This is the submitted version of **Lindsay, J.B., 2016. The practice of DEM stream burning revisited, *Earth Surface Processes and Landforms, 41(5): 658–668***, which has been published in final form at: DOI:10.1002/esp.3888. This article may be used for non-commercial purposes only.

The practice of DEM stream burning revisited

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Abstract

Stream burning is a common flow enforcement technique used to correct surface drainage patterns derived from digital elevation models (DEM). The technique involves adjusting the elevations of grid cells that are coincident with the features of a vector hydrography layer. This paper focuses on the problematic issues with common stream-burning practices, particularly the topological errors resulting from the mismatched scales of the hydrography and DEM data sets. A novel alternative stream burning method is described and tested using five DEMs of varying resolutions (1 to 30 arc-seconds) for an extensive area of south-western Ontario, Canada. This *TopologicalBreachBurn* method uses total upstream channel length (TUCL) to prune the vector hydrography layer to a level of detail that matches the raster DEM grid resolution. Network pruning reduces the occurrence of erroneous stream piracy caused by the rasterization of multiple stream links to the same DEM grid cell. The algorithm also restricts flow within individual stream reaches, further reducing erroneous stream piracy. In situations where two vector stream features occupy the same grid cell, the new tool ensures that the larger stream, designated by higher TUCL, is given priority. TUCL-based priority minimizes the impact of the topological errors that occur during the stream rasterization process on modeled regional drainage patterns. The test data demonstrated that *TopologicalBreachBurn* produces highly accurate and scale-insensitive drainage patterns and watershed boundaries. The drainage divides of four large watersheds within the study region that were delineated from the *TopologicalBreachBurn*-processed DEMs were found to be highly accurate when compared with the official watershed boundaries, even at the coarsest grid resolutions, with Kappa index of agreement values ranging from 0.952 to 0.921. The corresponding Kappa coefficient values for a traditional stream burning method (*FillBurn*) ranged from 0.953 to 0.490, demonstrating a significant decrease in mapping accuracy at coarser DEM grid resolutions.

Keywords: digital elevation model; flow enforcement; streams; hydrography; drainage patterns.

1. Introduction

Many applications of spatial hydrology and geomorphology rely on the near-surface drainage networks derived from regular grid DEMs. Flow algorithms use information about local surface gradient and orientation calculated from DEMs to model spatial patterns of flow direction (O'Callaghan and Mark, 1984). DEMs in their raw form contain problems that limit their usefulness for flow-path modeling applications. Various flow enforcement techniques have been developed to remove topographic depressions and flat areas within DEMs, thereby improving the representation of local drainage patterns (Barnes et al., 2014; Lindsay and Creed, 2005; Liu et al., 2009; Martz and Garbrecht, 1998; Planchon and Darboux, 2002). Depressions and flat areas, with their undefined downslope directions, are obvious obstacles for flow algorithms. A subtler problem occurs where the DEM-derived stream network, usually defined as a set of grid cells with relatively high flow-accumulation values (Marks et al., 1984; O'Callaghan and Mark, 1984), does not match the photogrammetrically mapped stream network for an area (Mizgalewicz and Maidment, 1996). This situation is frequently handled either by the use of specialized interpolation routines (e.g. the ANUDEM algorithm described by Hutchinson, 1989) that incorporate hydrographic data into the DEM creation process, or by using a practice known as *stream burning* (Saunders, 1999), which attempts to adjust the elevations within an existing DEM such that flow algorithms create local drainage patterns consistent with the mapped hydrography (Baker et al., 2006; Callow et al., 2007; Chen et al., 2012; Kenny et al., 2008; de Paz et al., 2008; Turcotte et al., 2001). Stream burning is commonly applied in the preparation of national and global topographic data sets (Dewald and Roth, 1998; Graham et al., 1999; Renssen and Knoop, 2000).

The term stream burning is a reference to the print making technique of etching, during which an acid resistant coating is placed on a metal sheet with a design pattern created by scraping the coating away in areas. These unprotected sections of metal are then burned when treated with acid, effectively cutting or lowering the surface in these areas. Stream burning works like a digital analog to the etching process. Several stream burning techniques have been developed, however, each method operates in a similar fashion. A rasterized version of the mapped vector stream network serves as a mask and each stream grid cell is lowered in the DEM (Graham et al., 1999; Wesseling et al., 1997) relative to neighboring non-stream (land) cells, or alternatively, land cells are raised (Maidment, 1996; Maidment and Saunders, 1996; Saunders and Maidment, 1995). This process cuts a network of trenches into the DEM surface along sites coincident with the mapped hydrography, which then serves to redirect local drainage into these digitally carved stream channels.

While stream burning is a simple and effective means of enforcing mapped drainage patterns, there are several problems associated with the technique. The purpose of this paper is to identify some of the challenges with existing stream burning methods and to present alternative improved methods for performing topography-hydrography based drainage pattern modeling.

2. Stream burning methods

The exact origin of stream burning is unclear but its widespread adoption as a DEM pre-processing method has its roots in the work of researchers within the Center for Research in Water Resources (CRWR) at the University of Texas during the mid- to late-1990's (Graham et al., 1999; Hellweger and Maidment, 1997; Maidment, 1996; Maidment and Saunders, 1996; Mizgalewicz and Maidment, 1996; Saunders, 1999; Saunders and Maidment, 1995). Several stream burning methods were developed at the CRWR at this time. The idea of incorporating mapped hydrographic data in the creation of a DEM used in hydrological applications appears to have been inspired by ANUDEM, the specialized interpolation routine of Hutchinson (1989). However, stream burning methods differ from this approach in that they incorporate mapped hydrographic information into existing, already interpolated DEMs through the modification of a set of individual grid cell elevations.

