Computing more realistic flow-routing surfaces using FlowFill

Integrating drainage as runoff fills depressions

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Abstract

Flow-routing calculations require an appropriate flow-routing surface. This is generally a DEM, pre-processed to remove all depressions from its surface, allowing for a continuous, integrated drainage network. However, **real landscapes contain natural depressions** that can store water and break up the drainage network. These are an important part of the hydrologic system, and should be represented in flow-routing surfaces. The challenge is in removing from a DEM only those depressions that would be filled (and therefore overflow) under reasonable hydrologic conditions at a given location, and not all depressions indiscriminately. To address this problem, we developed **FlowFill**, an algorithm that **routes a prescribed amount of runoff across the surface to flood depressions, but only if enough water is available**. This method conserves water volume and allows a user to select a runoff depth that is reasonable for the region of interest. Typically, smaller depressions or those in wet areas or with large catchments are flooded, while other depressions may not be completely filled, thus permitting internal drainage and disruptions to hydrologic connectivity.

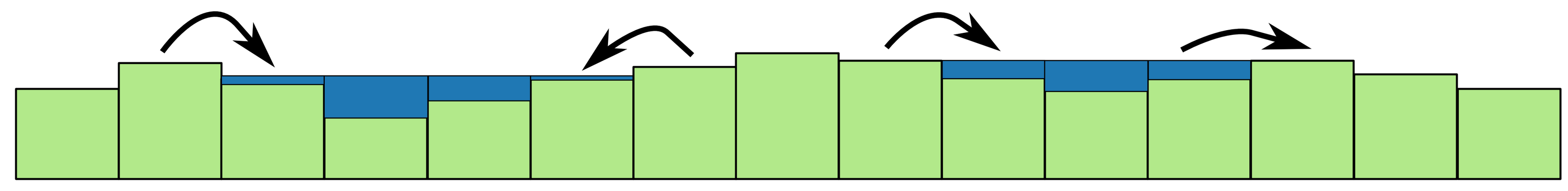

Figure 1: Filled depressions allow runoff to pass over them while unfilled depressions act as sinks to flow. The lake on the left is not completely filled, and its level therefore is lower than the height of cells on either side. Water would continue to flow into this depression from all directions. On the right, water has completely filled a depression. Any flow entering this area from the left is able to flow out on the right and continue downslope.

