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Parallelization of a Fully-Distributed Hydrologic Model using Sub-basin Partitioning

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AGU, Fall Conference, 2005
H13H: Advances in Distributed Modeling of Watershed Processes
Poster No: H13H-1399

Abstract

A primary obstacle towards advances in watershed simulations has been the limited computational capacity available to most models. In this study, we present novel developments in the parallelization of a fully-distributed hydrologic model. Our work is based on the TIN-based Real-time Integrated Basin Simulator (tRIBS), which uses a multiple resolution terrain representation based on a triangulated irregular network (TIN). The sequential version of the model is currently limited over large basins and long simulation periods. To address this, a parallel MPI-based version of the tRIBS model has been implemented and tested. Our approach utilizes domain decomposition based on sub-basin partitioning of the watershed. We demonstrate how the sub-basin partitioning provides computational feasibility and efficiency for a small watershed in northeastern Oklahoma. We compare the performance of the sequential and parallelized versions to highlight the efficiency gained as the number of processors increases. We also discuss how the use of TINs and parallel processing can lead to feasible long-term simulations in regional watersheds while preserving basin properties at high-resolution.

Problem Statement

Computational limitations prevent applications of distributed hydrological models over spatial and temporal extents of interest:

- Regional to continental-scale basins (10^3 km^2 to 10^6 km^2).
- Hydroclimatological studies (seasonal to multi-year periods).
- Scales comparable to field and remote-sensing resolutions.

Our objective is to eliminate the existing computational limits in distributed hydrological modeling to enable:

- Efficient simulations while capturing high-resolution data sets.
- Coupling to other complex models (atmospheric, biospheric).
- Ensemble forecasting and data assimilation.

Hydrological Model

TIN-based Real-time Integrated Basin Simulator (tRIBS)

tRIBS Model Features:

- ✔ Continuous simulation over storm and interstorm periods.
- ✔ Spatially-distributed forcing, parameters, boundary conditions.
- ✔ Complex terrain representation from hillslope to basin scales.
- ✔ Complete water/energy cycle (surface-subsurface coupling).
- ✔ Multiple capabilities (forecasting, estimation, synthesis).

Additional details: *Ivanov et al.* [2004]; *Vivoni et al.* [2005]

Parallelization Strategy

Overview and Approach

Distributed hydrological models typically function sequentially on a single computer processor [*Singh and Woolhiser*, 2002]. In groundwater and atmospheric models, parallelization into rectangular domains is common [e.g., *Wu et al.* 2002; *Chang et al.* 2001]. Here, we propose a new strategy for parallelization of watershed models based on:

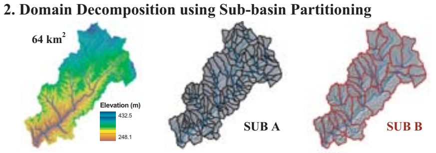
1. Terrain discretization using irregular meshes.
2. Domain decomposition via sub-basin partitioning.
3. Hydrologic exchanges for lateral surface-subsurface fluxes.

A watershed as an organizational unit provides an excellent framework for parallelization. Physical constraints on hydrological fluxes between sub-basins can be exploited to *reduce communications time* and provide a *modular approach*.

1. Terrain Discretization based on Triangular Irregular Networks

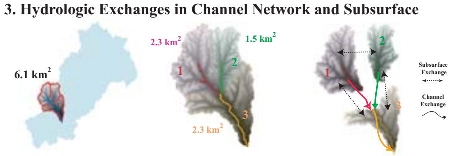
Irregular discretizations allow terrain representations with low node numbers without accuracy loss [*Vivoni et al.* 2004]. Here, a 30-m DEM (70,966 nodes) is sampled into different TINs (A = 15,205; B = 5,551), with low RMSE (1 and 2.3-m for A and B).

2. Domain Decomposition using Sub-basin Partitioning



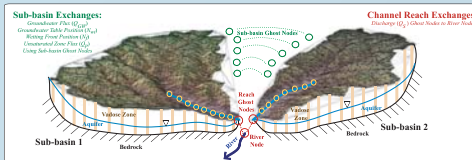
Sub-basin delineation allows partitioning the domain into smaller units of variable size connected via the channel network. Here, a single basin is decomposed into many sub-basins (A = 203; B = 45), using a constant area threshold (0.225 and 0.9 km^2).