Most stream burning techniques use similar workflows. First, a vector stream network is rasterized onto a streams grid with the same resolution and extent as the DEM. It is common to apply a line-thinning algorithm at this stage to ensure a single-cell wide stream network (Saunders, 1999). The DEM elevations of stream cells are then separated from adjacent land cells, either by lowering the stream elevations or equivalently raising the land. Many of the earliest applications of stream burning used the land-raising approach (e.g. Saunders and Maidment, 1995), perhaps because they focused on coastal areas and negative elevation values within cut stream channels were undesirable. Nonetheless, the stream-lowering approach is equivalent, modifies fewer grid cells, and is conceptually simpler. Regardless of which approach is used, it is the stream-land elevation separation step that differentiates each of the existing stream burning algorithms. The simplest and most common separation method applies a constant elevation offset to stream cells (Saunders, 1999). The stream-land separated DEM then has a procedure applied for removing depressions and flat areas, most commonly a depression filling technique (Jenson and Domingue, 1988). The result is a hydrologically corrected DEM, with continuously monotonically descending flow path connecting each grid cell to the data edge and with burned-in trenches coincident with the mapped stream network. This final elevation model can then be used for subsequent drainage pathway modeling, including the calculation of local drainage direction, flow accumulation (upslope area), watershed delineation, etc. Saunders (1999) described an algorithm, referred to as *FillBurn*, which used this combination of line thinning after rasterization, a constant elevation offset, and depression filling.

One of the challenges with stream burning is deciding how to calculate elevation offset values. When a constant offset is applied, the tendency is to use a large value to ensure that the entire stream network lies below the surrounding land surface even after the depression filling step (Wesseling et al., 1997). Previous research has however demonstrated that deeply incised stream networks resulting from large offset values can significantly alter the terrain attributes derived from DEMs (Callow et al., 2007; Saunders, 1999; Turcotte et al., 2001). More sophisticated methods apply varying offsets in an attempt to minimize the impact of burning on the DEM. Saunders (1999) describes two burning methods that use varying elevation offsets including the *Expocurv* method, which assigns stream cells with values fitted to an exponential curve between the highest and lowest elevations in the reach, and the *Tribburn* method, which iteratively smooths stream cells along reaches from upstream to downstream. Baker et al. (2006) describe a 'normalized excavation' method in which streams are assigned a height based on the minimum elevation within a local neighborhood surrounding each stream cell. While minimizing the degree that incising stream channels modifies the DEM is clearly desirable, Jones (2002) argues that the issue of offset height is immaterial because only the drainage direction information is used in subsequent hydrological analysis of the DEM. That is, a stream-burned DEM is not suited for use in measuring local slope gradient, curvature and other morphometric attributes, for which the original DEM is better applied.

In addition to the impact altering the DEM has on subsequent analysis, another frequently cited issue with stream burning is the occurrence of parallel stream channels where the original DEM representation of a channel is well defined but misaligned with the corresponding mapped stream line. The problem of these erroneous parallel streams has been addressed using surface reconditioning techniques such as the AGREE method of Hellweger (1997), which alters the surface of the DEM in the areas adjacent to streams so that they slope towards the channel. More recently, Getirana and colleagues (Getirana et al., 2009a, 2009b) have proposed a 'double DEM burning' method that also applies a secondary gradient within the adjacent floodplain areas. Surface reconditioning can impact extensive areas within DEMs, potentially significantly altering modeled drainage patterns (Callow et al., 2007). Soille et al. (2003) offered a conservative alternative to surface reconditioning by only burning streams in places where the digital stream deviates by more than a specified threshold from the hydrography.

The stream burning process requires careful editing of the vector hydrography layer prior to rasterization. In particular, loops in the network that result from stream braiding, inclusion of lake and wetland polygons, and wide streams where both banks are visible at the map scale, must each be resolved (Saunders, 1999). Discontinuous stream lines, which do not intersect the DEM edge, must also either be removed or digitized to continuous features. Lakes and wide two-bank stream features are generally replaced with their centerlines. Turcotte et al. (2001) and Kenny et al. (2008) both presented modified stream burning methods for directly handling the presence of lakes and wetlands.

Many of the less well recognized problems associated with stream burning techniques are the result of the stream rasterization process and the inability of a modified DEM to characterize stream topology through elevation decremented flow paths alone. Frequent use of line-thinning methods with stream burning algorithms is particularly problematic. Many line rasterization methods used for vector-to-raster conversion in GIS software packages yield 'fat' or widened raster line networks. Although these wide line networks can cause ambiguous pathways through the rasterized stream network, line thinning causes the rasterized streams to further deviate from the topology of the original vector hydrography layer. Line thinning forces nearby streams to occupy the same channel grid cell. This can result in large discrepancies between stream burned DEM-derived flow paths and the mapped hydrography. Thus, the assumption that vector stream lines can be represented as single line features does not necessarily translate to an equivalent assumption of a thin-line rasterized stream network.

Rasterization often results in inadvertent stream adjacency and stream collisions. Stream adjacency occurs where two stream channels, separated by a short distance relative to the DEM resolution, are in contact (i.e. neighboring cells) within the raster. When stream burning is applied using a rasterized network containing inadvertent adjacency, erroneous stream capture (piracy) will occur as the flow from the higher channel is directed towards the lower neighboring channel. A stream collision, or what Turcotte et al. (2001) refer to as an artifact confluence, is where two or more vector streams pass through the same grid cell (excluding actual confluences where this condition is expected); it is a more severe form of stream adjacency and also results in topological errors (artifact capture) in the final drainage direction raster derived from the stream-burned DEM. While collisions occur most commonly immediately upstream of acutely oriented confluences, the condition can also occur at key mid-reach positions and channel head locations, where the impact on the modeled regional drainage patterns can be large. A less severe form of this problem occurs where a single stream link collides with itself at tight meanders causing erroneous cutoffs in the rasterized stream network and flow direction grid. While cutoffs are unlikely to affect regional drainage patterns significantly, they can impact DEM-derived measures of channel length by causing spurious channel shortening (de Paz et al., 2008). Line thinning a rasterized stream network converts stream adjacencies into collisions and will impact drainage patterns accordingly. Turcotte et al. (2001) modified the rasterized stream network, prior to burning, to remove some instances of these topological errors.

