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Watershed Delineation in the Field: A New Approach for Mobile Applications Using LiDAR Elevation Data

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Abstract. As mobile devices improve, the possibility of bringing watershed management tasks typically performed in the office to the field can be realized. High-resolution digital elevation models that capture microtopographic features such as natural depressions, road embankments, and ditches further enable field-scale analyses to take place. A sequential depression-filling algorithm (SDFA) designed to operate in mobile, resource-constrained environments has been developed to allow users to perform watershed delineations in the field. Depressions are filled based on their retention capacity and accumulation rate, and as they are filled, surface hydrologic connectivity increases. While complete hydrologic connectivity is assumed by many algorithms, natural depressions in specific terrains are filled only in extreme rainfall events by SDFAs. Additionally, users in the field may identify man-made structures such as culverts and tile risers that affect localized drainage, and means to integrate such features in the SDFA have been developed. Visualizations of hydrologically connected subcatchment polygons are presented and have been used in the field via the publicly available Android application.

Keywords. *watershed delineation, Digital Elevation Model (DEM), hydrologic connectivity, microtopography, depression filling, mobile application*

Introduction

Recent widespread development of high-resolution, Light Detection and Ranging (LiDAR)-derived *digital elevation models* (DEMs) and simultaneous advances in the cost, performance, and screen resolution of mobile devices are enabling the process of automated watershed delineation to move from research labs, offices, and desktop computers into the hands of people on the ground at almost any location. High-resolution DEMs are of particular interest in regard to hydrologic analyses performed by field conservation agents as they assess farmland for potential conservation practices and associated environmental impacts.

Applying existing, large-scale watershed delineation algorithms to these microtopographic DEMs can produce results which conflict with in-person observations in the field. Existing algorithms designed for large-scale watersheds and coarse resolution elevation data fail to properly account for the effectors of depression storage on microtopographic surface flow (Chu et al., 2010; Appels et al., 2012; and Yang & Chu, 2012). A person in the field can easily account for features that affect localized drainage such as tile risers and culverts that are not easily identified by automated methods.

The glaciated landscapes of the Midwestern United States present additional complications in enclosed natural depressions that are not hydrologically connected via surface flow, even in 100-year flood events. Since standard large-scale watershed delineations require hydrologic surface connectivity, then areas which do not naturally drain over the surface such as these depressions become key problem areas. Existing algorithms artificially alter either water flow direction or the DEM itself by filling or breaching depressions until complete connectivity is obtained (O'Callaghan & Mark, 1984; Martz & Garbrecht, 1999; Lindsay & Creed, 2005). This guarantees that the contributing area to a downstream point is continuous. However, sometimes these alterations can be quite dramatic, creating unrealistic scenarios and flow predictions that may not agree with in-person observations at line-of-sight scales.

Field-scale watershed delineations should not require hydrologic connectivity. Interesting questions at a field scale are generally related to actual rainfall events: e.g. the size of tile riser needed to drain a large area in a typical growing season, or the type and size of grassed waterway needed to reduce erosion at a particular location. In addition, much of the rainfall on active farmland drains through infiltration or underground structures such as tiles and culverts rather than over the surface. A person in the field can easily identify manmade structures, real stream locations and flow directions, changes to the landscape over time, or other conditions that may not be accurately captured by existing automated watershed delineation algorithms.

This paper will present an algorithm that delineates watersheds over time given a finite rainfall event amount and duration, similar to the algorithms proposed in Darboux et al., 2001; Antoine, et al., 2009; Chu et al., 2010; Appels et al., 2012; and Yang & Chu, 2012. Pit-filling and overflowing is modeled given the rainfall amount (rate and duration), depression retention capacity, and contributing area. Closed depressions that will not overflow for the rainfall event under consideration remain unfilled, and therefore represent a watershed subcatchment that does not contribute to surface runoff. The effects of noise in the elevation data are reduced since rainfall events large enough to be of interest will naturally fill most small, high-frequency pits almost immediately. The algorithm is optimized to run in a resource-constrained mobile environment, and is capable of performing delineations in a reasonable timeframe on smart phones or tablets.

Background

2.1 Watershed Delineation

Current watershed delineation practice is based on a set of functions first described by O'Callaghan and Mark (1984) for the purpose of digital terrain modeling and stream network extraction. For each cell in a DEM, the direction of water flow out of that cell is computed by looking at the 8 surrounding cells to find the one with the steepest downhill slope away from the current cell. The direction to the neighbor of steepest descent is assigned as the *flow direction* for the cell in question. This flow direction method is widely known by the name D8. Given a fully computed set of flow directions, the path of water through a DEM can be followed. All of those cells upstream and directed toward a cell may be delineated as the contributing area, or *watershed*. Cells with many other cells draining to them are considered to have high *flow accumulation*. Paths with flow accumulation above a user-specified threshold can then be considered as streams.