3. Hydrologic Exchanges in Channel Network and Subsurface



Parallelization is achieved by exchanging data among reaches and sub-basins, each a TIN with internal reaches. Hydrologic data is exchanged downstream along reaches (1 and 2 to 3) and in subsurface between sub-basins along flow direction (1-2, 2-3, 1-3).

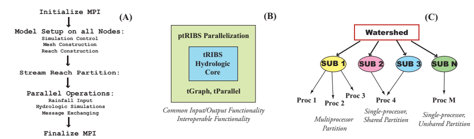
Implementation



Major Features of Parallelized tRIBS (ptRIBS):

- ✔ Stream graph partitioning using channel network as binary tree.
- ✔ Master - slave node architecture with variable number of processors.
- ✔ Sub-basin computations using local triangulation network.
- ✔ Limited message passing using MPI protocols (hydrologic fluxes).
- ✔ Ghost nodes utilized to exchange data between reaches and sub-basins.
- ✔ Fully compatible with single-processor version.
- ✔ Parallel processing extensions as new modules (C++ classes).

Software Development using Object-Oriented Approach

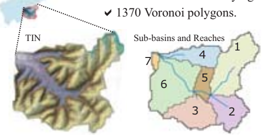


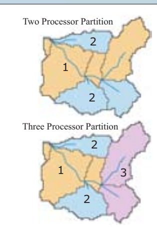
Object-oriented programming allows modular design of parallelization algorithms with flexibility in terms of processor partitioning. (A) Simple flowchart of ptRIBS model. (B) Diagram of class structure for ptRIBS. (C) Options for partitioning sub-basins (N total) into available processors (M total).

A Simple Example

SMALLBASIN ***Example:***

- ✔ Wilkerson Hollow, OK.
- ✔ Area = 2.57 km^2.
- ✔ Seven subbasins of varying area.
- ✔ 1370 Voronoi polygons.

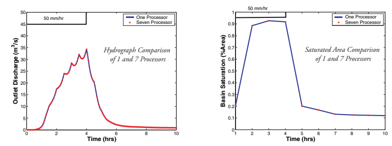




Example basin used for parallelized model development and testing versus single processor version. Due to its small size, a limited number of sub-basins were derived. Sub-basin size discrepancy is due to simple partitioning not optimized for equal area.

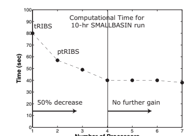
Results

Hydrological Performance of ptRIBS



Comparisons of the single processor tRIBS and the ptRIBS model for the SMALLBASIN (7 processors: full partition) demonstrate the parallel version is adequately constructed. For a synthetic storm (4-hr, 50-mm/hr), both the outlet hydrograph (a lumped measure) and the basin saturated area (a distributed measure) are identical (over 10-hr simulation time).

Computational Performance of ptRIBS



- ✔ Small problem with ~1400 nodes; 10-hr simulation time; 7 total processors.
- ✔ Model setup significant percentage of time for this short simulation (thus leveling of speed).
- ✔ Run on 164-node LINUX cluster: Two Intel Pentium 3 per node (1 Ghz, 1G memory).

A 2-x speedup is achieved for the example basin, but a significant leveling off after 4 processors is observed. This is due to the small basin and model time spent on setup (initial I/O; mesh generation). For larger problems, the computational efficiency is anticipated to be higher. Parallelization gains achieved as individual processors balance computational effort.

Future Efforts

Given the confidence in the parallelization of the distributed model, next steps include further evaluations and tests:

- Speed-up tests for larger basins (10^3 km^2 to 10^4 km^2).
- Analysis of effect of balanced sub-basin partitioning.
- Analysis of effect of TIN resolution on parallelization.
- Additional performance metrics from a hydrologic perspective.

Few studies have achieved watershed-based parallelization taking advantage of network organization. One notable exception is the work of *Apostolopoulos and Georgakakos* [1997]. ***We believe this effort has significant potential to advance the state of modeling science in hydrology.***

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