Stream burning may be a poor flow enforcement option when the level of detail in a vector hydrography layer is so fine that it cannot be represented as a raster at a certain resolution without significantly modifying the original network topology owing to the presence of artifact stream adjacency, collisions, and meander cutoffs. There is a clear relation between the scale of the mapped streams layer, the grid resolution, and the occurrence of topological errors (Saunders, 1999). When the vector scale and grid resolution are poorly matched, errors will be more frequent. The grid resolution of the rasterization process is fixed and set by the resolution of the DEM. Thus, in situations where the detail of the mapped hydrography layer is too fine to be accurately represented at the scale of the DEM, the best option may be to prune the lower-order, headwater streams from the network and to only rasterize a subset of higher-order streams. This should minimize the degree to which erroneous stream capture affects modeled drainage patterns. Reducing the level of detail of the vector hydrography layer by pruning low-order streams may also be justified by the fact that these reaches are often the least accurately mapped features in the network because they are narrow, are often intermittent, and tend to be obscured by dense vegetation cover.

With existing stream burning methods, all of the topological information contained within the vector hydrography layer is lost during rasterization, i.e. streams are simply represented as a Boolean grid of stream vs. non-stream cells with no information about how stream grid cells are connected to one another. Incorporating basic information about the topology of the hydrography layer into the stream burning method could further reduce the occurrence of errors. For example, erroneous mid-reach stream capture could be eliminated while maintaining the topological correctness of the original hydrography layer by only allowing in-channel flow between neighboring grid cells that belong to the same stream link, except at link-end points where flow can leave one link and enter another. This implies the need to incorporate a link identifier value rather than representing the network as a Boolean stream/non-stream, similar to how Turcotte et al. (2001) processed the stream topology of their rasterized streams. The impact of erroneous stream capture could be further reduced during the rasterization process if grid cells with more than one contained stream (i.e. collisions) were assigned the link identifier of the stream line with the higher magnitude. Although this approach does not reduce the frequency of erroneous stream capture, it does lower the impact of collisions on regional drainage patterns. Stream magnitude could be calculated from the vector hydrography layer as either a measure of stream order (e.g. Strahler-Horton order) or TUCL. This same measure of stream magnitude could also form the basis of the network pruning operation described above.

To summarize, the main criticisms and limitations associated with the stream burning approach include:

1. The difficulty in determining an appropriate elevation offset and its impact on the resulting DEM.

2. The prevalence of parallel streams in places where mapped streams do not coincide with drainage lines in the DEM.

3. The need to manually edit hydrography data to handle wide streams where both banks are mapped, lakes, discontinuous streams, and loops resulting from channel braiding.

4. The prevalence of topological errors (manifested as erroneous stream adjacency and collisions) introduced in the drainage network derived from stream-burned DEMs arising from the stream rasterization process.

3. An alternative stream burning procedure

A new stream burning method is introduced here, the components of which are illustrated in Fig. 1. The method has been developed as a plugin tool called *TopologicalBreachBurn* for the open-source GIS Whitebox GAT (Lindsay, 2014). The source code for the tool is distributed under an open source license and is available from the Whitebox GAT project homepage (http://www.uoguelph.ca/~hydrogeo/Whitebox/).

The method explicitly aims to reduce the occurrence and impact of topological errors during the rasterization and burning processes. This is achieved by:

1. Tracking the occurrence of collisions during rasterization and reducing their prevalence by simplifying the stream network by pruning low TUCL links,

2. Assigning the streams raster unique stream link identifier values during rasterization and prioritizing stream links with higher TUCL where there are stream collisions, thereby lowering the impact of collisions, and

3. Confining in-stream flow between neighboring cells of the same link identifier value except at link end nodes (handles the adjacency problem).