2.2 Pit Filling and Breaching

Most empirical DEM datasets contain pit-like depressions or low spots that terminate these flow paths because no downhill neighboring flow paths exist. If many pits exist, especially in low-relief landscapes, then this approach of flow direction provides little useful information since most areas in a DEM will not drain beyond a few cells. In times when only coarse-resolution DEMs were available (> 30-meter resolution), it was assumed that these pit depressions were artifactual, likely the result of noisy measurement data, and means to remove these depressions were devised in the form of pit filling (O'Callaghan & Mark, 1984).

Specifically, a *pit cell* is defined as a cell whose elevation is at or below that of all eight of its neighbors, meaning there is no available downslope flow path. The pit cell and all the cells which flow to it are a *depression*. For each depression, there is a minimum ridge elevation along the perimeter whereby if the depression were filled with water, it would begin to spill over. O'Callaghan and Mark (1984) employed a technique which reconnects the broken streams by altering flow direction from the spillover point to the pit cell at the bottom of the depression, simulating the filling of these pits by accumulation of water.

As DEM resolutions improved to the point that small-scale obstacles such as roads and ditches became discernible, it was necessary to handle the man-made structures which route water through them. Martz & Garbrecht (1999) identified elevated cells at the perimeter of depressions as obstructions to continuous flow. By lowering these few cells in the DEM at the depression edges (known as *breaching*), more appropriate flow paths could be computed.

2.3 Hydrologic Connectivity

Filling and breaching, together, are known as *hydrologic conditioning*: methods for altering a DEM or flow directions in order to make hydrologic analyses (i.e. stream network extraction, large-scale watershed delineation) more effective. In each method, pits are removed in order to guarantee complete *surface hydrologic connectivity:* i.e. yield a depressionless DEM where each cell has an unbroken, monotonically descending path to the DEM edges. This requirement ends up modeling unrealistic scenarios: some depressions would require a relatively large flood in order to overflow, but these depressions are filled the same as small depressions which overflow after a relatively small rainfall event.

It has been widely assumed that natural depressions are rare in coarse-resolution DEMs, with the exception of a few terrain types such as glacial, karst, and limestone areas as well as man-made rock quarries (Lindsay & Creed, 2006; Tribe, 1992; Muehrcke & Muehrcke, 1998; Mark, 1988; O'Callaghan & Mark, 1984). There is considerable debate on the appropriateness of requiring hydrologic connectivity given that surface depressions widely exist in nature and are readily apparent in higher resolution DEMs (Martz & DeJong, 1988; Tribe, 1992; MacMillan et al., 1993; McCormack et al., 1993; Burrough & McDonnell, 1998; Metcalf & Buttle, 1999).

It is also our experience that it is the unnatural modifications made to the DEM or flow direction to guarantee hydrologic connectivity which conflict most with observations in the field. At higher resolutions (less than 5-meter) in low relief landscapes such as those in the American Midwest, nearly every cell in the DEM belongs to a depression, as shown in Figure 1 where 99% of all cells in a 100-hectare area belong to a depression. Those cells that are not part of a depression are likely edge effects: if the dataset extent were slightly larger, they would also belong to a depression. According to MacMillan et al. (2003), the number of depressions increases exponentially with increasing DEM resolution. The depressions become so numerous that it is no longer safe to assume they are all artifacts which can be removed indiscriminately.

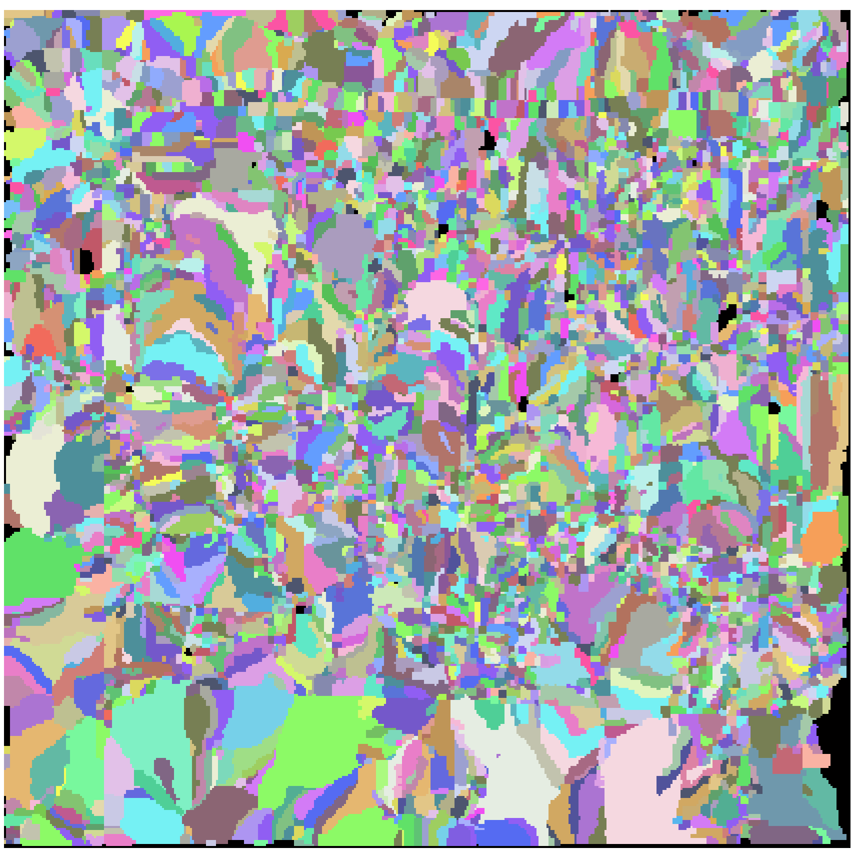


Figure 1. An agricultural field in Fulton County, Indiana, USA (approximately 100 hectares). Each polygon is comprised of a single pit cell (see definition in Section 3) and the non-pit cells that flow into it. In other words, each polygon is a hydrologically connected area. Note that almost every cell initially belongs to a depression. Those cells in black flow off the edge of the image.

