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# Implementation of cell-to-cell routing scheme in a large scale conceptual hydrological model

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ABSTRACT

A cell-to-cell routing (ROU) module has been implemented in a large-scale conceptual hydrological model, developed for the entire landmass of India with a 5 km × 5 km grid cell resolution. The ROU module is based on the principle of time variant spatially distributed direct hydrograph (SDDH) travel time method to route streamflow to the catchment outlet. The integrated model has been calibrated and validated at the Kabini dam flow measurement site over 2001–2006 and 2007–2010, respectively. Nash Sutcliffe Efficiency (NSE) is found to be 0.55 and 0.47 for the calibration and the validation period, respectively. The obtained NSE value shows that the model is satisfactorily calibrated and ROU module compliments the other modules. The comparison between model simulation results with implemented and original routing schemes show that implemented method, with modified parameterization, outperforms the original one. The overall results support the applicability of the implemented routing scheme.



## 1. Introduction

In the estimation of watershed response to precipitation, flow routing is essential (Du et al., 2009; Shelef and Hilley, 2013; Markovic and Koch, 2015; Niu et al., 2017). It is a mathematical method to predict changes in the magnitude and the velocity of flood wave propagating down the streams or reservoirs (Linsley et al., 1982). All hydrological models have two major components, the first one dealing with the conversion of rainfall into the runoff and base flow, and the second one dealing with the routing of runoff and base flow to the catchment outlet as streamflow (Todini, 1988, 2007; Peel and Bloschl, 2011). From the implementation perspective, Olivera et al. (2000) have classified flow routing algorithms into three types, namely, cell-to-cell flow routing (Vörösmarty et al., 1989; Liston et al., 1994; Miller et al., 1994; Lohmann et al., 1996; Coe, 1997, 2000; Hagemann and Dumenil., 1998; Melesse and Graham, 2004; Du et al., 2009; López-Vicente et al., 2014; Terink et al., 2015; Jung et al., 2015; Mizukami et al., 2016; Piccolroaz et al., 2016; Adams et al., 2017), source-to-sink flow routing (Naden et al., 1999; Olivera et al., 2000) and element-to-element flow routing (U.S. Army Corps of Engineers (USACE), 2001; Goodrich et al., 2002). Among these, the cell-to-cell routing method is the cardinal technique as it is simple to implement, and provides simulated flow with a higher degree of accuracy (Liston et al., 1994; Marengo et al., 1994; Miller et al., 1994; Sausen et al., 1994; Coe, 1997; Hagemann and Dumenil, 1998).

The cell-to-cell routing algorithms consider rainfall and flow properties distributed in space and time (Du et al., 2009). They are developed by using either the kinematic wave (Vörösmarty et al., 1989; Liston et al., 1994) or diffusion wave (Julien et al., 1995; Ogden, 1998; Downer et al., 2002) approximations of Saint Venant equations. The kinematic wave approximation considers only the frictional and gravity force terms whereas diffusive wave takes pressure term along with the frictional and gravity force terms of the Saint Venant equations (Singh, 2002). The diffusive-wave form

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of the equation is superior as it takes the backwater effects and attenuation into consideration (Ponce et al., 1978). However, Ponce et al. (1978) also stated that in regions where backwater is not a significant phenomenon, kinematic wave models give similar results to the diffusive wave models because the numerical solution of the kinematic wave model is identical to the analytic solution of the diffusive wave model. The kinematic waves are dominant for streamflow in the rivers without artificial structures, and a kinematic wave model provides sufficiently accurate results for both overland and channel flow (Singh, 2002). Singh (2002) also stated that the hydrologic nature could indeed be approximated quite closely by kinematic wave theory. Therefore, kinematic wave approximation technique is better option to use over the diffusive wave approximation technique for routing scheme in a hydrological model to simulate flow at the outlet of a catchment. Different kinematic wave models have been successfully applied for cell-to-cell flow routing in various studies for different grid cell resolutions over the past years.

Vörösmarty et al. (1989) used a water transport model (WTM) of resolution 0.5° × 0.5° to route runoff generated by drainage basin model (DBM) at Amazon and Tocantins river system. Each grid cell was assumed to be a linear reservoir. They used a transfer coefficient (retention time in each cell), which was dependent on the geometries of the grid cells. Liston et al. (1994) applied a routing scheme of 2.0° × 2.5° grid cell resolutions for Mississippi river basin. They used a transfer coefficient by calculating it using an empirical relationship between stream length, overland slope and mean discharge. Later, Jayawardena and Mahanama (2002) proposed a runoff routing method at a resolution of 5' × 5' (~9 km) resolution, similar to the model proposed by Liston et al. (1994), except for the inclusion of floodplain inundation as presented by Vörösmarty et al. (1989). They applied it to the Mekong river basin in China and Chao Phraya river basin in Thailand.