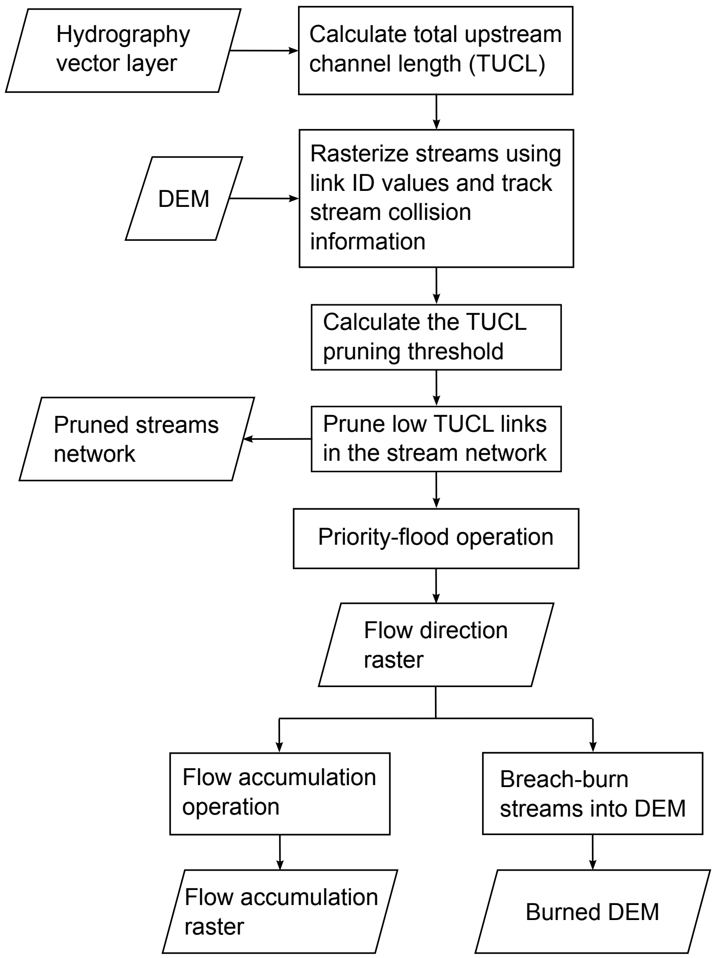

Figure 1: The *TopologicalBreachBurn* stream burning method.

The first two of these topology-preserving strategies are integrated into the method's rasterization process. The resulting raster, which contains stream link identifier values, rather that Boolean stream/non-stream values, is then input along with the DEM into a specialized priority-flood algorithm (Soille and Gratin, 1994) to calculate a D8 flow-direction raster (Fig. 1). Once the priority-flood operation is complete, the flow-direction raster can be used to calculate flow accumulation and to breach-burn the DEM. The breach-burn operation is similar to a regular depression breaching operation (i.e. carving depressions at their spill points rather than filling their interiors; for details see Soille, 2004), except that there are special carving rules applied to stream cells. This method can result in a burned DEM with minimal alteration.

3.1 Calculation of total upstream channel length (TUCL)

TUCL is estimated at the downstream node of each stream link in the vector hydrography layer. These data are then used to prioritize higher TUCL links during the assignment of link identifier values to cells with collisions and to prune smaller headwater streams when necessary. The algorithm requires the input of a vector hydrography layer in ESRI's Shapefile data format (ESRI, 1998), which is one of the most common data formats used for distributing hydrography data. Importantly, the Shapefile is a non-topological data structure, meaning that it does not store information about the connectivity between features. Instead, the algorithm determines link connectivity by evaluating the proximity of the coordinates of all stream link end vertices.

The algorithm first identifies all stream links that intersect with areas of valid data (non-NoData) within the DEM. All other links are marked as beyond the edge and are excluded from further analysis. All exterior links in the network are identified, including first-order headwater streams and outlet links. These links are denoted by the fact that they have at least one end vertex that is not connected to another stream link within the boundaries of the DEM's valid data. The minimum elevation of each exterior link (*MinLinkElev*) is measured based on the underlying DEM and is stored in a list. Exterior links are visited in order from lowest to highest *MinLinkElev* and a recursive tree-walking algorithm is used to traverse the network of streams connected to exterior links. Links can be traversed by the algorithm only one time. This means that outlet exterior links need not be explicitly distinguished from first-order streams; first-order streams with their relatively high *MinLinkElev* will be encountered during the traverse of their lower outlets. As the algorithm traverses the network, it records the TUCL for each link in the connected network.

The TUCL values are used during the stream rasterization step to simplify the network and reduce the number of stream collisions. Pruning the stream network based on TUCL removes all links with values less than the pruning threshold (Fig. 2A). However, if a stream network is simplified in this way, the network extent is severely reduced and large areas within the headwater regions of the catchment are left with no streams at all. To resolve this issue, an upstream-propagated TUCL index was used as the basis for network simplification (Fig. 2B). The upstream-propagated TUCL can be calculated by traversing,outlet-link trees a second time to propagate the TUCL value (calculated during the first traverse) of each link upstream, assigning the higher-valued inflowing link at each confluence the value of the downstream link. In this way, the main stem of a stream network is assigned the TUCL value of the whole catchment while its tributaries are given the values of their own sub-catchments and each tributary can be traced upstream to their source links. This allows for a more conservatively pruned stream network that maintains the original network's extent while also thinning smaller headwater streams (Fig. 2B). By using upstream-propagated TUCL (Fig. 2B), more of the network's original extent is preserved after thresholding because by marking tributaries all the way to their sources some headwater streams will always be retained. A fully pruned stream network based on thresholding upstream-propagated TUCL would include only the main stem, from outlet to source, and no tributaries. By comparison, using TUCL (without upstream propagation) as a metric of stream importance, a fully pruned network would include only the stream link connected to the catchment outlet.