2.4 Sequential Depression-Filling Algorithms (SDFAs)

The results of surface water quality models are affected drastically by requiring complete surface hydrologic connectivity. Surface flow plays a large role in the transport of pesticides and phosphorus to surface water bodies and aquatic ecosystems (Blanchoud et al, 2007; Louchart et al., 2001; Probst, 1985; Turtola & Jaakkola, 1995; Simard et al, 2000; Heathwaite et al., 2005). Surface flow concentrations of phosphorus are, on average, ten times higher than groundwater or tile-drained effluent concentrations (Rozemeijer, 2010). However, surface depressions act as detention basins, providing short-term storage for water, sediment, and nutrients while allowing water to evaporate and infiltrate (Lindsay & Creed, 2006; Hubbard & Linder, 1986; Rosenberry & Winter, 1997; Hayashi & van der Kamp, 2000; Antonic et al., 2001). Assuming that all water flows across the surface of the ground rather than being held in surface depressions will therefore result in very different estimates of the transport of pesticides, nutrients, and sediment when estimating water quality.

The effects of hydrologic connectivity on infiltration, runoff generation, and evaporation have been studied recently with the use of *sequential depression-filling algorithms* (SDFAs). By understanding the dimensions of each depression in the DEM, rainfall may be simulated over time, resulting in the filling and merging of depressions in order. In doing this, the hierarchy of and hydrologic responses resulting from these depressions may be understood (Darboux et al., 2001; Antoine et al., 2009; Chu et al., 2010; Appels et al., 2012; Yang & Chu, 2012). Each depression has a set of cells of greater elevation along the perimeter that enclose it (Figure 2). Of these border cells, the cell of minimum elevation is defined as the location where the depression would begin to overflow once filled to that *spillover elevation*. Given this elevation, the total volume of the depression may be determined: for each cell in the depression with an elevation below the spillover elevation, the volume may be computed as the difference between this spillover elevation and the DEM surface elevation of that cell multiplied by the DEM cell size (Equations 1, 2).

$$Pixel\ Area = (DEM\ Cell\ Size)^2 \tag{1}$$

$$Depression\ Volume = \sum_{i=0}^{n}(Spillover\ Elevation - Elevation_i) \times Pixel\ Area \tag{2}$$

Where n = number of pixels in the depression with an elevation < overflow elevation

Once the volumetric capacity of the depression is exceeded during a rainfall event, it overflows at the spillover cell, merging with the neighboring depression to create a new pit with a new volume and spillover elevation.

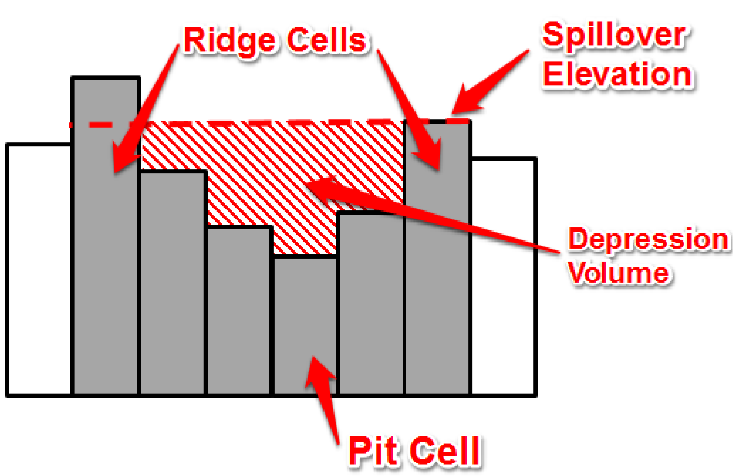


Figure 2. A 2-D depression annotated to illustrate terminology.

Objectives

Our goal is to facilitate watershed delineation through the development of a SDFA that handles the filling of depressions. Specifically, the algorithm should:

1) *Match observations:* The visualized results must be verifiable while on site and should not conflict with ground observations.
2) *Handle microtopography:* Since a user on-location is far more likely to be interested in their immediate surroundings rather than large-scale watersheds that could be easily delineated in the office, the algorithm must operate on microtopographic DEMs covering at least a square mile at less than 5 meter resolution.
3) *Allow modifications:* The algorithm should be able to account for small-scale hydrologic modifications (tile risers, culverts, and bridges).
4) *Be optimized for mobile devices:* Because it is aimed at field scale delineations while on location, the algorithm was designed to operate in mobile, resource-constrained environments.