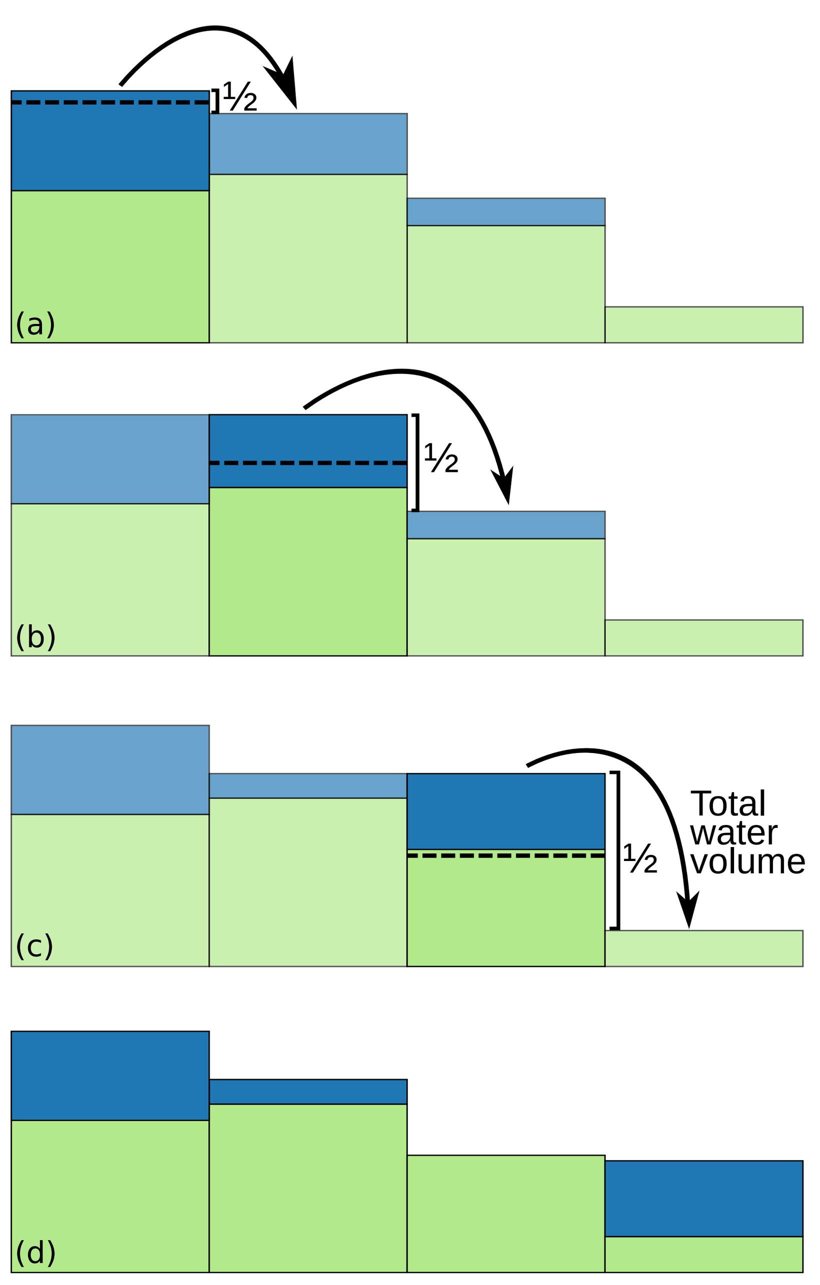

Figure 2: Water flow during a single iteration of FlowFill. Water moves starting with the highest cell and ending with the lowest. Each 'target cell' routes water into its steepest downslope neighbour. The amount of water moved is the min(all the water available, half the difference in elevation between the two cells). This latter criterion ensures numerical stability, but slows convergence towards a solution.

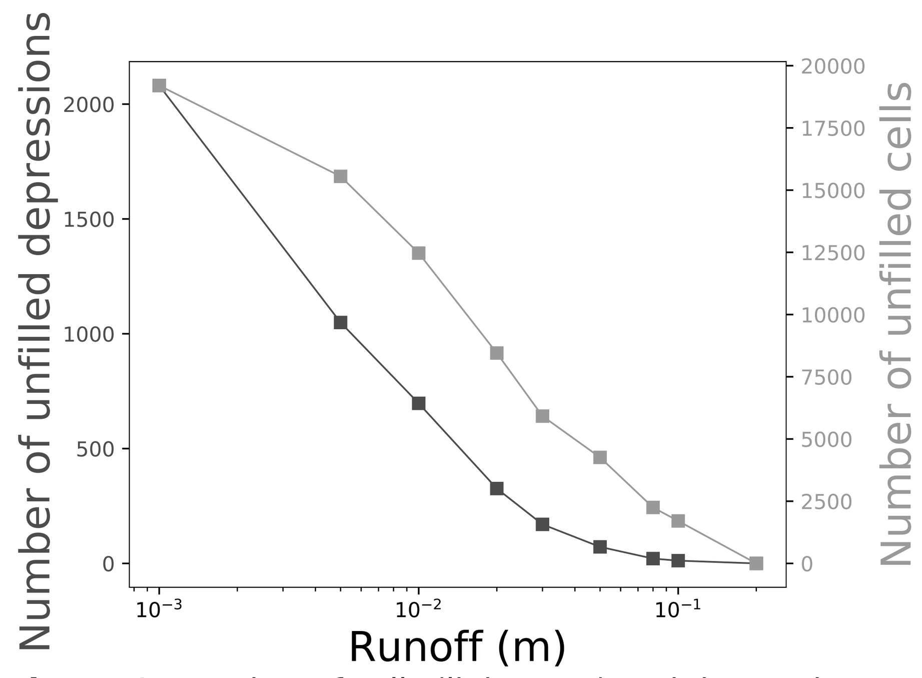

Figure 3: Number of cells (light grey) and depressions (dark grey) that remain unfilled under different starting runoff depths in the Sangamon River basin site. Higher runoff results in more depressions being completely filled.

