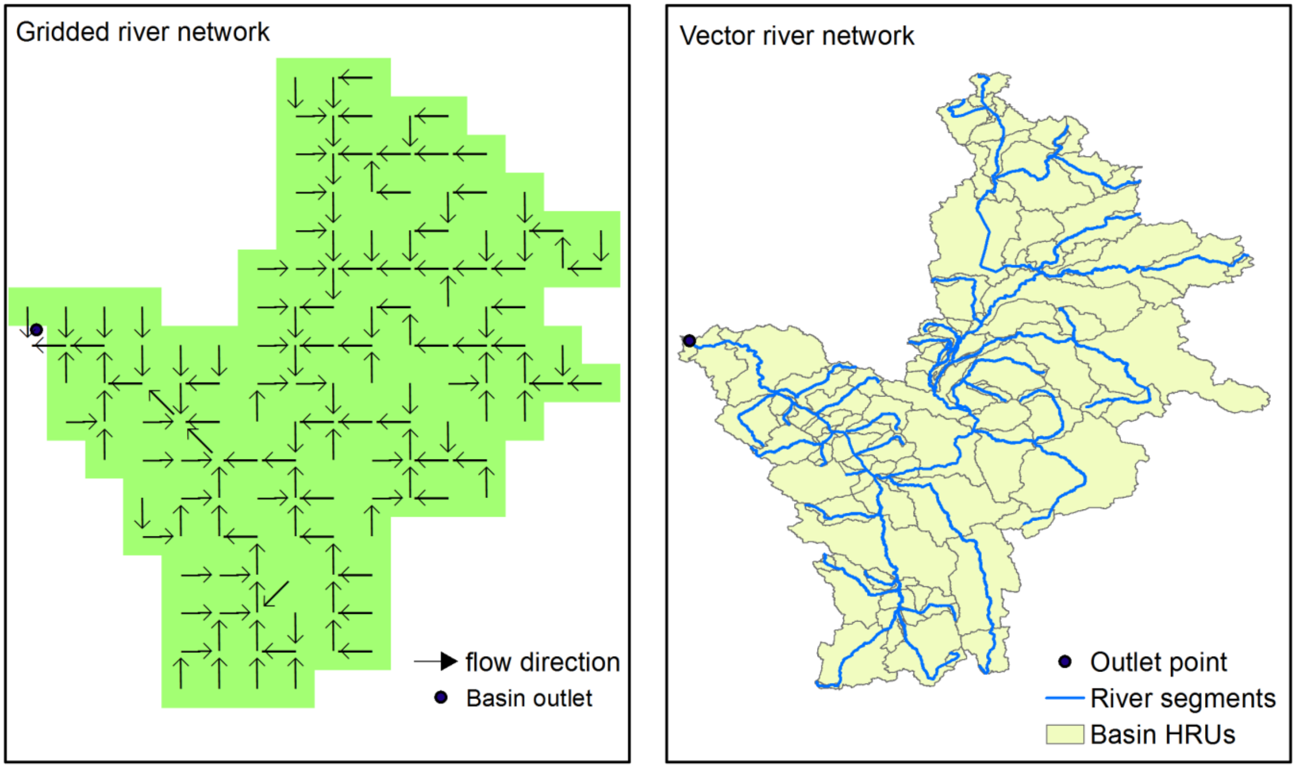

Figure 1. Comparison of gridded river network and vector river network.

The river routing tool in this document is also based on vector type-river networks to aim for nationwide streamflow estimation from the largest river systems (i.e., the Mississippi River basin) to much smaller headwater basins across the US. This technical note utilizes the United States Geological Survey (USGS) Geospatial Fabric (GF) dataset (Viger 2014; http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/GeospatialFabric.html) to incorporate into river routing tool. The GF dataset was developed primarily to facilitate nation-wide watershed modeling with USGS Precipitation Runoff Modeling System (PRMS). The dataset is generated by aggregating fine spatial scale geometry from the 1st version of National Hydrography Dataset Plus (NHDPlus v1; HorizonSystemsCorporation 2010) to eases computational burden, but still represents detailed river basins for small basin (equivalent to Hydrologic Unit Code 10). The vector geometry (polygon, line, and point) representing catchments, river segments, and points of interests (POI, e.g., gauge location, confluence, etc.) with associated physical attributes can also be used for continental scale river routing. Further information on GF is given in section 3.2.

The reminder of the note is organized as follows. Section 2 provides theoretical descriptions of hillslope and river routing schemes used in the routing tool. Section 3 provides technical details on the routing tool, including input data (both runoff and river network data), specification of routing tool (i.e. control file), and parameter specification. As a demonstration of the routing tool's capability, we provide streamflow simulations over the upper Colorado River basin in section 4. Finally, summary and future work are discussed in Section 5.

2 Theoretical background of runoff routing

This section provides brief theoretical descriptions of hillslope routing and river channel routing implemented in the routing tool. The hillslope routing takes into account time of concentration (Tc) of a catchment to estimate temporally delayed runoff (or discharge) at the outlet of the catchment from instantaneous runoff computed by the hydrologic model.

2.1 Hillslope routing

Although more physically based hillslope routing methods are possible such as kinematic wave approximation (e.g., Koren et al. 2004), the current routing tool uses a two-parameter Gamma distribution to delay instantaneous runoff depth from a hydrologic model. The Gamma distribution is expressed as:

$$\gamma(t\colon a, \theta) = \frac{1}{\Gamma(a)\theta^{k}} t^{a-1} e^{-\frac{t}{\theta}} \tag{1}$$

where a is the shape parameter (a>0), and θ is a scale parameter. μ_{τ} is the mean of the Gamma distribution [T] expressed as:

$$\mu_t = a\theta \tag{2}$$

Both scale and shape parameters can be adjustable depending on the catchment physical characteristics. The gamma distribution is used to compute the fraction of runoff at the current time step which is discharged at each future time step as follows:

$$q(t) = \int_0^{t_{max}} \gamma(s, a) \cdot R(t-s) ds \tag{3}$$

where R is cHRU-mean total runoff depth [LT^{-1}] from hydrologic model. This method was also used in several hydrologic modeling studies such as Clark et al. (2008a).

2.2 River routing

Two schemes for river channel routing are implemented - 1) One dimensional (1D) Kinematic Wave- Particle Tracking (KW-PT) routing and 2) IRF-Unit Hydrograph (IRF-UH) routing. The following sub-sections describe fundamental flow equations used in the two methods.

Both schemes are based on the 1D full Saint-Venant equations (continuity and momentum equations) that describe flood wave propagation through channel, given by

$$\frac{\partial q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{4}$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0 \tag{5}$$

where q is discharge [L^3T^{-1}] at time step t [T] and location x [L] from reference point in a river network, A is cross-sectional flow area [L^2] in continuity equation (eq.4) and v is velocity [LT^{-1}], y is depth of flow [L], S_0 is a channel slope, S_f is a friction slope, and g is gravitational constant [~9.8 m/s^2] in momentum equation (Eq.5). The continuity equation (Eq. 4) assumes no lateral flow adding to a channel segment.

2.2.1 Kinematic Wave - Particle Tracking (KW-PT)

This method performs kinematic wave flow routing through an individual stream segment as described by Goring (1994) and Clark et al. (2008b). Many other routing models also use a KW approximation for large scale river routing (e.g., Arora and Boer 1999; Lucas-Picher et al. 2003; Koren et al. 2004; Li et al. 2013). We assume the channel shape is rectangular as shown in Figure 2, and the geometry is constant throughout one river segment.