Methods

A sequential pit filling algorithm is key to enabling the visualized output to match real-world situations with varied rainfall events. Given the volumetric capacity of the depression, the area over which rain would fall, and the rainfall intensity during an event (depth/time), the time at which a pit will overflow can be computed. The accumulation rate may be computed using Equation 3 while the total time to overflow the pit may be computed using Equation 4.

$$Depression\ Accumulation\ Rate = Depression\ Contributing\ Area * Rainfall\ Intensity \quad (3)$$

$$Depression\ Overflow\ Time = \frac{Depression\ Volume}{Depression\ Accumulation\ Rate} \quad (4)$$

Once the parameters for each pit have been computed, the pits are sorted in ascending order based on the overflow time. At this point, the set of depressions are prepared for rainfall simulation: the simulation starts by overflowing the first depression in the list, and continues in order until either the list of depressions is empty or until the rainfall event is over. Note that the loop runs once per depression rather than once per time step.

When one depression overflows into another, a new depression is made from the merging of the overflowing depression into the region which it overflows. The total time to fill that aggregate depression is computed, and it is placed back into the sorted list of depressions accordingly. The merging function determines whether the depression will overflow into another depression or the depression will overflow into an area which flows out the edges of the DEM.

The DEM is then adjusted during merging, raising those cells of the depression that are below the overflow elevation (i.e. filled with water) up to the overflow elevation. Flow direction within this depression is then resolved by aggregating these cells into a single “virtual DEM cell” with many inflow points and a single outlet toward the neighboring cell outside of the depression at the spillover point.

Since the list of depressions is sorted according to the time to overflow a depression from the start of the rainfall event, it is important that the time to overflow this new aggregate depression be referenced to the same start time rather than just the incremental time. As a result, it is necessary to include previously filled volumes as a component of the merged depression’s total volume. As such, Equation 4 may be rewritten as Equation 5.

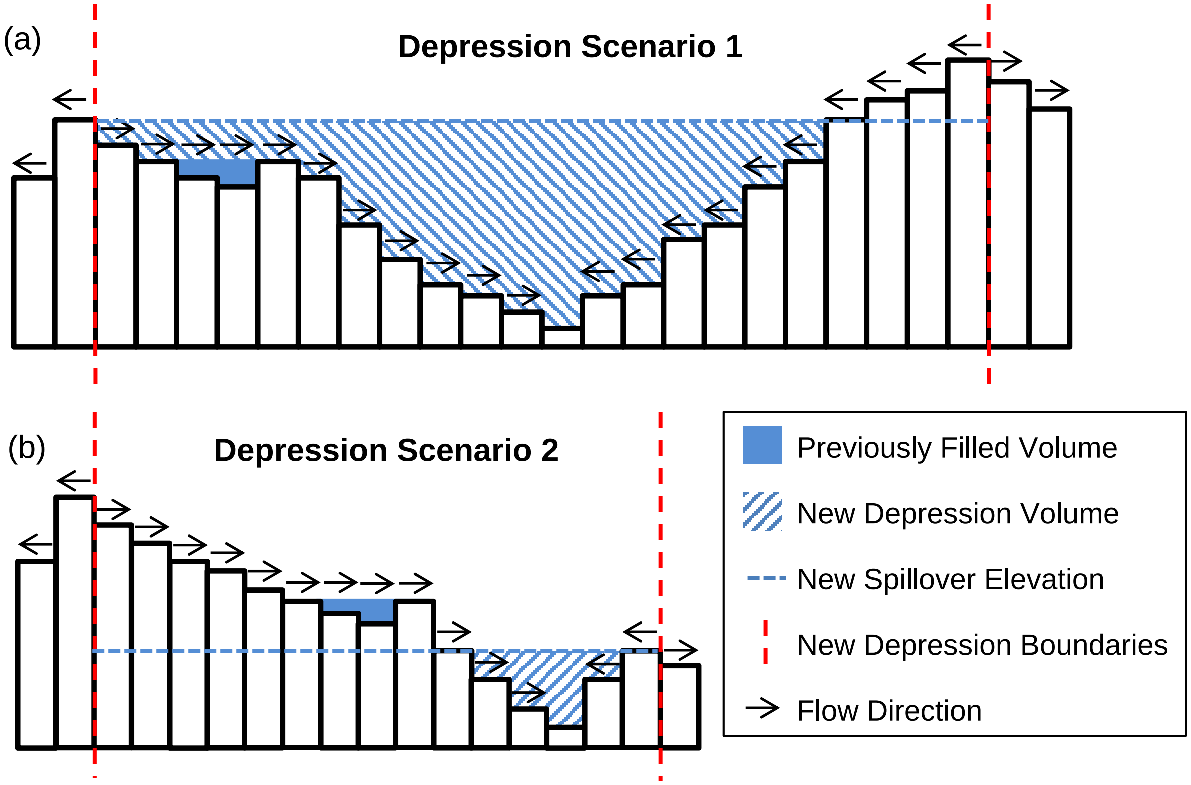


Figure 3. Comparison of depression scenarios: (a) the total volume of the new depression is the sum of the differences between cell elevations and the new spillover elevation. (b) the previously filled depression retains water above the spillover elevation which necessitates recording any previously filled volumes as any two depressions merge.