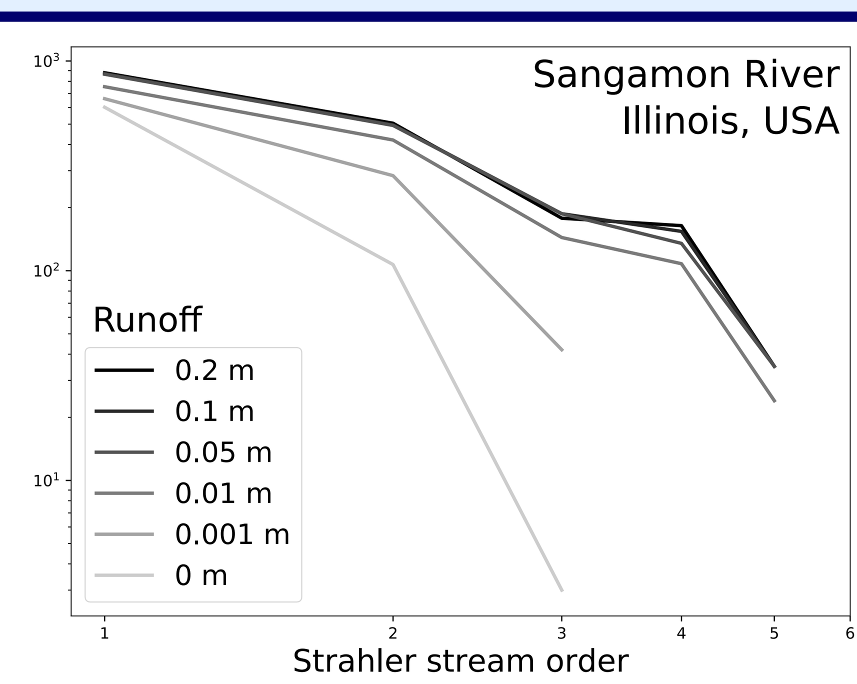

Figure 4: As more water is added to the landscape, more depressions are flooded and drainage integration (and therefore hydrologic connectivity) increases. More stream segments overall exist on the landscape, and they become more connected, increasing the fraction of higher-order streams.

