PARALLEL COMPUTATION OF FLOW DIRECTIONS AND FLOW ACCUMULATION ON HEXAGONAL DISCRETE GLOBAL GRID SYSTEM

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Abstract
Global small-scale hydrological modeling datasets are needful component of Earth system models. These datasets typically include flow direction and flow accumulation models. Regardless of the method of obtaining global hydrological product, one will face the task of processing at least continent-scale datasets, which may be time-consuming or hardware-expensive. Hexagonal mesh grid computations have shown better performance than rectangular ones, boosting interest in global-scale simulations on hexagonal grids. There are studies where hydrological modelling is successfully applied on hexagonal discrete global grid systems (DGGS), although locally. This research presents an algorithm for parallel computation of flow directions on the hexagonal DGGS. Referring to the hierarchical nature of DGGS, we cut the study area into tiles along one of the small-scale levels cells boundaries. Hydrological modeling is then performed on the desired level child cells of each tile. Afterwards the results are stitched into a single coverage.

Keywords: *parallel computing, hydrological analysis, discrete global grid systems*

INTRODUCTION

Low spatial resolution GIS-representations of entities and phenomena are essential for modeling global processes like the hydrological cycle or climate change. A crucial component of any Earth system model is a flow direction model, which is typically calculated on a regular grid of squares. For high-resolution spatial data, a metric grid in a projected coordinate system is often applied, and digital elevation models (DEMs) are serving as input data. The water mass is being virtually sent from a grid node towards the neighboring node along the steepest slope direction. For low-resolution spatial data, a grid georeferenced in geographic coordinates is typically employed. However, these grids have a complex geometry due to the decreasing extent of one degree of latitude from the equator to the poles potentially distorting the modeled parameters, even if their cells are nominally square.

Discrete global grid systems (DGGS) are spatial reference systems that use a hierarchy of equal area tessellations to partition the surface of the spherical Earth into grid cells [10]. Thay are seems to be an efficient way to prevent distortions caused by the variability of the shape and area of the cells. DGGS grids can comprise different shapes: triangles, squares, diamonds or hexagons [19]. Hexagonal mesh grids are used more and more often in hydrological simulations mainly due to their uniform adjacency. This feature solves the problem of ambiguity in determining the neighborhood of cells and defining a weight matrix for focal operations often used in hydrological modeling [15].

Previous studies of hexagonal mesh grids have focused on the valley lines extraction [22] and the adaptation of the basic methods of hydrological parameters computation developed earlier for square grids. These parameters include flow direction and accumulation, watershed delineation, stream network, stream order [14]. Notable research has been carried out to migrate same techniques to one of the types of hexagonal DGGS [12].

Small-scale flow direction models can be obtained by generalizing large-scale models [6, 25]. The value of the initial scale is determined by spatial resolution of the DEM that used in the modelling. A significant advantage of DGGS is their allowance for hierarchical partitioning, enabling spatial data refinement and bypassing several typical square regular grid limitations. A pyramid framework formed by hexagonal and triangle mesh grids was introduced by J. Wright [24]. The study presents hierarchical model to perform hydrological geomorphometry analysis and in particular it includes generalization functions.

Although, there are lack of research utilizing hierarchy structure of DGGS to obtain low resolution global flow direction models. In this case, one should process at least continent-scale datasets at fine resolution, which can be time-consuming or require significant computational resources. This study aims to perform a technique for parallel computation of flow directions on the hexagonal DGGS using the example of the African hydrological system.

MATERIALS AND DATA PREPROCESSING

Discrete global grid system

The study was conducted on the H3 DGGS, implemented by Uber [21]. It is based on an icosahedron, uses hexagons as a paving figure and a gnomonic projection of each face to transition to a sphere. The polyhedron is located in the body of the Earth in such a way that all its vertices fall into the World Ocean, thereby reducing distortion on land. For cells with an aperture of seven forming 16 levels a hierarchical indexing system is used in which each index is a 64-bit number. The H3 library is written in the C programming language, but has many interfaces in other languages. This work is done through the interface for the C++ language and results are designed as a library in the R language (fork of [8]).