$$Depression\ Overflow\ Time = \frac{Depression\ Volume + Previously\ Filled\ Volumes}{Depression\ Accumulation\ Rate} \quad (5)$$

When any two pits merge, there are two possible orientations of the depressions. In the first scenario (Figure 3a), a small depression overflows into a larger depression, and the ridges of the two merging depressions were oriented such that the newly merged depression's spillover elevation is greater than those of the two merging depressions. In other words, the two original depressions shared the same overflow elevation. The volume of this merged depression may be calculated using Equation 4. This scenario may represent a large, natural depression with smaller noise depressions within.

However, in the second scenario (Figure 3b), a small depression fills, cascading down to the second depression. The application of Equation 4 to this scenario would result in a miscalculation of the total volume of the merged depression because none of those cells that belonged to the first (filled) depression are below the new spillover elevation. As a result, the volumetric capacity of the first depression would be neglected, resulting in a lesser total volume and time to overflow for the new depression.

4.1 Identifying Proper Spillover Points

Because flow direction is defined as the direction of steepest descent and each pixel may belong to only one depression, it is possible that a cell of greater height lays one cell beyond the edge depression cells. Looking at Figure 4, the minimum boundary elevation of cells that belong to Depression 2 would initially appear to be at Elevation B. However, it is apparent that Depression 2 would not overflow until filled to Elevation B. This distinction is important with respect to the calculation of each depression's retention volume, time to fill,

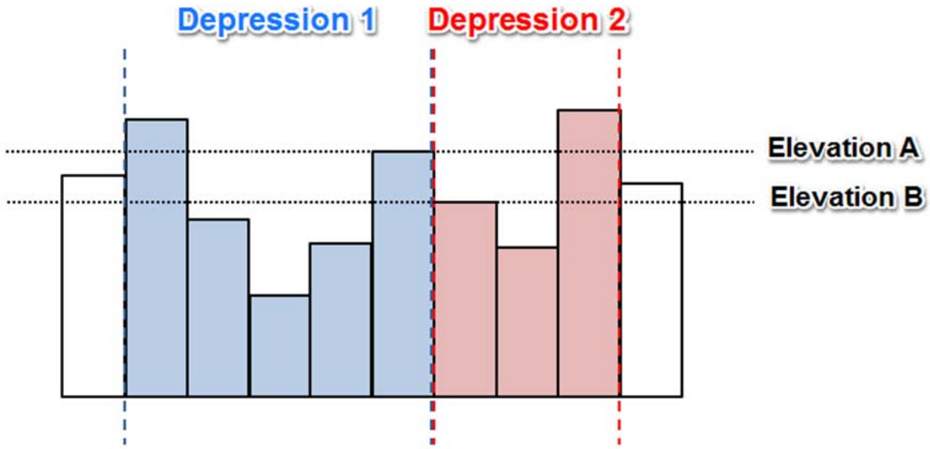


Figure 4. Illustration of the need to look one cell beyond pit boundaries: the minimum elevation for Depression 2 is at Elevation B, but it will not overflow until filled to Elevation A.

and, consequently, ordinal position in the filling process. It is therefore important when gathering information about each depression to search one cell beyond the depression boundaries. This special case also provides for the existence of single cell pits whereby no adjacent cells flow into the pit cell.

4.2 Handling Flat areas, Sub-surface Transport, Drainage Rates, and DEM Reshaping

The standard flow direction algorithms only allow one of eight neighboring cells to be the outlet for a given cell. This approach works well in all cases but two: perfectly flat areas and areas with substantial subsurface drainage like tile risers and culverts. Rather than limit the outflow of one cell to one neighboring cell, an attribute may be associated to each cell recording the index of the cell to which it is directed (i.e. its 'child'). This enables connections between non-adjacent cells; for example, a culvert may pipe water from one side of a road embankment to another.

The cells pointing into the current cell may also be associated as another attribute (i.e. a list of 'parents'). Because flow direction within a region of flat cells may be difficult to determine in natural topography, and more specifically in those areas that have been filled with water, all of the cells that are part of a flat area may be associated as a single "virtual cell" for which there is one child outflow and a list of inflowing parents. Grouping cells as such may also allow for more rapid modifications such as altering the elevation of the group if it is further filled or coloring the group for visualizations.

As previously mentioned, sub-surface drainage tiles are a common practice across the Midwest to drain otherwise oversaturated and unarable lands. While these tiles are typically laid horizontally several inches below the ground surface, they are sometimes routed up to the ground surface to drain concentrated surface runoff. Oftentimes, natural depressions in the Midwest are tile drained because they are so prone to puddle following rainfall. Once tile drained, these areas become much less likely to overflow and contribute surface flow to adjacent areas during reasonably normal rainfall.