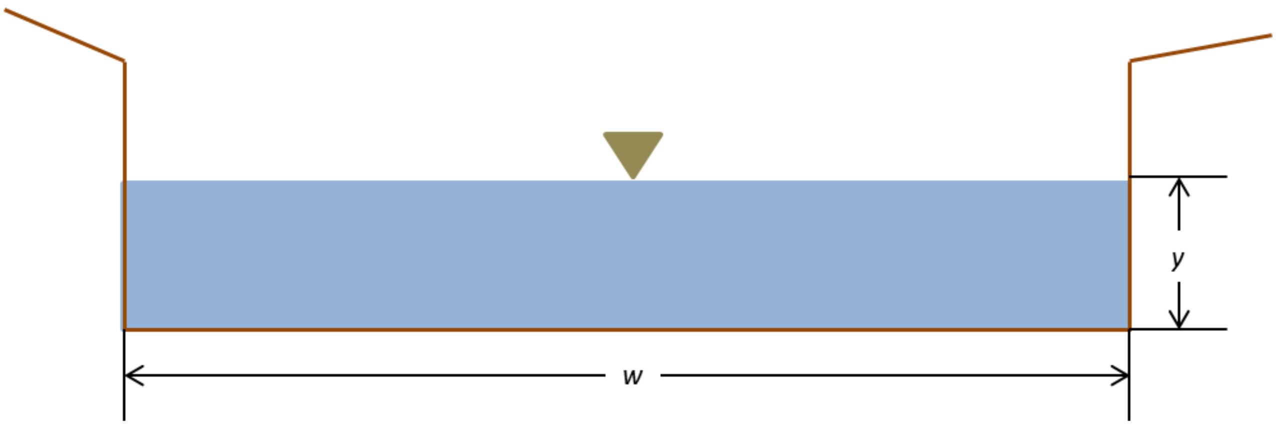

Figure 2. Schematic of rectangular channel geometry.

The kinematic wave approximation to the full Saint-Venant equations (Eqs.4 and 5) is basically a continuity equation combined with a simplified momentum equation. The simplified momentum equation for the kinematic wave approximation is based on the assumption that friction slope is equal to channel slope and flow is steady and uniform; therefore eq. 5 is reduced to $S_0 = S_f$. This assumption leads to the discharge q can be uniform flow formula. For example, the KW-PT method uses the Manning equation;

$$q = \frac{k}{n}\sqrt{S_0}(R_h)^{\alpha}A \tag{7}$$

where k is a conversion factor between Standard Units (SI) and English Units where k=1 for SI units, and k=1.49 for English units, n is manning coefficient, R_h is hydraulic radius [L], which is defined as the cross sectional flow area A [L^2] divided by wetted perimeter P [L] and α is coefficient (α=2/3). Given a rectangular channel (See Figure 2) where $A = w \cdot y$ and $P = 2y + w$, and assuming the channel width w is hydraulically wide (i.e., w>> y), the hydraulic radius R_h is expressed as

$$R_h = \frac{wy}{w + 2y} \cong y \tag{8}$$

By substituting Eq. 8 into Eq. 7, the Manning equation is re-written as

$$q = \frac{k}{n} \cdot \sqrt{S_0} \cdot y^{\alpha+1} \cdot w \tag{9}$$

The continuity equation (eq. 4) can be then re-written in terms of discharge, q

$$\frac{\partial q}{\partial x} = -\frac{dA}{dq}\frac{\partial q}{\partial t} = -\frac{1}{C}\frac{\partial q}{\partial t} \tag{10}$$

where C is the wave celerity [LT^{-1}], which is derivative of q with respect to cross-sectional flow area A. For each stream segment within which the channel width w of rectangular channel is constant, the wave celerity C is given by.

$$C = \frac{dq}{dA} = \frac{dq}{d(wy)} \cong \frac{dq}{wdy} \tag{11}$$

By substituting manning equation (Eq.9) into Eq. 11, the wave celerity C can be given by

$$C = (\alpha + 1) \cdot \frac{k}{n}\sqrt{S_0} \cdot y^{\alpha} \tag{12}$$

or expressed in terms of discharge q as

$$C = (\alpha + 1) \cdot \frac{1}{w} \cdot \left(\frac{k}{n}\sqrt{S_0}\right)^{\frac{1}{\alpha+1}} \cdot q^{\frac{\alpha}{\alpha+1}} \tag{13}$$

Two unknown quantities need to be provided – Manning coefficient (n) and river width w. The river width is computed with the following equation:

$$w = W_a \cdot {A_{ups}}^{b} \tag{14}$$

where W_a is a width factor, A_{ups} is total upstream basin area [L^2] and b = 0.5 is an empirical exponent. Given the wave celerity, travel time is computed with segment length/celerity.

Time delayed flow from each cHRU (see Section 2.1) is tracked through the river network as the flow is routed via kinematic wave routing. The time at which each particle is expected to exit the river segment is computed for each river segment. If the "exit time" occurs before the end of the time step, the particle is propagated to the downstream segment. The "exit time" then becomes the time the particle entered the downstream segment. This process is repeated for all river segments. River segments are processed in order from upstream segments to downstream segments, and it is possible for a particle to travel through several segments in a given time step. Time step averages for each time step are computed by integrating over all the flow points that exit a river segment in a given time step.

To avoid boundary problems in the interpolation, the last routed wave from the previous time step and the next wave that is expected to exit the segment are used. A decrease in the time between kinematic waves eventually produces a discontinuity known as a kinematic shock. When this occurs the kinematic waves are merged and the celerity is modified.

2.2.2 Impulse Response Function-Unit hydrograph (IRF-UH)

Impulse Response Function-Unit Hydrograph (IRF-UH) method mimics the river routing model implemented in VIC Model (Lohmann et al. 1996). Only one difference between the current tool and VIC routing tool is the way in which river network is defined. As shown in Figure 1, the VIC model uses a grid for its model domain, therefore the river network in VIC routing model is defined on the same grid domain.

The mathematical developments of IRF-UH are briefly given in Lohmann et al. (1996). Here, we also describe the derivation of diffusive wave equations from Saint-Venant equations (Strum 2001). The development of IRF-UH starts with derivation of diffusive wave equation from 1D Saint Venant equations (Eqs. 4 and 5) by neglecting inertia terms (2nd term in Eq. 5) and assuming steady flow (eliminating 1st term). The momentum equation (Eq.5) can be reduced to:

$$\frac{\partial y}{\partial s} = S_0 - S_f \tag{15}$$

Now, manning equation is expressed with channel conveyance, K_c (carrying capacity of river channel);

$$q = K_c \cdot \sqrt{S_f} \tag{16}$$

where $K_c = k/n \cdot A \cdot {R_h}^{\alpha}$. Substituting S_f in Eq. 16 into Eq. 15 and differentiating with respect to time, the momentum equation (Eq. 14) becomes

$$\frac{2q}{{K_c}^2}\frac{\partial q}{\partial t} - \frac{2q^2}{{K_c}^3}\frac{\partial K_c}{\partial t} = -\frac{\partial^2 y}{\partial x \partial t} \tag{17}$$

Also, continuity equation (Eq.4) can be re-rewritten by differentiating both sides of the equation with respect to distance x as,

$$\frac{\partial^2 q}{\partial x^2} + w\frac{\partial^2 y}{\partial x \partial t} = 0 \tag{18}$$

Combining Eq.17 and Eq. 18,

$$\frac{2q}{{K_c}^2}\frac{\partial q}{\partial t} - \frac{2q^2}{{K_c}^3}\frac{\partial K_c}{\partial t} = \frac{1}{w}\frac{\partial^2 q}{\partial x^2} \tag{19}$$

Because the channel conveyance K_c is a function of y or flow area, A, the second term of Eq. 19 is

$$\frac{\partial K_c}{\partial t} = \frac{dK_c}{dA}\frac{\partial A}{\partial t} = -\frac{dK_c}{dA}\frac{\partial q}{\partial x} \tag{20}$$

Finally, inserting Eq. 20 into Eq.19, one-dimensional diffusive wave equation is expressed as

$$\frac{\partial q}{\partial t} = D\frac{\partial^2 q}{\partial x^2} - C\frac{\partial q}{\partial x} \tag{21}$$

where

$$\begin{aligned} C &= \frac{q}{K_c}\frac{dK_c}{dA} = \frac{dq}{dA} \\ D &= \frac{{K_c}^2}{2qw} = \frac{q}{2wS_0} \end{aligned} \tag{22}$$

where parameters C and D are wave celerity [LT^{-1}] and diffusivity [L^2T^{-1}], respectively. Here, we assume the flow is uniform (i.e., $S_f = S_0$) and substituting the channel conveyance, $K_c = q/\sqrt{S_0}$ into celerity and diffusivity expressions (Eqs. 21).