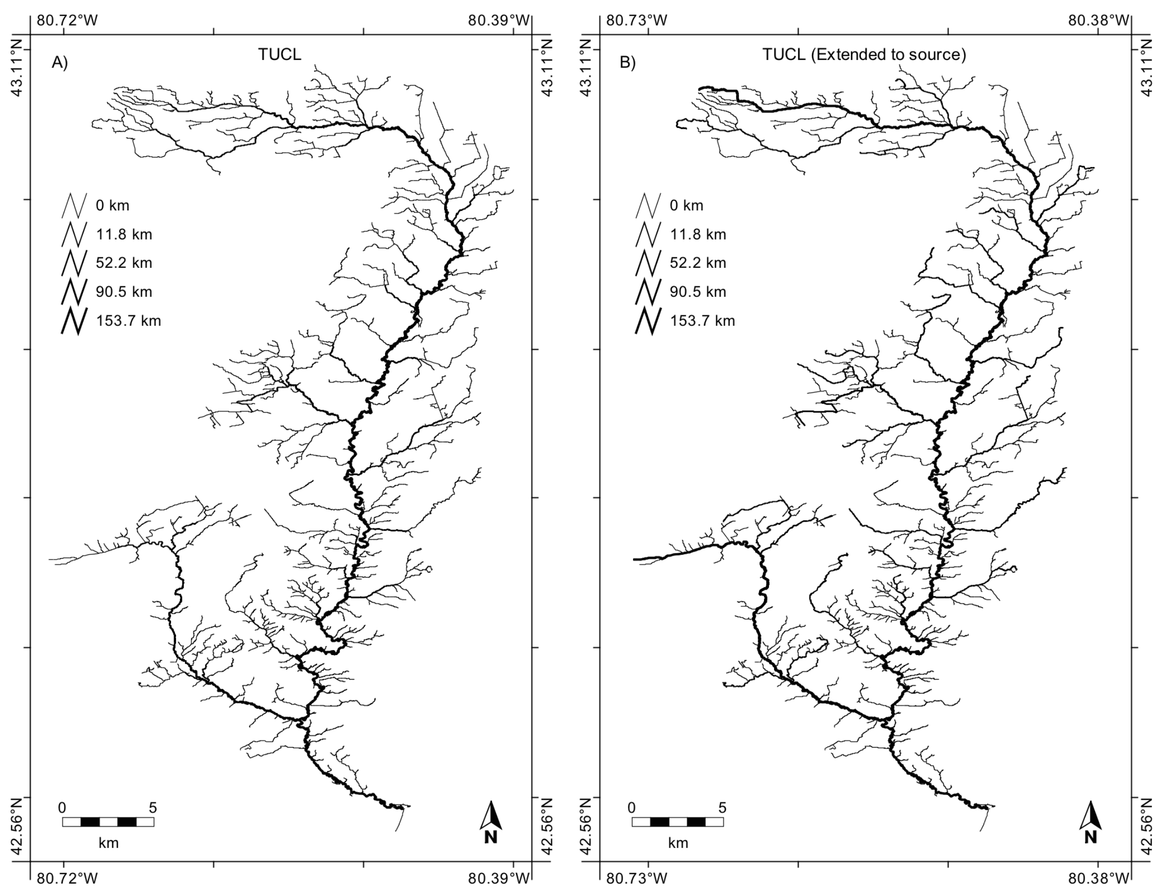

Figure 2: Pruning the Big Creek (Long Point, Ontario) stream network based on various thresholds of A) TUCL, and B) TUCL after extending main stems to their sources. The extent of each pruned network is denoted by the varying line thickness.

3.2 Topologically guided stream rasterization

There are several vector-to-raster methods in use. Many GIS use a technique whereby if the vector line crosses a grid cell at any point (i.e. intersects the cell boundary) it will be included in the rasterized feature. This approach can yield ‘fat’ line networks when the vector is highly curved, as is often the case with stream lines. This may be one of the reasons why line-thinning operations are commonly applied during stream burning. Instead, we prefer a grid centerline intersection method for rasterization (Fig. 3), which yields relatively thin lines, although the network will not necessarily be a single cell wide everywhere.

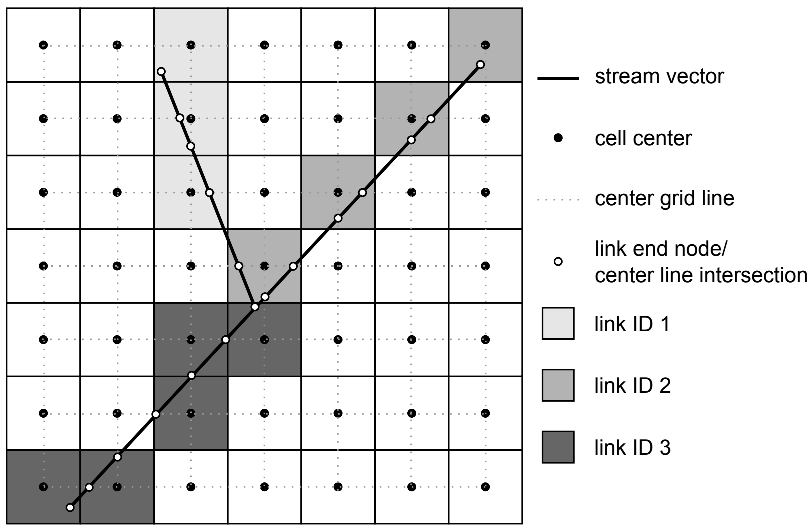

Figure 3: A description of the grid centerline rasterization method used by *TopologicalBreachBurn*.

Note that line thinning is not needed with the *TopologicalBreachBurn* method because stream adjacencies are correctly handled by the priority-flood operation by disallowing flow between neighboring channels (indicated by their different link identifiers) except at link end-nodes. Stream collisions, however, are dealt with through the rasterization processes by 1) assigning grid cells with more than one inclusive vector stream the identifier of the link with the larger TUCL value, and 2) removing links with a TUCL value less than a threshold.

Determining the threshold TUCL value used to prune the network is a two-criteria optimization problem. In choosing a TUCL threshold, we aim to minimize both the percentage of collisions remaining after pruning and the percent of the network that is pruned. Therefore, the threshold is determined by the minimum point in the combined function of the two criteria. The number of collisions that remain after pruning the network to a specified TUCL value is calculated during a first-pass rasterization in which the TUCL of the minor tributaries of each collision is identified and stored (Fig. 1). After the pruning threshold is calculated, the streams are then re-rasterized, this time only rasterizing features with

TUCL values greater than the calculated threshold.

A second raster is created during rasterization to store the along-line distance (position) of each stream cell relative to the link starting position. This raster is used later to identify link-end-node cells, i.e. cells that are either the maximum or minimum link position value for the set of neighboring cells with the same link identifier value. This information is used in the priority-flood operation.