DEM quantization

Since elevation data are not distributed on hexagonal grids, it was necessary to produce a hexagonal grid by converting square grid elevations. The source terrain data were the ETOPO Global Relief Model 2022 with a 60 arc-second resolution [7]. The level of H3 DGGS was chosen so that the average area of the hexagon was approximately 2 times smaller than the area of the raster cell [20]. Since approximate area of the DEM cell is 3.4 sq. km, we had to look for 1.7 sq. km area hexagon cells. The nearest smaller H3 level is eights with 0.7 sq. km area. Then the elevations at centroid locations of hexagonal cells were resampled using bilinear interpolation of elevations at square cells [16]. The same quantization technique was utilized previously to convert elevations into the Icosahedral Snyder Equal Area Aperture 3 Hexagonal Grid (ISEA3H) DGGS [13].

METHODS

Determining flow direction for each cell of a DGGS or hexagonal mesh grid involves solving the problem of closed depressions or pits — unnatural minima that can lead to serious errors in hydrological modeling. Numerous algorithms have been suggested to address this issue on square grid DEMs. There are iterative algorithms [9, 11 17, 18] and more computationally efficient single-pass ones generally called “priority-flood” [5, 23].

Richard Barnes carried out several significant studies based on the priority-flood algorithm. His RichDEM terrain analysis software [1, 4], among other things, can fill depressions and calculate flow accumulation in parallel, by tiles [2, 3] — the task we are solving for hexagonal DGGS. However, we did not succeed in migrating parallel priority-flood depression processing as the algorithm is sensitive to the elevation distribution of edge cells and often reverses the flow direction on adjacent tiles.

Thus, the Jenson and Domingue depressions filling algorithm was implemented [11]. It creates planes on site of closed depressions and process edge cells separately to the inner area. The original algorithm produced cycles when it modeled the flow directions on flat areas. Therefore, we represented these areas in the form of a graph with cells as nodes and neighboring cells were connected by edges. Then the shortest paths between all flooded area cells and the corresponding pour point were found and collapsed to form flow lines.

The hierarchy of the DGGS makes it a natural tool for tiling and parallel processing of vast territories spatial data. Tiles can be obtained by cutting the study area along one of the small-scale levels cells boundaries. In the current work Africa was cut into 377 fragments by second-level cells, while flow directions were calculated on eight-level grid.

As mentioned above, the Jenson and Domingue algorithm eliminates edged cells from processing. Thus, it is necessary to make overlapping tiles of at least 2 cells, so small buffers were made for each tile.

Note that to record flow directions we do not use conventional for square grids encoding scheme, but make pair of H3 indexes. The first one means the cell from which water will flow out and the second shows where it will flow. As D6 non-divergent algorithm [14] is used to determine flow directions, final table of pairs will have unique values at first column.

Flow accumulation, which is the number of cells contributing flow to each downstream cell, then calculated by recursive passage through the flow directions table:

1. Initialize the inflow count of all cells as 0. Iterate rows.
2. Take current pair and increment second cell value.
3. Scan the table to find the current second cell at first place.
4. Repeat steps 2 – 3 until nothing found, then take next row from the iterator.

RESULTS AND DISCUSSION

The flow directions were calculated for 377 tiles covering Africa. These calculations were performed on the DGGS H3 level 8, where the cell diameter is approximately 1 km. The processing time for each tile varied between 0.5 and 28 seconds, depending on the area of flat regions (former closed depressions) present in the fragment. The total computation time for the continent was roughly 3 hours. This processing was conducted on a computer equipped with 16 GB RAM and an 8-core processor running at 3201 MHz.

Next, we combined the tables with the flow directions and calculated flow accumulations using the summary table (Fig. 1) consisting of about 44 million records. This process took about 6 minutes on the same machine.

Our accomplishment of computing one of the fundamental parameters for hydrological modeling entirely within the DGGS ecosystem proves its standalone value in GIS tasks.

However, there is potential to increase the computational efficiency of processing each tile, which could be achieved by refining the current algorithm or adapting the priority-flood algorithm. Another interesting task is to stitch the tiles of the flow accumulation.

CONCLUSION

This study focused on developing a novel technique for parallel computation of flow directions on the hexagonal Discrete Global Grid System (DGGS), using Africa's hydrological system as a case study. The digital elevation model was converted into hexagonal grid of appropriate resolution and then cut into distinct fragments. Each tile was processed separately to calculate flow directions. This approach was necessitated by the challenge of handling large-scale datasets. The study demonstrated that computations performed on a DGGS proved its efficiency. The results from each fragment were then stitched together to create a single, comprehensive coverage. This research not only advances the field of flow direction modelling on H3 discrete global grid system but also offers a practical approach to managing large geospatial datasets. Further research will be devoted to improving the efficiency of calculating flow directions for individual tiles and developing a method for generalizing flow directions using DGGS to obtain global low spatial resolution hydrological model.