Eq. 21 can be solved using convolution integrals;

$$q = \int_0^t U(t-s)\, h(x,s) ds \tag{22}$$

where

$$h(x,t) = \frac{x}{2t\sqrt{\pi D t}} \exp\left(-\frac{(Ct-x)^2}{4Dt}\right) \tag{23}$$

This solution is a mathematical representation of impulse response function (IRF) used in unit hydrograph theory. This assumes that streamflow at location x is a result of linear response to runoff depth poured into a river segment. The runoff hydrograph (here streamflow) is a convolution of Impulse Response Function (Eq. 23) and unit depth of runoff represented as $U(t\text{-}s)$ in Eq. 22.

3 Runoff routing tool

3.1 Overview of the routing tool

The routing tool post-processes total runoff (i.e., the sum of surface and subsurface runoff) produced by any hydrologic model. The routing tool routes total runoff at all segments at one time step from the most upstream segment. In other words, a segment loop is inside a time loop in the code. Prior to river routing, segment order, which is the order of segment in which river routing is performed, is identified. Segment order is typically from upstream to downstream. Identification of all upstream river segments for each segment facilitates this computation and more details are given in section 3.2.1. At each segment, the routing program starts with computation of the hillslope routing to compute delayed runoff from all the cHRUs. Delayed runoff from the cHRU is poured at downstream side of the stream segment corresponding to the cHRUs. This is denoted by circled number in hypothetical river basin in Figure 3. For the river routing, KW-PT routing and/or IRF-UH routing are performed to produce discharge at a selected outlet within the domain and all upstream segments. The outputs (i.e., routed flow at each upstream segment and outlet segment as well as intermediate flow information) are output in NetCDF version 4. Further information on output NetCDF is given in section 3.2.3. Since headwater catchments do not have an upstream stream segment, the segment attached to headwater cHRUs requires no river routing.

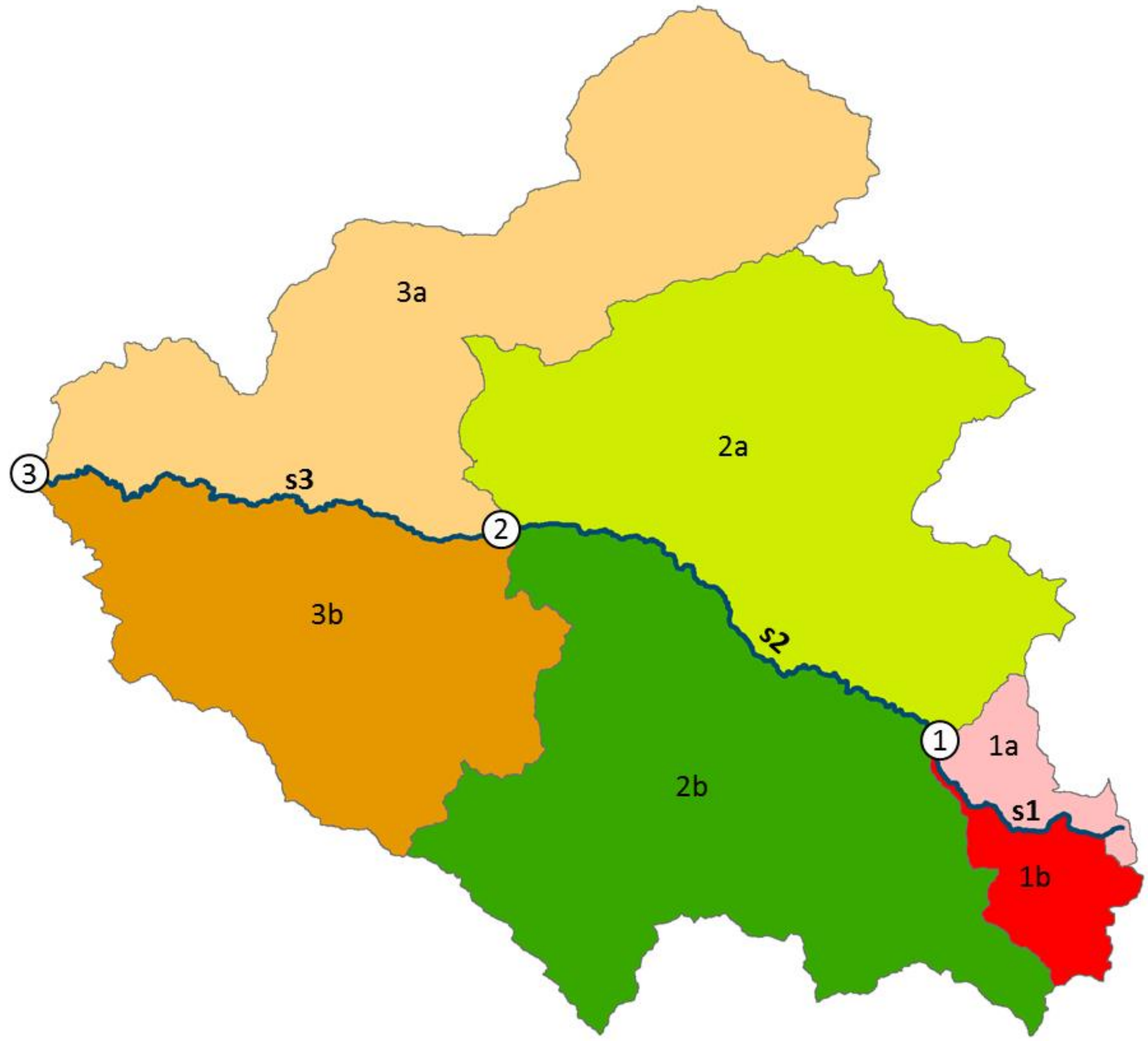

Figure 3. Hypothetical basins with associated river segments.

3.2 Datasets

3.2.1 Geospatial Fabric (GF) and its augmentation

The GF datasets were developed by USGS based on aggregation of finer catchments defined by the 1st version of NHDPlus at point of interests (POI) such as streamflow gage location, river confluence points, etc. The routing tools utilize river segments (line geometry - **nsegment**) and catchment (polygon geometry – **nhru**) defining cHRUs with some basic physical attributes. There is also point data indicating POI location, but not required for routing tool. Table 1 shows all the necessary attributes for the routing tool. The GF datasets already have two pieces of topological information - 1) ID of downstream segment and 2) association between river segment and cHRU. Since cHRU in the GF is left or right bank of each segments shown in Figure 3, relation between river segment and cHRU is one-to-many relation.

To enable CONUS applications we augment the topological information in the GF and produce this as a NetCDF input file, specifically, we first combine two attributes from river segment and cHRU polygons to link each segment to cHRU polygon into the same attribute table. Second, using the information on downstream segment for each segment, immediate “upstream” river segment(s) from each segment are identified and then all the upstream segments for each segment are listed by tracing upstream segments. For the hypothetical river basin in Figure 3, the segments s1 and s2 are all the upstream segments for segment s3. Third, we include additional geometric parameters needed for the routing (transferred from GF or computed); the area of cHRUs draining to each river segment (basinArea) and sum of all the cHRUs contributing to that river segment (UpstreamArea), and total length of upstream segments. Using the example basin in Figure 3 again, the basinArea for segment s3 is sum of cHRUs 3a and 3b and total length of upstream segments is sum of lengths of s1 through s3. In many cases, two river segments are confluent into one river segment. Therefore, the segment can have multiple upstream river networks and corresponding total upstream lengths.