3.3 The modified priority-flood operation

This specialized priority-flood operation, used to create the flow-direction raster, has been modified to assign a higher priority to stream cells and also to account for the third topology-preserving strategy above. The priority-flood method has been widely applied to DEM flow enforcement previously (Barnes et al., 2014; Liu et al., 2009; Soille, 2004; Wang and Liu, 2006) and provides an efficient means of visiting DEM grid cells in their flood order. This is the sequence in which grid cells would be inundated by rising water originating from the area beyond the grid's edges. As this digital flood wave progresses inward and uphill, grid cells are entered into a priority queue when they are first contacted by the advancing wave. A priority queue is a data structure that allows for efficient storage and retrieval of data values based on an assigned priority. The priority metric is usually determined in these types of algorithms by elevation such that lower cells are assigned higher priority. However, the modified priority-flood algorithm used here assigns priorities first based on the stream/non-stream condition of grid cells and secondly based on their elevation within the DEM. Notice that there is no need to perform the typical stream-land elevation separation step before executing this specialized priority-flood algorithm.

The process is initialized by entering the cells along the edges into the priority queue, with priority values determined by a combination of cell stream/non-stream value and elevation. The highest priority cell within the queue is then removed and its eight neighbors are scanned. All stream grid cells that are currently in the priority queue will be popped (removed) before land cells because of the hierarchy used in assigning priority values. Any newly found neighbors (i.e. cells that have not previously been added to the priority queue) are candidates for enqueuing. The process of popping the highest-priority cell and discovering and enqueuing new cells iterates until each grid cell has passed through the queue. The rules for adding newly encountered cells to the priority queue are:

1. Any non-stream cell neighboring the active cell can be added to the queue.
2. Stream link end-node cells (i.e. cells at either end of a stream link) can be added to the queue by any non-stream cell and any stream cell draining to the same outlet link (determined during the TUCL traverse). The fact that non-stream neighbors can add link-end nodes is necessary to handle discontinuous stream lines (discussed below).
3. If the active cell is a stream cell, it can add neighboring stream cells if they are of the same stream link identifier value.

Therefore, land cells cannot add non-end-node stream cells to the queue and non-end-node stream cells cannot enqueue other non-end-node stream cells with different identifiers. Each time a new cell is added to the queue, the flow-direction raster is updated so that the corresponding cell is assigned the direction to the neighboring cell from which the newly discovered cell was identified.

3.4 The flow accumulation and breach-burn operations

The flow accumulation and breach-burn (stream burning) operations can be performed simultaneously. The flow-direction information is used to identify the inflowing and down-flow-path neighbors of each cell in the raster. First, a new grid is created to store the number of inflowing neighbors for each cell, which is assessed using a 3×3 roving window. Cells with no inflowing neighbors (located at drainage divides) are identified and serve as the starting locations of downslope directed flow-path tracing operations. A flow path can be traced downslope of a cell only when every inflowing cell has been traversed. As flow paths are traced from their sources to their outlets, the number of upslope grid cells (i.e. flow-accumulation value) is tracked and stored in the flow-accumulation raster.

If a down-flow-path land cell is equal to or higher than its lowest inflowing neighbors (based on the elevations in the input DEM), the cell's elevation is lowered in the output breach-burned DEM to the lowest inflowing neighbor's elevation less a small value (e.g. 0.001 elevation units). Stream cells are handled in a similar fashion with an additional rule. Stream cells must be lower than all inflowing neighbors and lower than all neighboring land cells, inflowing or not. Once a flow-path trace has encountered a stream cell, all down-flow-path cells are treated as streams and follow the above rules. This allows for the presence of discontinuous (i.e. dangling) streams in the vector hydrography layer, without the need for prior digitizing. In this case, the algorithm will burn in the flow path dictated by the flow-direction raster from the dangling stream's bottom-most cell, downslope until it either encounters a downslope stream cell or the edge of the raster.

The breach-burn process breaches the topographic depressions and forces a gradient within flat areas and will ensure continuous flow paths in the hydrologically corrected output DEM. Depression breaching has an advantage over filling methods in that the flow-direction information contained within depressions are preserved; filling methods replace the interior of depressions with flat areas raised to the level of their outlets. Topographic depressions can be extensive in the low-relief landscapes in which stream breaching is typically applied.

Notice that the flow-direction grid that is produced by the priority-flood operation described above will not necessarily be the same as what would be produced by calculating flow direction from the output breach-burned DEM because doing so would be based solely on local elevations and does not account for stream link topology. The flow-direction and flow-accumulation rasters are the primary outputs of the *TopologicalBreachBurn* tool; the breach-burned DEM is only useful for visualization and in cases where the user wishes to apply an alternative flow algorithm to D8.

3.5 TopologicalBreachBurn and the limitations of stream burning

The main focus of the *TopologicalBreachBurn* tool is to reduce topological errors resulting from the stream rasterization step of stream burning. However, the new tool also addresses other issues identified with the stream burning method. While not completely removing the need to manually edit the vector hydrography layer, the algorithm does automatically cope with loops in stream networks resulting from braided channels as well as the problem of dangling streams. Wide channels (with both banks present) and lakes must still be replaced with feature centerlines prior to application. The tool also addresses the issue of choosing an appropriate elevation decrement value. Although a burned DEM may be created, the primary output of the tool is a flow-direction raster, which can then be used for subsequent flow modeling applications. The use of a breaching-based priority-flood operation ensures that when a stream-burned DEM is created, grid cells that are coincident with streams will be lowered only by the minimum elevation decrement needed to ensure a continuously decreasing (i.e. monotonically downward) flow path. The fact that stream grid cells are given highest priority during the priority-flood operation serves to draw flow in from the areas adjacent to streams, somewhat reducing the prevalence of the parallel stream artifact common with other stream burning methods. Parallel stream artifacts may still occur where stream channels are deeply entrenched within the original DEM. A strong topographic signature of fluvial incision within the DEM, however, may be indicative of a situation where the DEM is a more accurate representation of the stream course than the mapped hydrography, in which case, stream burning may be dubious.