Tile risers have the potential to affect drainage and hydrologic connectivity greatly, but the infiltration of water into the soil is another component that affects how well the model represents reality. Without soil infiltration, the ground is modeled as a lossless surface where all rainfall hitting the surface is conveyed immediately and directly to the local depression bottom, working to fill it up. This accurately represents conditions when soil is frozen, saturated, compacted, or when the rainfall rate is much greater than the infiltration rate. In other scenarios, soil has the potential to absorb water before runoff begins (Appels et al, 2011).

In terms of the algorithm developed, the incoming rainfall rate (intensity) must exceed the drainage rate of that cell before a flow direction is assigned. If not exceeded, the cell is denoted as a pit cell. Naturally, cells associated with the location of a tile riser (by user input) have higher drainage rates than those cells relying only on soil infiltration, and, consequently, are more likely to become pit cells. Depressions with such pit-cells with excessive drainage will have negative accumulations rates. As a result, the time to overflow will be negative, and these pits will come first when placed in ascending order. Instead, any depressions with a negative drainage rate are assigned an infinite overflow time until sufficient cells contribute to the depression to bring the accumulation rate up a positive value.

It is also possible that changes to the topography of an area of interest can occur after the LiDAR data was collected. These might include a fence row that has been cleared, a new grass waterway installation, newly built structures, etc. If the watershed delineation algorithm shows unreliable flow paths due to out-of-date elevation data, then users will be frustrated and discouraged when they cannot easily correct the DEM. The ability to virtually recontour the DEM via an interface on a mobile device that allows a user to build up or plow down elevations when in the field is a simple solution. The user may not easily achieve a perfect solution without manual surveying, but their modifications will likely produce better results than the use of an obviously incorrect DEM.

4.3 Optimizations for Mobile

By precomputing the time to overflow for each pit and sorting the overflow times, algorithmic complexity improves substantially. The algorithm does not waste time looping through time steps where nothing happens. This makes the algorithmic complexity dependent solely on the number of pits that need to be filled rather than the number of time steps in simulation.

Our algorithm also avoids the computationally intensive maintenance of dynamic water levels in each pit during the simulation. When one pit overflows into another, the total time to fill that aggregate pit is computed rather than the incremental time difference from the current time. This new aggregate pit may then be placed back into the sorted list of pits according to its total overflow time. Since the list is already sorted, inserting the new merged pit into the list is algorithmically fast.

Also, it is common to implement flow accumulation as a recursive function. However, this can quickly overflow the function call stack when operating on high resolution DEMs that may contain several thousands of connected pixels. Given the tree structure outlined in Section 1, flow paths are simple to traverse iteratively to generate a flow accumulation raster. For the purpose of surface connectivity for cells in a pit, only the indices draining to the pit are desired. Therefore, the doubly-linked tree which allows traversal both up and downstream, the order in which the cells are traversed does not matter as long as each parent is traversed and subsequent additional parents of that cell are added to the list of connected cells. While this doubly-linked tree structure can multiply the size of a DEM in terms of memory usage, the cost of the increase can be mitigated through caching of large flash storage that is generally available on mobile devices.

Results

We have developed a mobile app for Android which implements the algorithm described above using a 3-meter DEM derived from LiDAR elevation measurements. We have tested the app in agricultural fields covering approximately 700 acres in northern Indiana to follow the progression of watershed delineation over time, identify depressions too large to overflow in a 100-year rainfall event, identify and compensate for man-made drainage features, and quickly survey an area using visually-verifiable subcatchment maps.

5.1 Watershed Delineation Progression Over Time

As presented in the previous sections, the extent of hydrologic connectivity depends on time during a rainfall event, i.e., the rainfall amount. In Figure 5a-f, the change in the watershed delineated at point X over time with increasing rainfall can be observed. Clearly, the proper watershed delineation depends heavily on the amount of rainfall stored in depressions, and therefore changes over time as depressions fill and overflow. When comparing the SDFA with those that assume complete hydrologic connectivity, it should be emphasized that equivalent results may be produced by running a SDFA for infinite time and rainfall such that all pits are filled.

5.2 Pits too Large to Overflow in a 100-year, 24-hour Rainfall Event

Figure 5 demonstrates a watershed delineated in an agricultural field in Fulton County, Indiana, USA. Figure 5f is the result of filling all depressions and achieving complete hydrologic connectivity, which occurs only after the 100-year flood event. However, closer inspection reveals the presence of a large natural depression just upstream of the outlet selected. This depression, in fact, has a potential retention capacity of 14.4 acre-feet of water. Given that the watershed is 33 acres and, neglecting infiltration (a significant reduction to the rate of accumulation), it would require approximately the 100-year, 24-hour rainfall event for this region in order to fill this depression. The algorithm proposed here connects it to the watershed outlet for only the most extreme rainfall scenarios. Since it is unrealistic in most design problems to build for once-in-a-lifetime rainfall, then watershed management engineers should have the tools to accurately model realistic situations.