Table 1. Attributes in GF dataset required for routing tools.

Vector data	**Type**	**Attributes**	**Descriptions**
hru	polygon	hru_id	ID of cHRU
		hru_segment	ID of segment to which the cHRU discharge
		hru_area	Area of cHRU
segment	line	seg_id	ID of segment
		tosegment	ID of immediate downstream segment
		length	length of segment [m]

This document uses GF river and cHRU vector data, but the river network topology can be obtained from any other similar hydrogeographical GIS data (e.g., NHDPlus) or the datasets developed by users. The datasets must include information at least on an immediate downstream segment and associated cHRU basin for each segment.

3.2.2 Final input datasets

Table 2 provides all the information contained in two input NetCDF data for the routing tools – cHRU average runoff time series and river network topology. The names of all the variables and attribute as well as NetCDF name can be freely changed by users, but specified in the control file (see section 3.3.3) accordingly.

The runoff NetCDF including cHRU averaged runoff is saved as 2-D variables (**runoff (nTime, nHRU)** or 3-D variables (**runoff (nTime, nHRU, nModel)** for ensemble model applications. Typically, time dimension is record dimension, but this is not requirement. Note that most of the existing hydrologic models use a spatial discretization different to the cHRUs (e.g., a grid). Therefore, it is most likely that cHRU-averaged runoff needs to be computed based on areal weights of overlapped portions of grid boxes for each cHRU to create runoff NetCDF.

River network topology NetCDF is more complex dataset with 4 different dimensions, including various information about river segment connectivity and cHRU associated with each river segment. This dataset also include some geometric information such as river segment length and cHRU area as described in the previous section. All the necessary information is given in Table 2.

Table 2. Input NetCDF Dataset required and their attribute information for routing tools.

Input data	Dimension name	Variable (attribute) name
hru_avg_runoff.nc	1. Hru_id(nHru) 2. Time (nTime)	1. hru_id (nHru) – list of hru_id 2. runoff (nTime, nHru) – total runoff time series 3. time (nTime) – list of time stamps
network_topology.nc	1. sHru(nHru) – number of cHRU 2. sSeg (nSeg) – number of segment 3. sUps(nUps) – sum of immediate upstream segment of all the segments 4. sAll(nAll) – number of all the upstream segments of all the segments All the dimensions are index, e.g., [1,…nHru] for sHru dimension.	<u>Segment information</u> 1.reachIndx(nSeg) – segment index [1,..,nSeg] 2.reachID(nSeg) – segment ID 3.reachLength(nSeg) – length of segment <u>cHRU information</u> 1.hruIndex(nHru) 2.hru_id(nHru) <u>Downstream information</u> 1. downReachIndex(nSeg) – immediate downstream segment index [1,…nSeg] 2. downReachID(nSeg) – immediate downstream segment ID <u>Upstream information</u> 1. upReachIndex(nUps) – immediate upstream segment index [1,…nUps] 2. upReachID(nUps) – immediate upstream segment ID 4.basinArea (nSeg) –sum of cHRU areas draining to the segment 5.upstreamArea (nSeg) – immediate upstream cHRU area 6.totalArea(nSeg) – sum of cHRU area and all the upstream cHRU area 7.reachList(nAll) – list of IDs of all the upstream segments 8.upReachTotalLength(nAll) – total length from each upstream segment <u>Miscellaneous information</u> 1.reachStart (nSeg) –start index in upstream reach listed in reachList 2.reachCount (nSeg) –number of all the upstream segments for each segment 3.upReachStart (nSeg) –start index in immediate upstream reach listed in upReachID 4.upReachCount (nSeg) –number of immediate upstream segments for each segment. 5.upHruStart (nSeg) –start index in upstream Hru listed in hru_id 6.upHruCount (nSeg) –number of upstream Hrus for each segment

3.2.3 Output

Simulated routed runoff at each segment is saved in NetCDF. Various intermediate runoff values are also included for diagnostic purpose. Output NetCDF includes information on some of river network topology and cHRU. Table 3 lists two dimension variables and variables related to runoff values.

Table 3. Attributes in GF dataset required for routing tools.

Variables	Dimension	Unit	Descriptions
Time	Unlimited(time)	days	time (number of days from reference time). This is record dimension
reachID	(sSeg)	-	Segment ID
instBasinRunoff	(time, sSeg)	m^3/sec	Instantaneous total runoff from contributing cHRUs
dlayBasinRunoff	(time, sSeg)	m^3/sec	Delayed total runoff via hillslope routing from contributing cHRUs
sumUpstreamRunoff	(time, sSeg)	m^3/sec	Sum of Instantaneous total runoff from all the upstream cHRUs at each segment
UpBasRoutedRunoff	(time, sSeg)	m^3/sec	Sum of delayed total runoff from all the upstream cHRUs at each segment
routedRunoff	(time, sSeg)	m^3/sec	Routed runoff at each segment with KW-PT method
VICroutedRunoff	(time, sSeg)	m^3/sec	Routed runoff at each segment with DW-UH method

3.3 Organization of routing tool

3.3.1 Directory structure

Table 4 shows directory structure for the routing tool and this section explains what data should be stored in each directory. All the Fortran 90 source codes are located in the *build* directory. The *build* directory also includes the Makefile and the compiled executable is saved in the *bin* directory. For a default, the executable is named **route_runoff.exe**. There are two input data required to run **route_runoff.exe** (See section 3.2.2) – cHRU runoff NetCDF, which should be stored in input directory and another is river network topology NetCDF, which should be located in the *ancillary_data* directory. The *setting* directory includes a control file and Fortran namelist containing 4 routing parameters (See Table 5 in section 3.4).

Table 4. Directory structure for the routing tool.

Subdirectory name	Contents
./ancillary_data	River network topology NetCDF
./bin	Complied executable
./build	Source codes and make file
./input	cHRU average runoff NetCDF
./output	Routed flow NetCDF
./setting	Control file and routing parameter namelist file

3.3.2 Control file

Control file is an input file for the routing executable (i.e., **runoff_route.exe**). The program reads a control file that defines input (runoff NetCDF), output, and ancillary directories (River network topology NetCDF) as well as parameter namelist file defining routing parameters (See section 3.4). The contents in the control file and descriptions of each specification are shown in Table 5. Part 3 in a control file specifies ID of an outlet segment where river routing is performed all the upstream segments above the specified segment. If negative ID (e.g., -999) is specified, routing program routes all the segments included in the river network topology. This option is useful when routing over regions where multiple river basins have their own outlets (e.g., New England, Mid-Atlantic, South-east regions etc.).

Table 5. Control file.

	Tag of information	descriptions
1. Directory	<ancil_dir>	Directory for ancillary data
	<input_dir>	Directory for input runoff data
	<output_dir>	Directory for output data
2. River network topology	<fname_ntop>	NetCDF name of River network topology
3.Outlet segment	<seg_outlet>	ID of outlet segment
4.Runoff	<fname_qsim>	NetCDF name of cHRU runoff time series
	<vname_qsim>	Name of runoff variable in NetCDF
	<vname_time>	Name of time variable in NetCDF
	<vname_hruid>	Name of cHRU id variable in NetCDF
	<units_qsim>	Unit of runoff
	<dt_qsim>	Time interval of the runoff
5. Output	<fname_output	NetCDF name of routed flow time series
6.Routing parameter	<param_nml>	Namelist name of routing parameters

3.4 Parameter specification

There are two routing parameters for each of scheme (KW-PT and DW-UH) as shown in Table 6. Currently, all parameters are uniform across all the river segments. One of future enhancements of the routing tool will be implementing spatially varying parameters based on river channel information, particularly, manning coefficient in KW-PT and velocity and diffusivity in DW-UH.

Table 6. Routing model parameters.