4. Case study

To demonstrate the *TopologicalBreachBurn* tool, the algorithm was applied to a 4° × 4° region within southwestern Ontario, Canada (Fig. 4). The topography of southwestern Ontario is dominated by the Niagara Escarpment, above which the land slopes gently in a northwest-southeast direction. Below the escarpment, the topography is dominated by the Lake Ontario basin. The elevation of the region ranges from its highest point of approximately 520 m, located along the northern length of the escarpment, to the lowest elevation of 73 m, the height of Lake Ontario. Other than the Muskoka region north of Lake Simcoe, which is situated on the Canadian Shield, most of the study area is marked by well-developed fluvial systems. Fig. 4 shows four of the major inland watersheds of the region, including the drainage basins of the Grand, Thames, Maitland, and Saugeen rivers. The watershed divides served as comparisons for the performance of the *TopologicalBreachBurn* tool.

Five DEMs of varying grid resolutions and data source were used with the new stream burning tool (Table 1). The SRTM-1 and SRTM-3 DEMs were created from the Shuttle Radar Topography Mission (SRTM) InSAR 1 arc-second (~27 m resolution at 43° latitude) and 3 arc-second (~80 m resolution) data products (Jarvis et al., 2008). Individual 1-degree data tiles were mosaicked using nearest-neighbor resampling to form the two test DEMs. The GMTED2010-7.5 (~200 m resolution) and GMTED2010-15 (~400 m resolution) DEMs were derived from the Global Multi-resolution Terrain Elevation Data 2010 global data set created and maintained by the United States Geological Survey (USGS) and the National

Geospatial-Intelligence Agency (NGA). The coarsest resolution DEM was the GTOPO-30 test DEM derived from the Global 30 Arc-Second Elevation data set, with an approximate grid resolution of 800 m at the study site's latitude. Although the USGS has replaced the GTOPO-30 data set with the improved GMTED2010 elevation models, these data remain in common usage. The original data sources contained elevations stored as integers (nearest meter), however, the mosaicked (SRTM) and cropped (GMTED2010 and GTOPO) DEMs were stored as 32-bit precision floating point rasters.

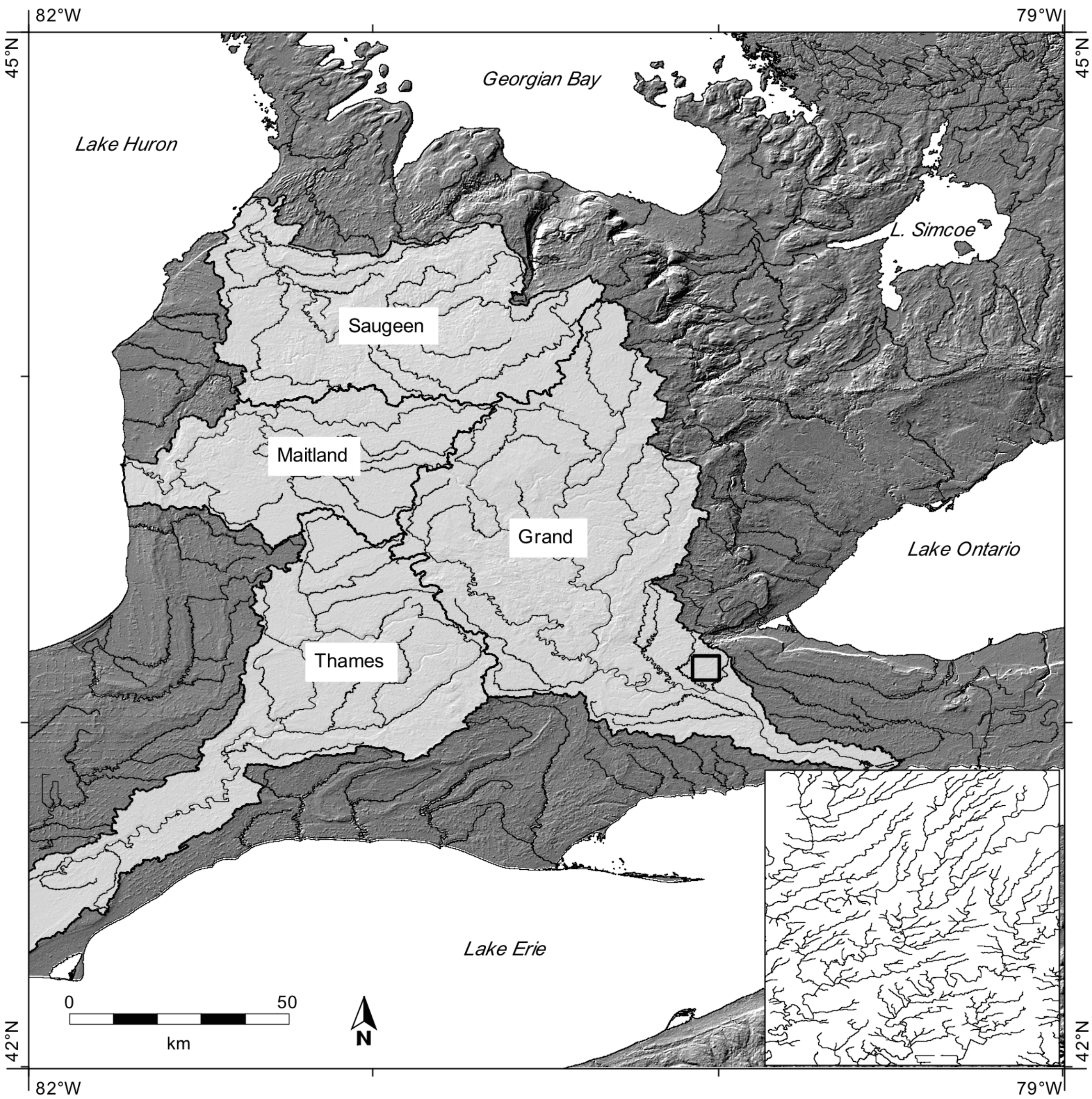

Figure 4: The southwestern Ontario study site. An inset map shows a section (thick black rectangle) of the hydrography data in detail.