Miller et al. (1994) developed a linear reservoir river routing model of 2° × 2.5° resolutions for some World rivers, coupled with an atmospheric-ocean model. The velocity of flow was calculated either empirically using a topography gradient or taken a constant value over time and space. Marengo et al. (1994) applied routing method proposed by Miller et al. (1994) to the Amazon and Tocantins River basins. Oki et al. (1996) used the runoff routing model of Miller et al. (1994) to model the Amazon, Ob and Amur River basins at a cell resolution of 5.6° × 5.6° fixing flow velocity in the river channel at 0.3 m/s. Later, Costa and Foley (1997) used the same model in the Amazon River basin at a cell resolution of 0.5° × 0.5°. Ma et al. (2000) also used the linear reservoir concept, similar to the model proposed by Miller et al. (1994) and Oki et al. (1996), in their macroscale hydrological model to analyze the Lena River Basin at a cell resolution of 0.1° × 0.1° using a constant channel flow velocity of 0.4 m/s. Coe (1997) developed a terrain based surface water area model (SWAM) using linear reservoir approach for simulating surface water area and river transport at the continental scale and applied to northern Africa at a cell resolution of 5' × 5' (~9 km). The transfer coefficient used to determine flux from the grid cell was taken to be proportional to the ratio of the distance between the grid cell centers and the effective velocity, which in this case was chosen to be $0.^{003\ ms^{-1}}$.

Lohmann et al. (1996) coupled a horizontal routing model with the land surface parameterization (LSP) schemes, with the assumption that the horizontal routing process can be lumped as a linear time-invariant system. The routing model essentially describes the concentration-time for runoff reaching the outlet of a grid cell and the transport of water in the channel system. Lohmann et al. (1998) subsequently coupled the horizontal routing model with the two-layer Variable Infiltration Capacity hydrological model VIC-2L.

Ducharne et al. (2003) developed a River-Transfer Hydrological Model (RTHM) consisting of a river routing module with grid cell resolution of 25 km × 25 km. Transfer of water from one cell to another was independent of the cell, and the transfer coefficient was calculated as a function of the distance, the slope between the two cells and a scaling factor.

Melesse and Graham (2004) introduced a routing model and estimated the flow based on travel time. The entire basin was divided into two types of cells: overland cells and channel cells depending upon the threshold value for the flow accumulation area. The travel time was calculated by combining kinematic wave approximation with Manning's equation for overland cells and steady-state continuity equation in combination with Manning's equation for the channel cells. After that, the travel time from each grid to outlet was computed as the sum of travel times of all grids across the flow path and direct runoff was estimated adding up the total flow from all the contributing grids at their respective travel time. The major drawback of this model was that it did not account for travel time field variation occurring during the storm. Du et al. (2009) addressed the issue of the invariant travel time of Melesse and Graham (2004) and developed a time-variant spatially distributed direct hydrograph (SDDH) travel time method by introducing travel time field variation due to the rainfall variation. We have selected this approach to implement it in a large scale conceptual "Satellite-based Hydrological Model (SHM)" as a separate flow routing (ROU) module along with other four modules: Surface water (SW), Snow (S), Forest (F) and Groundwater (GW). Since in this routing approach, calculation of overland and channel travel time uses a physically based method, this technique needs adjustment while implementing it in a conceptual hydrological model.

The primary objective of this study is to test the applicability of a modified time variant SDDH method as a flow routing (ROU) module in the "Satellite-based Hydrological Model (SHM)." The study proposes a conceptual cell-to-cell routing approach with modified parameterization (for details see section 5.1.4) replacing two existing parameters of time variant SDDH process with three new parameters, and implements it in SHM. The integrated model is applied to a well-monitored Kabini dam sub-basin for testing the ROU module. Sensitivity analysis is conducted to study the effect of ROU module parameters on the predicted hydrograph at basin outlet during validation.

The organization of the paper is as follows: Section 1 is the introduction, followed by section 2 which gives the detailed description of the study area and data used. Section 3 presents a brief description of SHM. After that, section 4 includes the information on availability and transferability of the integrated model. Section 5 describes methodology with a detailed procedure used for developing the routing scheme, followed by results and discussion in section 6, and conclusions in section 7.

## 2. Study area and data

Kabini dam sub-basin (2479 $km^2$) of the Kabini river basin (7847 $km^2$) (Fig. 1) is chosen as the study area. It is located in the southern part of India. The elevation in the study area ranges from 622 m to 2026 m above mean sea level. According to the Food and Agriculture Organization (FAO) data, soils in the study area may be broadly classified as sandy, clay loam and loamy. Further, the sub-basin has the forest (87 percent), agricultural (10 percent) and non-agricultural area as its primary land use/land cover (LULC). The average annual temperature lies between 17 °C and 37 °C, and annual mean rainfall is 3100 mm, with June to September being the monsoon months. For testing of routing scheme in Kabini dam sub-basin, required data have been collected from various sources. The