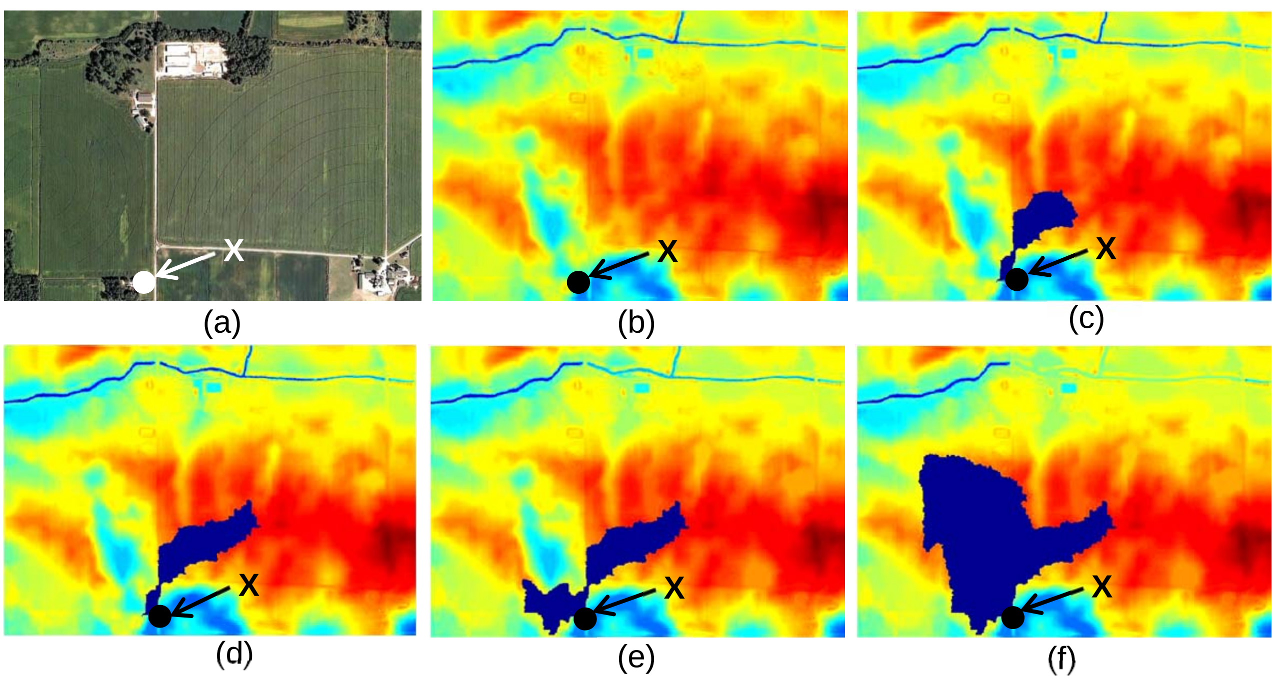
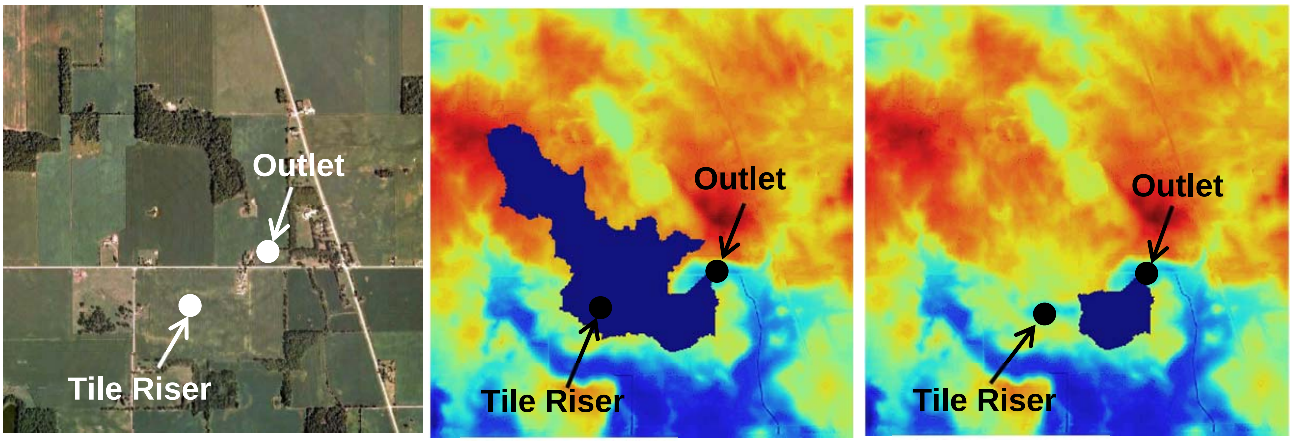


Figure 5. Watershed delineation in Fulton, County, Indiana: (a) Reference image and the progression of a watershed (in dark blue) delineated at outlet point X after: b) No rainfall, c) less than a 2-year, 24-hour rainfall (0.4 inches), d) a 2-year, 24-hour rainfall (3 inches), e) a 50-year, 24-hour rainfall (5 inches), and f) a 100-year, 24-hour rainfall (5.5 inches), neglecting infiltration. Note that (f) is equivalent to the watershed produced using tradition methods where all depressions are filled.