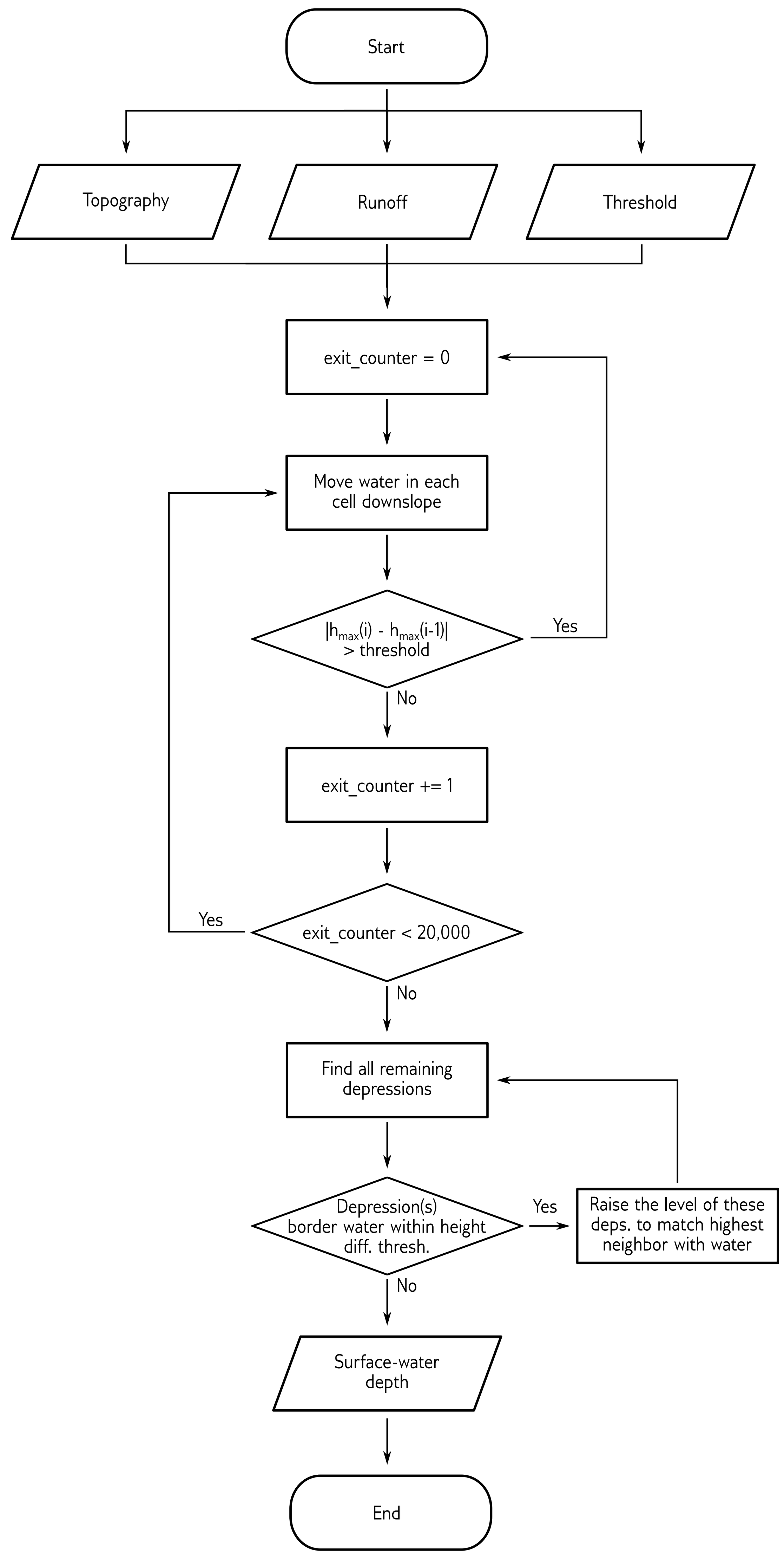

Figure 5: FlowFill flowchart. 'h_{max}' is the maximum amount of water moved from a single cell to another during each iteration ('i'). The majority of the runtime is spent sorting the cells into a queue and moving water from the highest cell to those below.