Parameters	Routing methods	descriptions	Default values
n	KW-PT	Manning coefficient [-]	0.01
W	KW-PT	River Width scale factor [-]	0.001
C	DW-UH	Wave velocity [LT^{-1}]	1.5 [m/s]
D	DW-UH	Diffusivity [L^2T^{-1}]	800 [m^2/s]

4 Illustration of river routing simulation– Upper Colorado River basin

This section shows streamflow simulations for river segment within a large river basin using the routing tool. We use the upper Colorado River basin (See Figure 4). The streamflow simulations with the routing tool are compared to the results with traditional grid-type river network. This particular example illustrates how streamflow estimates are affected by choices of river routing modeling. The methodological choices include 1) routing schemes (KW-PT or DW-UH) and 2) river network definition (grid-type or vector-type river network). However, the purpose of this section is demonstration of the capability of routing tools; therefore detailed examination of streamflow simulations are not discussed here because they depend largely on LSM's representation of catchment scale hydrologic process (though observed streamflow is shown as a reference). An expected effect of different routing modeling choices (routing scheme, parameters, and river network) is attenuation of runoff (i.e., peak timing, the magnitude of peak and rate of rising and recession limbs), not total volume of discharge over a certain period.

For these simulations, we utilize the daily historical runoff simulation made by Reclamation (2014) -"Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections". In their project, the retrospective VIC simulations were performed from 1950 through 1999 at 1/8th degree resolution using Maurer et al. (2002) forcings. The runoff simulations from the VIC model is subsequently routed using the DW-UH river routing scheme with gridded river network at 140 selected gauge points over the western part of US. Information on the VIC configuration is provided by Reclamation (2014). For this document, we selected 3 basins with different sizes (see Figure 4 for the selected basin) for hydrograph analysis.

The input data and control file of the routing tool used for this simulation are shown in Appendix. Routing parameters use default values listed in Table 6. As shown in the control file (Figure A1), the outlet segment is set to 14001949, which is the segment ID of the most downstream of the upper

Colorado River basin (i.e., at Colorado River at Lees Ferry). However, streamflow simulations at any upstream segments can be easily extracted from output NetCDF with segment IDs corresponding to the POI of interest. In this case, they are Colorado River at Cameo and East River near Almont.

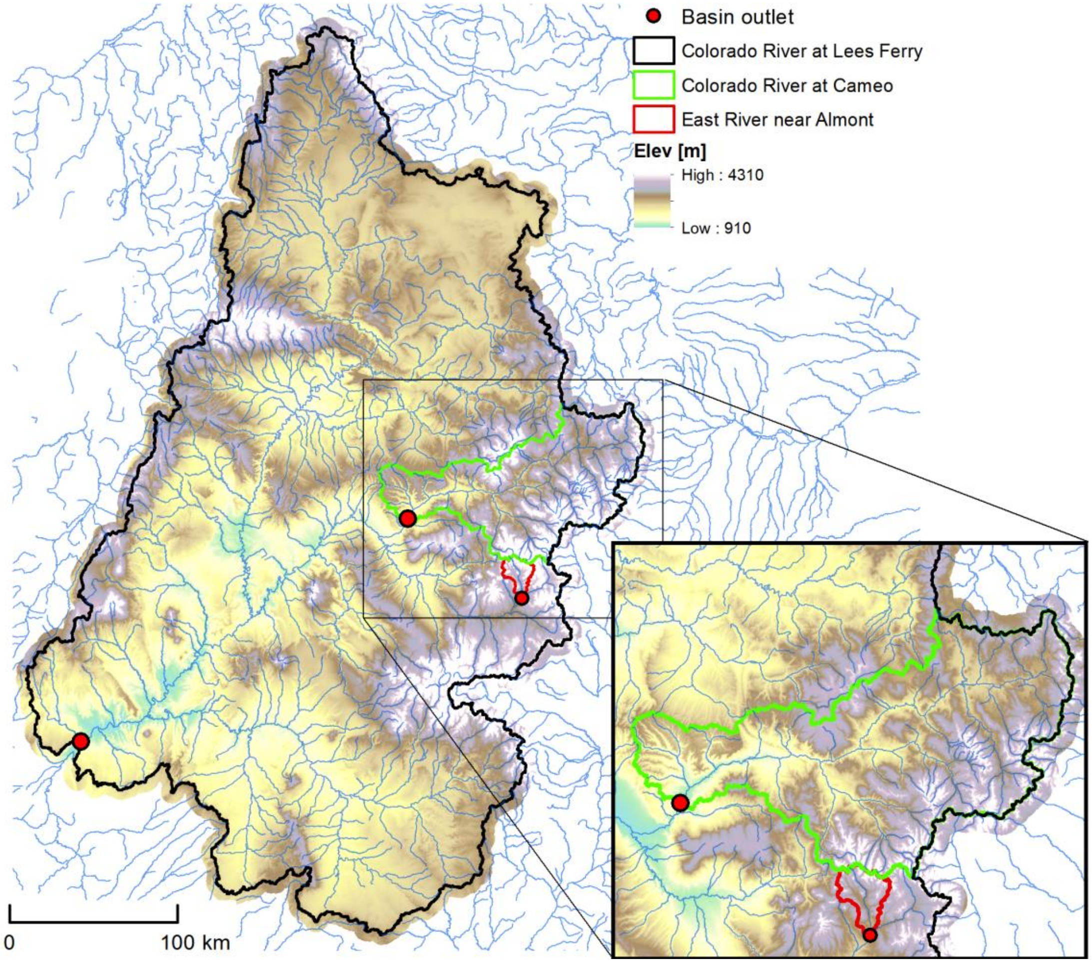

Figure 4. Locations of three basins and their outlet where streamflow is simulated, in the upper Colorado River Basin.

Figure 5 shows daily time series of simulated streamflows during the period between 10/1/1994 and 9/30/1995 along with the observed flow at three basins (East River, Cameo and Lees Ferry from top). Note that there is no naturalized daily flow available at Lees Ferry. Overall, it appears that differences in routed flow among the routing methods are much smaller than their differences (i.e., errors) from observations. It also appears that differences in routing schemes (KW-PT versus DW-UH with the same river network) causes a smaller difference in routed flow than the difference in river network (gridded versus vector river network) does. Evaluations of the other gauges exhibit similar characteristics of the differences (not presented in this technical note). Another note is that runoff simulations from the hydrologic model appears to contribute to a larger degree of error in simulated routed flow.