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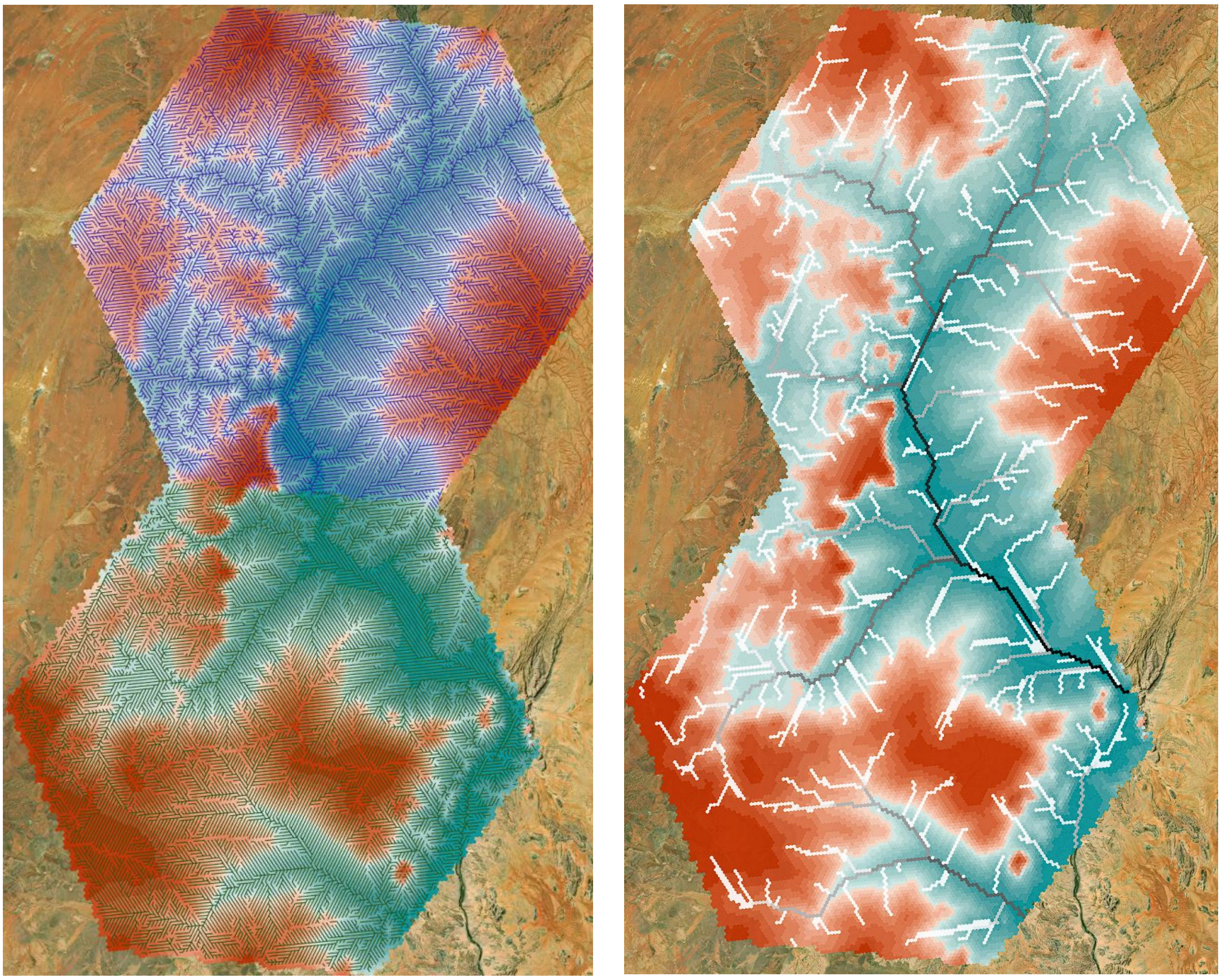

Figure 1. Calculation steps based on the example of two hexagonal tiles. Complimentary flow directions of adjacent tiles (on the left) and corresponding flow accumulation (on the right, the darker the black, the more cells the cell accepts upstream)

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