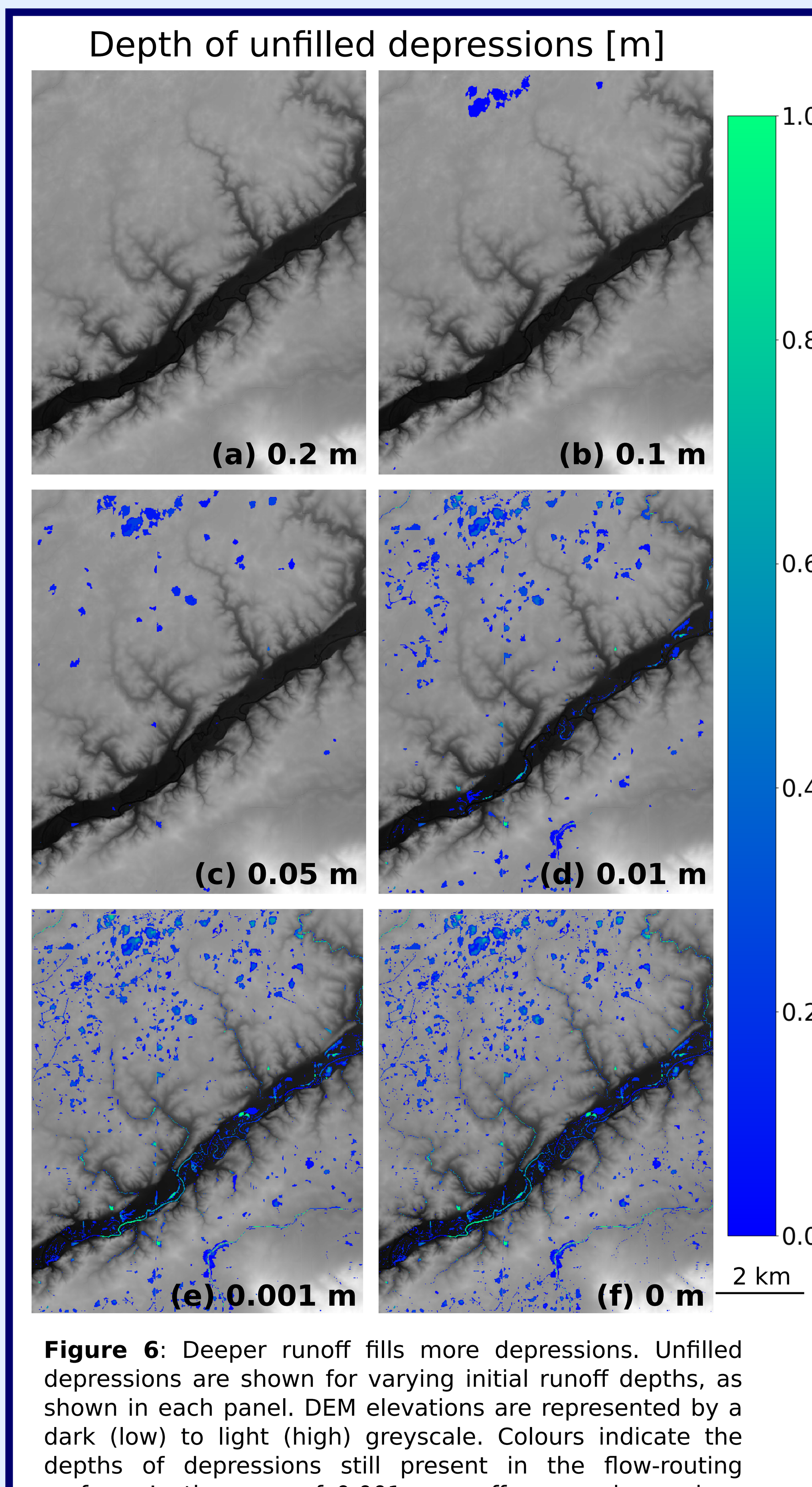

Figure 6: Deeper runoff fills more depressions. Unfilled depressions are shown for varying initial runoff depths, as shown in each panel. DEM elevations are represented by a dark (low) to light (high) greyscale. Colours indicate the depths of depressions still present in the flow-routing surface. In the case of 0.001m runoff, many depressions still remain, while with 0.1 m of starting runoff all but the largest depressions are filled. Depressions were fully filled with a starting runoff depth of 0.2 m.