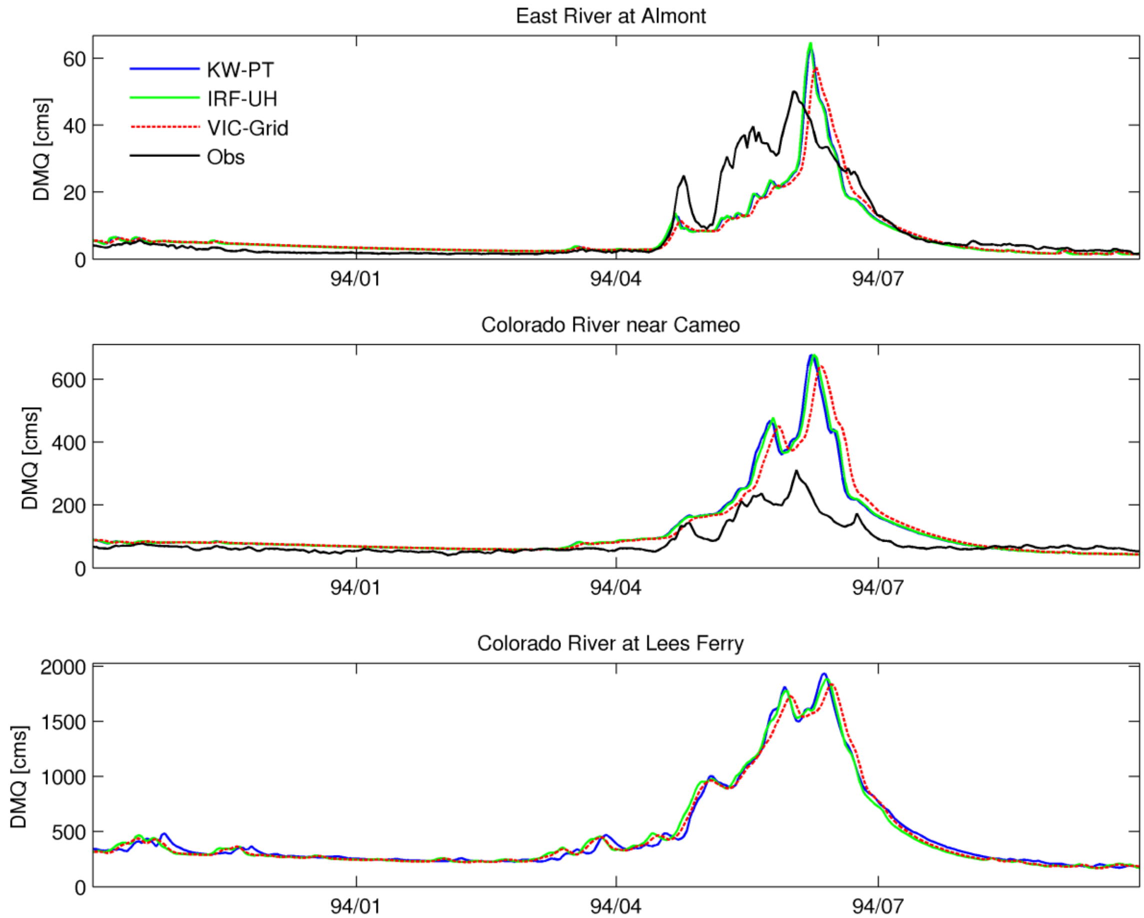

Figure 5. The daily streamflow routed with three different methods (for 1994 water year.

Analysis of sensitivity of simulated hydrograph characteristics to routing parameters (See the parameters in Table 4) needs to be performed to examine the effect of parameter values on the streamflow simulations relative to the impact of the choice of routing methods. In this document, brief sensitivity simulations were performed by using different parameter values (two parameters for each scheme).

Figure 6 shows effect of width factor W_a in Eq. 14 (top panels) and manning coefficient (bottom panels) for KW-PT scheme. Figure 6 shows only the results at Lees Ferry. In fact, the parameter sensitivity is greater with increasing basin size and there is little noticeable change in the hydrographs with different parameters at East river at Almont. As expected, narrower channel width (with smaller *w* value) produces greater velocity because smaller flow area produces faster velocity to conserve discharge. This effect is enhanced with larger manning coefficient *n* due to more friction slowing down water flow with larger manning coefficient. Similar effect is seen for sensitivity of simulated hydrograph to manning coefficient.

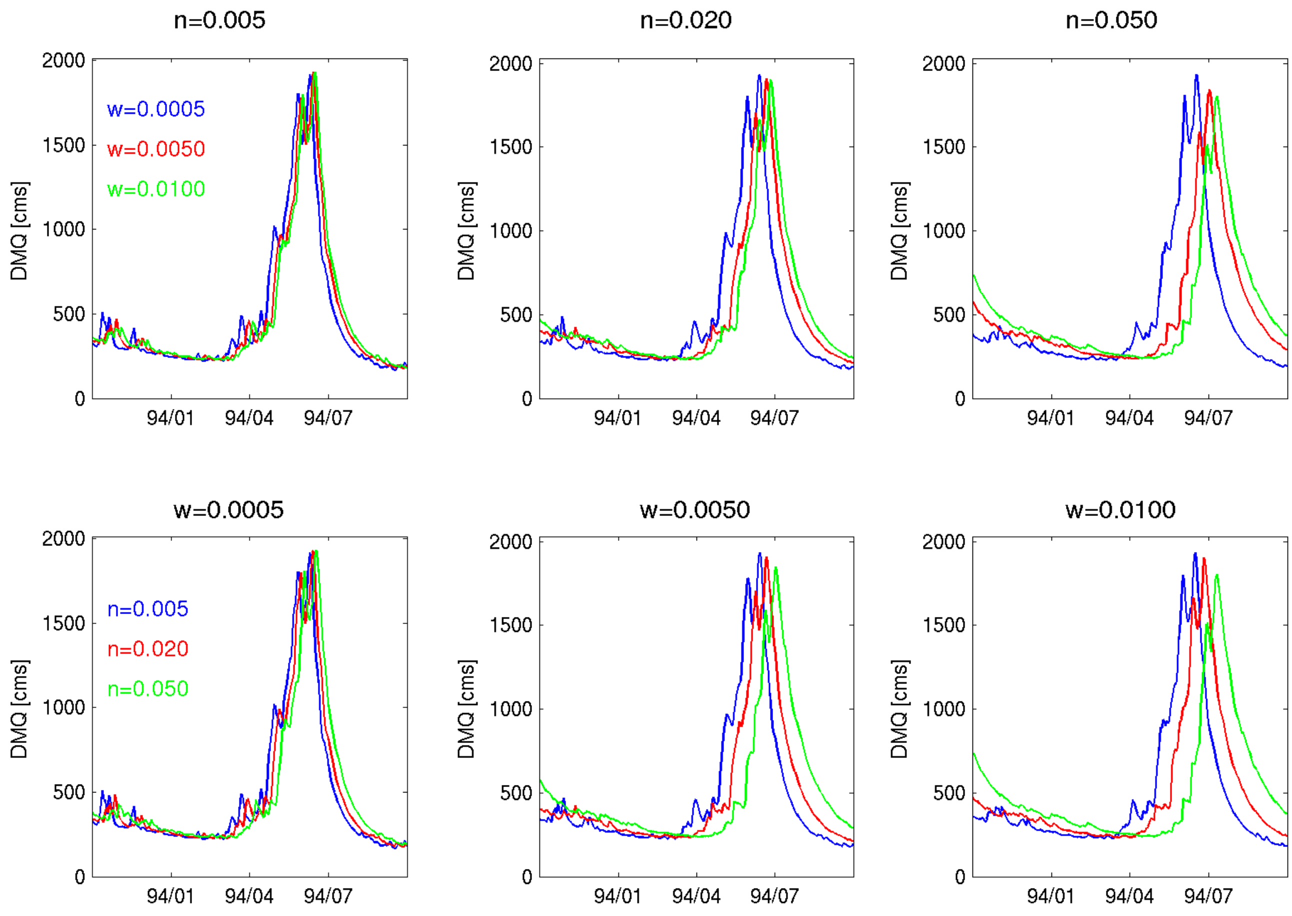

Figure 6. KW-PT parameter sensitivity to simulated runoff at Lees Ferry. Top three panels show sensitivity to width factor *w* with three fixed manning coefficients *n* (from left to right: *n* =0.005, 0.02, and 0.05). The bottom three panels show sensitivity to manning coefficient *n* with three fixed width factor *w* (from left to right: *W* = 0.0005, 0.0050, and 0.0100).

Figure 7 shows sensitivity of simulated hydrograph to two IRF-UH parameters at Lees Ferry. It is interesting to see there is little sensitivity to diffusivity while velocity affects timing of hydrograph peak. Due to little sensitivity to diffusivity in these steep mountainous basins, degree of hydrograph sensitivity to velocity is consistent across different diffusivity values.