5.3 Effects of a Tile Riser

In Figure 6, a delineation is performed in another agricultural field in Fulton County, Indiana, USA. At location X in Figure 6a, a natural depression is drained with a tile riser. Traditional delineation methods would overestimate the total contributing area downstream of this natural pit (Figure 6b). This is not an issue for delineations performed downstream from the outlet of the tile riser since the water has returned to the surface at a stream, but all delineations upstream from the outlet will be incorrect.

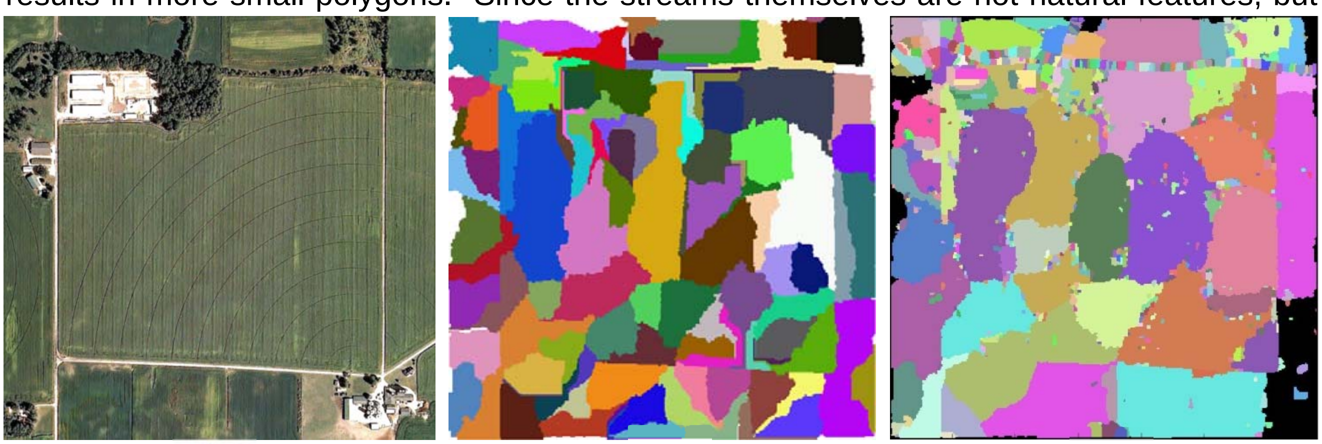


(a) (b) (c)

Figure 6. Watersheds delineated (in dark blue) at the marked Outlet point: a) reference image, b) ignoring existing tile riser and c) including tile riser. Note that b) overestimates the contributing area whereas c) does not because drainage through the tile riser has prevented the natural depression from overflowing.

5.4 Understandable Multi-Polygon Catchment Maps

Traditionally, multi-polygon maps of subcatchments have been generated by setting a flow accumulation threshold with all depressions filled (Figure 7b). A threshold number of contributing cells specifies the number of cells that initiate a stream (Mark, 1984; O'Callaghan & Mark, 1984; Tarboton et al., 1991). Once the stream network is determined, subcatchments are defined as the contributing area to the section of a stream between junctions. Choosing a larger threshold leads to larger polygons while a smaller threshold results in more small polygons. Since the streams themselves are not natural features, but



(a) (b) (c)

Figure 7. Multi-Polygon Catchment Maps: a) reference image, b) those produced using a flow accumulation threshold assuming complete hydrologic connectivity, and c) those produced using our algorithm before all pits have been filled.

rather artifacts of the chosen threshold, the resulting subcatchments are not clear and are largely unidentifiable when viewing the landscape in person.

In the algorithm outlined in Section 4, subcatchments can be defined as the contributing area to the pit-cell of each existing depression at any point during the rainfall event. In other words, watershed delineations are performed at the optimal set of points in a given topography which maximizes the contributing area, minimizes the number of polygons, and guarantees that every cell in the map is contained in exactly one delineation. The resulting map should be valuable to users and can be used to scout a field—similar to a person in the field using contour maps or other tools. By varying the filling process via the chosen rainfall event, topographically significant features may be identified at different hydrologic scales.

Conclusions

The coincidence of advances in mobile device technology with widely available high-resolution elevation data has enabled tools for watershed management in the field that previously were not possible. True microtopographic features and natural depressions can now be considered in ways that improve estimates of hydrologic connectivity and produce watershed delineation results which accurately reflect field-level features. The algorithm proposed here does not require that depressions in a digital elevation model be treated as measurement noise. Only with sufficient rainfall do these depressions fill, enabling visualization of natural depressions. Sequential depression filling algorithms (SDFAs) overflow depressions sequentially based on contributing area and retention volume. The SDFA described here and implemented as a mobile Android application allows users to make such distinctions and adjust the extent of hydrologic connectivity by specifying a rainfall event before watershed delineations take place.

Additionally, man-made alterations such as road embankments, culverts, ditches, and tile risers affect localized drainage and an interface has been developed that allows users in the field to compensate for such drainage features. Multi-polygon maps produced at varying levels of hydrologic connectivity have visual meaning in the field as the polygons are made up of verifiable topographic features.

Acknowledgements

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