A particle-set distributed hydrological model for the dynamic simulation of surface runoff

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ABSTRACT

This study proposed a particle-set distributed hydrological model for the dynamic simulation of rainfall-runoff process. With the supports of remote sensing, GIS, terrain analysis and distributed computing techniques, a representation-simplified and physically-based high-performance watershed framework has been developed. It simplifies the underlying watershed with a flow path network model, and represents the moving surface flow with independent runoff particles.

The original idea was to investigate a real-time modeling system for the space-time dynamics of increasingly frequent extreme rainfall events. Short-term heavy rains may cause further damages by spawning floods and landslides. It is quite essential to understand how the rainfall water moves across the watershed surface as early as possible. A modelling system with high-performance in simulation efficiency and space-time prediction accuracy would be very desirable.

Watershed modeling is the primary way to explore the hydrological cycle at a local scale. Existing models are classified as empirical lumped, conceptual semi-distributed and physically-based distributed models. The first two types of models have focused more on predicting outlet discharges rather than estimating spatiotemporal flow dynamics. The application of physically-based models has always been hampered by some common shortcomings like over-parameterization, inflexibility and computational burden. With the increasing support from terrain analysis and parallel computing techniques, a number of previous studies have made some efforts to improve the performance in dynamic and real-time simulation. However, research gaps still exist in realistic representation, physical description and real-time simulation.

This study, therefore, developed the particle-set modeling system on the basis of flow path network model. This one-dimensional topological structure was created beforehand to represent the three-dimensional watershed, and a series of particle beams were dynamically generated to simulate the surface flow. Under the control of flow velocities, these runoff particles would keep on moving along with the flow paths, which can represent the spatial distributions of surface water in time.

To validate the proposed particle-set framework, a prototype of particle-set system was implemented by programming methods with the assistance of third-party platforms. Three experiments were undertaken to respectively evaluate the performance in prediction accuracy, simulation efficiency and parameter sensitivity. More specifically, a total of 10 rainfall events and up to 128 computer processors were tested. In addition, the influences of underlying spatial scale and source sampling density on hydrological responses were explored with comparative tests.

The accuracy validation comes in two parts, the representation loss in terrain analysis, and the discharge error in hydrological modeling. The experimental results indicate that the TIN-based flow path network has maintained the terrain features at a very high level with much less data storage, and the particle-set framework has achieved quite acceptable predictions of outlet discharges. Besides, the efficiency evaluation concerns with two aspects, parallel portion and parallel efficiency. The speed-up results indicate that about 99% of the computational workloads can be computed in parallel, and the particle-based scheme can achieve almost the ideal parallel efficiency. In addition, the sensitivity test focuses also on two parameters, underlying spatial scale and source sampling density. The preliminary results show that the particle-set model has shown a good reliability and stability as scale gets coarser or density becomes sparser.

This study will contribute to the understanding of short-term rainfall-runoff events at a basin scale. The particle-set distributed hydrological model has been proven to provide real-time spatio-temporal dynamics of surface flow. Further studies would still be required to apply it to real world scenarios.

Keywords: terrain analysis, watershed hydrology, rainfall-runoff process, flow path network, particle system, parallel computing

Table of Contents