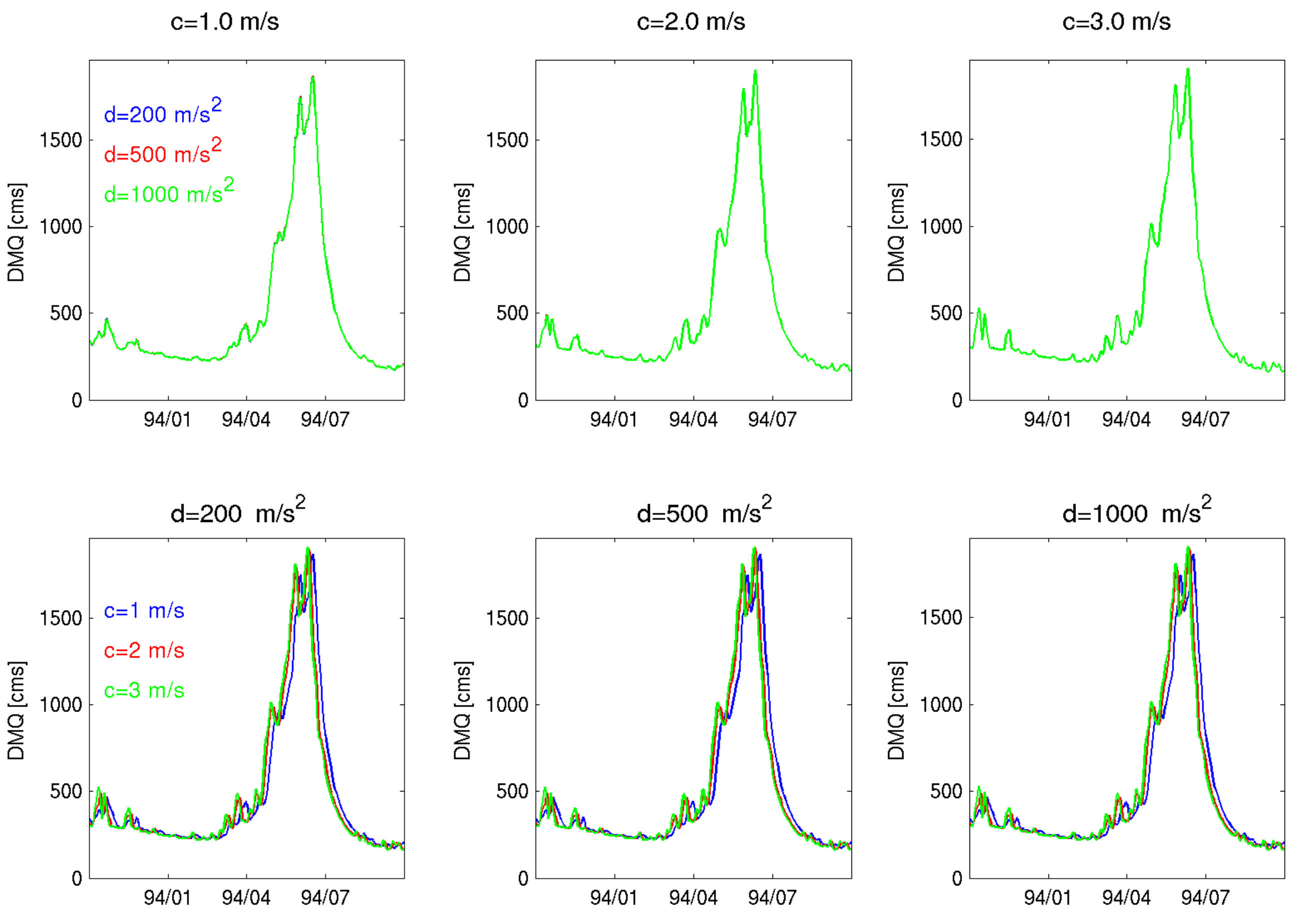

Figure 7. IRF-UH parameter sensitivity to simulated runoff at Lees Ferry. Top three panels show sensitivity to diffusivity *D* with three fixed velocity *c* (from left to right: *C* = 1.0, 2.0, and 3.0 m/s). The bottom three panels show sensitivity to velocity *c* with three fixed diffusivity *d* (from left to right: *D* = 200, 500, and 1000 m/s^2).

5 Summary and Future work

The routing tool described in this technical note is independent of any hydrologic models, making it possible to produce ensembles of streamflow estimations from multiple hydrologic models. The tools are expected to be useful for many hydrologic research or operations. The simulation presented in the last section shows river network representation may be as important as routing schemes (KW-PT versus IRF-UH). This suggests that accuracy of river segment geometry (e.g., river segment length) as well as rive segment connectivity is important. Higher resolution data such as NHDPlus v2 may have higher geometric, locational accuracy. However, large volume of river segments, which require large computation costs especially continental scale application and potential broken links in river segments that cause the first order of error in streamflow estimations, are a critical issue. Future work includes estimation of routing model parameters, identification and correction of river network connectivity in GF and other river segment data, updating the routing codes to parallel computing schemes such as use of Open Message Passing Interface (MPI). River physical parameters are extremely difficult to obtain in a consistent way at the continental scale, but potentially routed flow is sensitive to those parameter values. The parameter sensitivity and impact of river network definition (e.g., scale of river segment and cHRU, grid-type network versus vector-type network) are potential research topic to be explored. Also routing tool can use any time step (typically hourly or daily). The dependency of different time scale on routed flow needs to be understood.

Acknowledgements

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Appendix

Appendix shows contents of control file, input and output NetCDF files (input: cHRU runoff time series and river network topology, and output: simulated routed runoff) used for the simulation in Section 4.

```
! ***********************************************************************************************************************
! ***********************************************************************************************************************
! ***** DEFINITION OF MODEL CONTROL INFORMATION *************************************************************************
! ***********************************************************************************************************************
! ***********************************************************************************************************************
! Note: lines starting with "!" are treated as comment lines -- there is no limit on the number of comment lines.
!
! ***********************************************************************************************************************
! PART 1: DEFINE DIRECTORIES
! --------------------------
<ancil_dir>     /d3/mizukami/nHRU_routing_demo/ancillary_data/             ! directory containing ancillary data
<input_dir>     /d3/mizukami/nHRU_routing_demo/input/                      ! directory containing input data
<output_dir>    /d3/mizukami/nHRU_routing_demo/output/                     ! directory containing output data
! ***********************************************************************************************************************
! PART 2: DEFINE RIVER NETWORK TOPOLOGY FILE NAME
! -----------------------------------------------
<fname_ntop>    Network_Topology.nc                                   ! Name of file containing the River network topology
! ***********************************************************************************************************************
! PART 3: DEFINE OUTLET SEGMENT
! -----------------------------
<seg_outlet>    14001949                                              ! seg_id of outlet streamflow segment
! ***********************************************************************************************************************
! PART 4: DEFINE RUNOFF FILE
! -----------------------------
<fname_qsim>    UC012k_VIC.hru.nc                                     ! name of file containing the HRU runoff
<vname_qsim>    RUNOFF                                                ! name of HRU runoff variable
<vname_time>    time                                                  ! name of time variable in the HRU runoff file
<vname_hruid>   hru_id                                                ! name of the HRU id
<units_qsim>    mm/s                                                  ! units of runoff
<dt_qsim>       86400                                                 ! time interval of the runoff
! ***********************************************************************************************************************
! PART 5: DEFINE OUTPUT FILE
! ------------------------------
<fname_output>  UC012k_VIC.routed.nc                                  ! filename for the model output 1701
! ***********************************************************************************************************************
! PART 6: ROUTING PARAMETER FILE
! ------------------------------
<param_nml>     /d3/mizukami/nHRU_routing_demo/settings/param.nml.default  ! directory containing ancillary data1.0
! ***********************************************************************************************************************
! ***********************************************************************************************************************
! ***********************************************************************************************************************
```