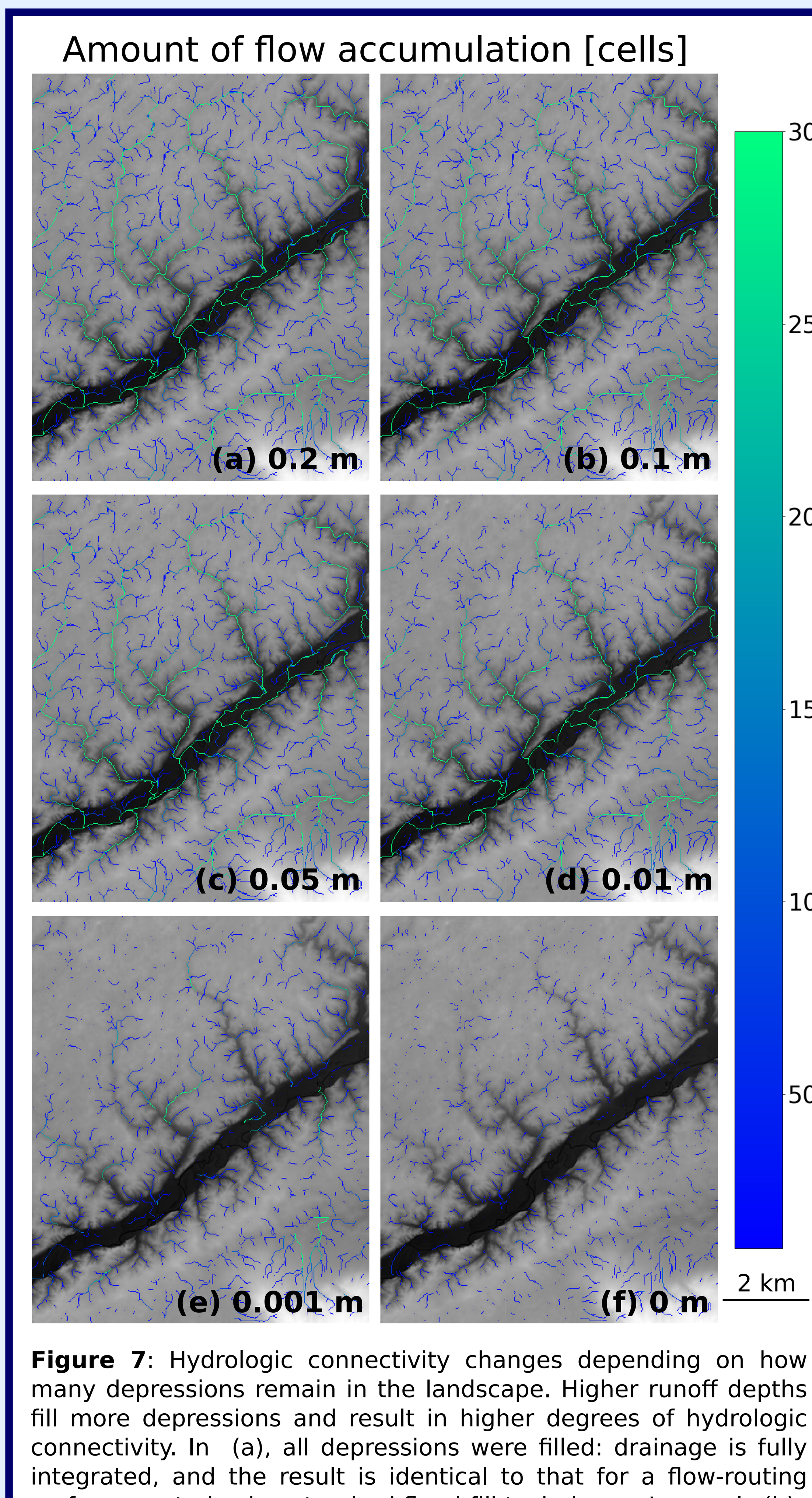

Figure 7: Hydrologic connectivity changes depending on how many depressions remain in the landscape. Higher runoff depths fill more depressions and result in higher degrees of hydrologic connectivity. In (a), all depressions were filled: drainage is fully integrated, and the result is identical to that for a flow-routing surface created using standard flood-fill techniques. In panels (b)–(e), decreasing amounts of starting runoff result in increasing segmentation of the stream network. Panel (f) shows the original DEM, which hosts only a few disconnected stream segments.

Discussion

FlowFill is able to create more realistic flow-routing surfaces by accounting for water stored in the landscape and disconnects in the drainage network. Depressions persist in flow-routing surfaces even when the prescribed initial runoff is deep. **The presence of depressions in the study site significantly reduced connectivity between stream segments**. It is likely that FlowFill will be most useful in cases where the geologic and geomorphic history of a landscape produce a surface with many depressions, such as this post-glacial landscape.

Using FlowFill with varying user-selected starting runoff values is ideal for **comparing network connectivity** in wet versus dry seasons, or for analysing the effects of storms of different sizes. Shallow runoff inputs to FlowFill imitate real-world conditions with low amounts of rainfall (e.g. during the dry season). During these times, hydrologic connectivity is significantly reduced, and routing flow across a completely depression-filled landscape becomes unrealistic. Deep runoff inputs simulate wet seasons or flood conditions. Due to the associated greater hydrologic connectivity, more of the region contributes water to basin outlets.

Limitations of FlowFill include long compute times, problems when input data contains three-dimensional structures such as bridges, and unique thresholds needing to be set for each study site.