Figure A1. Control files used for the upper Colorado routing in section 4.

```
hydro-c1:/d3/mizukami/nHRU_routing_demo/input> ncdump -h UC012k_VIC.hru.nc
netcdf UC012k_VIC.hru {
dimensions:
        time = UNLIMITED ; // (18627 currently)
        hru_id = 7320 ;
variables:
        float RUNOFF(time, hru_id) ;
                RUNOFF:units = "mm/s" ;
                RUNOFF:_FillValue = -9999.f ;
        float time(time) ;
                time:units = "days since 1949-01-01 00:00:00" ;
                time:long_name = "time" ;
                time:calendar = "noleap" ;
        int hru_id(hru_id) ;
                hru_id:longname = "HRU ID" ;

// global attributes:
                :source = "/d3/mizukami/route/preprocess/script/Calc_hru_wgtavg_nc.py" ;
                :projection = "lat/lon grid" ;
                :x-resolution = "12 km" ;
                :y-resolution = "12 km" ;
                :matlab\ file = "/glade/u/home/mizukami/hydro_nm/mtl/usbr/hydro/vic/M1_process1_VIC_output.m" ;
                :nco_openmp_thread_number = 1 ;
                :NCO = "4.3.4" ;
```
Figure A2. NetCDF input containing cHRU runoff time series used for the upper Colorado routing in section 4.

```
hydro-c1:/d3/mizukami/nHRU_routing_demo/ancillary_data> ncdump -h Network_Topology.nc
netcdf Network_Topology {
dimensions:
        sSeg = 54532 ;
        sUps = 53184 ;
        sAll = 4665642 ;
        sHRU = 103865 ;
variables:
        int reachIndex(sSeg) ;
                reachIndex:long_name = "Reach Index (0,1,..nrch-1)" ;
                reachIndex:units = "-" ;
        int reachID(sSeg) ;
                reachID:long_name = "Reach ID" ;
                reachID:units = "-" ;
        double reachSlope(sSeg) ;
                reachSlope:long_name = "Slope of reach" ;
                reachSlope:units = "-" ;
        double reachLength(sSeg) ;
                reachLength:long_name = "Length of reach" ;
                reachLength:units = "m" ;
        double basinArea(sSeg) ;
                basinArea:long_name = "Local basin area" ;
                basinArea:units = "m2" ;
        double upstreamArea(sSeg) ;
                upstreamArea:long_name = "Area upstream of each reach" ;
                upstreamArea:units = "m2" ;
        double totalArea(sSeg) ;
                totalArea:long_name = "Basin area + Upstream area" ;
                totalArea:units = "m2" ;
        int hruIndex(sHRU) ;
                hruIndex:long_name = "Index of hru dimension" ;
                hruIndex:units = "-" ;
        int hru_id(sHRU) ;
                hru_id:long_name = "Hru id" ;
                hru_id:units = "-" ;
        double hru_lon(sHRU) ;
                hru_lon:long_name = "Longitude of hru centroid" ;
                hru_lon:units = "degree" ;
        double hru_lat(sHRU) ;
                hru_lat:long_name = "Latitude of hru centroid" ;
                hru_lat:units = "degree" ;
        double hru_elev(sHRU) ;
                hru_elev:long_name = "Average hru elevation" ;
                hru_elev:units = "m" ;
        double hru_area(sHRU) ;
                hru_area:long_name = "hru area" ;
                hru_area:units = "m2" ;
        double hru_weight(sHRU) ;
                hru_weight:long_name = "Areal weight to total basin area" ;
                hru_weight:units = "-" ;
        double reachLat1(sSeg) ;
                reachLat1:long_name = "Start latitude" ;
                reachLat1:units = "-" ;
        double reachLat2(sSeg) ;
                reachLat2:long_name = "End latitude" ;
                reachLat2:units = "-" ;
```
Figure A3. NetCDF input containing river network topology used for the upper Colorado routing in section 4. This screenshot include first half of the content.

```
        double reachLon1(sSeg) ;
                reachLon1:long_name = "Start longitude" ;
                reachLon1:units = "degree" ;
        double reachLon2(sSeg) ;
                reachLon2:long_name = "End longitude" ;
                reachLon2:units = "degree" ;
        double upReachTotalLength(sAll) ;
                upReachTotalLength:long_name = "Total upstream length" ;
                upReachTotalLength:units = "m" ;
        int downReachIndex(sSeg) ;
                downReachIndex:long_name = "Immidiate Downstream reach index" ;
                downReachIndex:units = "-" ;
        int downReachID(sSeg) ;
                downReachID:long_name = "Immidiate Downstream reach ID" ;
                downReachID:units = "-" ;
        int upReachIndex(sUps) ;
                upReachIndex:long_name = "Immidiate Upstream reach index" ;
                upReachIndex:units = "-" ;
        int upReachID(sUps) ;
                upReachID:long_name = "Immidiate Upstream reach ID" ;
                upReachID:units = "-" ;
        int reachList(sAll) ;
                reachList:long_name = "List of all upstream reach indices" ;
                reachList:units = "-" ;
        int reachStart(sSeg) ;
                reachStart:long_name = "start index for list of upstream reaches" ;
                reachStart:units = "-" ;
        int reachCount(sSeg) ;
                reachCount:long_name = "number of upstream reaches in each reach" ;
                reachCount:units = "-" ;
        int upReachStart(sSeg) ;
                upReachStart:long_name = "start index for list of immediate upstream reaches" ;
                upReachStart:units = "-" ;
        int upReachCount(sSeg) ;
                upReachCount:long_name = "number of immediate upstream reaches in each reach" ;
                upReachCount:units = "-" ;
        int upHruStart(sSeg) ;
                upHruStart:long_name = "start index for list of upstream Hru" ;
                upHruStart:units = "-" ;
        int upHruCount(sSeg) ;
                upHruCount:long_name = "number of upstream Hru in each reach" ;
                upHruCount:units = "-" ;
}
```
Figure A4. The same as Figure A3 except for second half of the content.

```
hydro-c1:/d3/mizukami/nHRU_routing_demo/output> ncdump -h UC012k_VIC.routed.nc
netcdf UC012k_VIC.routed {
dimensions:
        time = UNLIMITED ; // (18627 currently)
        sSeg = 1940 ;
        sUps = 89273 ;
variables:
        double time(time) ;
                time:long_name = "time" ;
                time:units = "days since 1949-01-01 00:00:00" ;
        int reachID(sSeg) ;
                reachID:long_name = "reach ID" ;
                reachID:units = "-" ;
        int reachOrder(sSeg) ;
                reachOrder:long_name = "processing order" ;
                reachOrder:units = "-" ;
        int reachList(sUps) ;
                reachList:long_name = "list of upstream reaches" ;
                reachList:units = "-" ;
        int listStart(sSeg) ;
                listStart:long_name = "start index for list of upstream reaches" ;
                listStart:units = "-" ;
        int listCount(sSeg) ;
                listCount:long_name = "number of upstream reaches in each reach" ;
                listCount:units = "-" ;
        double basinArea(sSeg) ;
                basinArea:long_name = "local basin area" ;
                basinArea:units = "m2" ;
        double upstreamArea(sSeg) ;
                upstreamArea:long_name = "area upstream of each reach" ;
                upstreamArea:units = "m2" ;
        double instBasinRunoff(time, sSeg) ;
                instBasinRunoff:long_name = "instantaneous basin runoff in each reach" ;
                instBasinRunoff:units = "m3/s" ;
        double dlayBasinRunoff(time, sSeg) ;
                dlayBasinRunoff:long_name = "delayed basin runoff in each reach" ;
                dlayBasinRunoff:units = "m3/s" ;
        double sumUpstreamRunoff(time, sSeg) ;
                sumUpstreamRunoff:long_name = "sum of upstream runoff in each reach" ;
                sumUpstreamRunoff:units = "m3/s" ;
        double routedRunoff(time, sSeg) ;
                routedRunoff:long_name = "routed runoff in each reach" ;
                routedRunoff:units = "m3/s" ;
        double UpBasRoutedRunoff(time, sSeg) ;
                UpBasRoutedRunoff:long_name = "sum of upstream basin routed runoff in each reach" ;
                UpBasRoutedRunoff:units = "m3/s" ;
        double VICroutedRunoff(time, sSeg) ;
                VICroutedRunoff:long_name = "VIC routed runoff in each reach" ;
                VICroutedRunoff:units = "m3/s" ;
```

Figure A5. NetCDF output file contacting routed runoff simulation from the upper Colorado routing in section 4.

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