Table 1: Test DEM data sources, resolutions (in arc-seconds), and raster grid sizes.

Source DEM	**Resolution**	**Rows**	**Columns**
SRTM-1	1.0	10,801	10,801
SRTM-3	3.0	3601	3601
GMTED-7.5	7.5	1442	1442
GMTED-15	15.0	722	722
GTOPO-30	30.0	362	362

A vector stream network for the study site was obtained from the Ontario Hydro Network watercourse data set, with the original source data derived from the 1:10,000 scale photogrammetrically mapped Ontario Base Map (OBM) data (Ontario Ministry of Natural Resources, 1994). The streams Shapefile contained 245,108 features and was 140 MB in size. By most modern standards, this file could be considered to be a large and complex vector data set and therefore serves as a good test for the new stream burning algorithm. The streams data contained several discontinuous features, particularly along the Oak Ridges Moraine, north of Lake Ontario. These features were not corrected by digitizing because they were handled through the automated procedure of the *TopologicalBreachBurn* tool. Manual editing was however required to correct several errors where channel heads were joined in the vector, effectively connecting separate drainage systems. While the priority-flood operation can handle this scenario, the procedure for measuring TUCL is sensitive to this type of digitizing error. Fortunately, the occurrences of these errors are easily identified and fixed.

The TUCL thresholds (km), number of stream collisions prior to and after stream pruning, and the extent of network pruning after applying *TopologicalBreachBurn* to each of the five test DEMs are presented in Table 2. The optimization procedure for determining the TUCL threshold yielded values that consistently removed between 87% to 92% of the artifact stream collisions for these data. The stream network was pruned substantially for the coarser DEMs, with the GTOPO-30 DEM requiring a 70.6% reduction in the number of links in the network. The remaining stream links were able to represent the essential character of the mapped hydrography, while substantially reducing the occurrence and impact of stream collisions.

Table 2: Results after applying *TopologicalBreachBurn* to the test DEMs.

DEM	**Threshold**	**Collisions**	**Remaining Collisions (%)**	**Links Pruned (%)**
SRTM-1	0.32	37,054	3677 (9.7)	9.7
SRTM-3	1.29	12,758	1647 (12.9)	30.9
GMTED7.5	3.30	7488	740 (9.9)	48.5
GMTED-15	5.83	4424	435 (9.8)	58.8
GTOPO-30	12.46	1696	140 (8.3)	70.6

DEM	Threshold	Collisions	Remaining Collisions (%)	Links Pruned (%)

The drainage patterns derived using the *TopologicalBreachBurn* method were remarkably similar despite the widely varying range in grid resolutions of the test DEMs. For example, Fig. 5A shows the drainage divides for the four major inland watersheds, extracted from the test DEMs using the *TopologicalBreachBurn* output flow direction raster. The five watersheds were vectorized and transparently overlaid along with the outline of the official mapped watershed boundaries. The level of consistency among the automatically mapped watersheds, and the degree of accuracy compared with the official divide lines, is so high that it is difficult to discern individual watersheds. The high level of agreement between the *TopologicalBreachBurn* mapped watersheds (at all resolutions) and the official watersheds was confirmed with Kappa Index of Agreement (KIA) analyses (Table 3). By comparison, Fig. 5B shows the same data extracted using the *FillBurn* methods. Overall, the divides mapped using the *FillBurn* method showed far greater sensitivity to the varying grid resolution of the test DEMs, manifested in large areas affected by erroneous stream capture. In many instances, the *FillBurn* watersheds deviated significantly from the official divides. The KIA analyses (Table 3) showed that *FillBurn* produced accurate watershed boundaries for finer grid resolutions but that at coarser resolutions the mismatch between the scale of the hydrography layer and the DEM resulted in relatively inaccurate watersheds. The fact that the *TopologicalBreachBurn* method does not allow in-stream flow between channels belonging to different stream networks (i.e. draining to different outlet links in the hydrography layer) resulted in more accurate and scale-insensitive delineation of major drainage divides.

Table 3: Results of the KIA analyses comparing the official and automatically mapped watersheds derived using the *TopologicalBreachBurn* (TBB) and *FillBurn* (FB) methods. The overall accuracies (%) of the tests are also reported.

DEM	TBB Kappa	TBB Accuracy	FB Kappa	FB Accuracy
SRTM-1	0.952	96.51	0.953	96.59
SRTM-3	0.949	96.30	0.940	95.62
GMTED-7.5	0.948	96.23	0.536	63.84
GMTED-15	0.935	95.22	0.724	79.72
GTOPO-30	0.921	94.19	0.490	60.04

DEM-modeled drainage patterns are best summarized by the flow-direction raster. These data are however not as intuitive for visualizing and interpreting drainage patterns as flow accumulation data. Fig. 6 is a comparison of a sub-area of the flow-accumulation rasters derived from the GMTED-7.5 and GTOPO-30 DEMs using the *TopologicalBreachBurn* and *FillBurn* stream burning methods. Each of the four rasters in Fig. 6 display flow accumulation measured as the number of upslope grid cells. Although each raster's greyscale

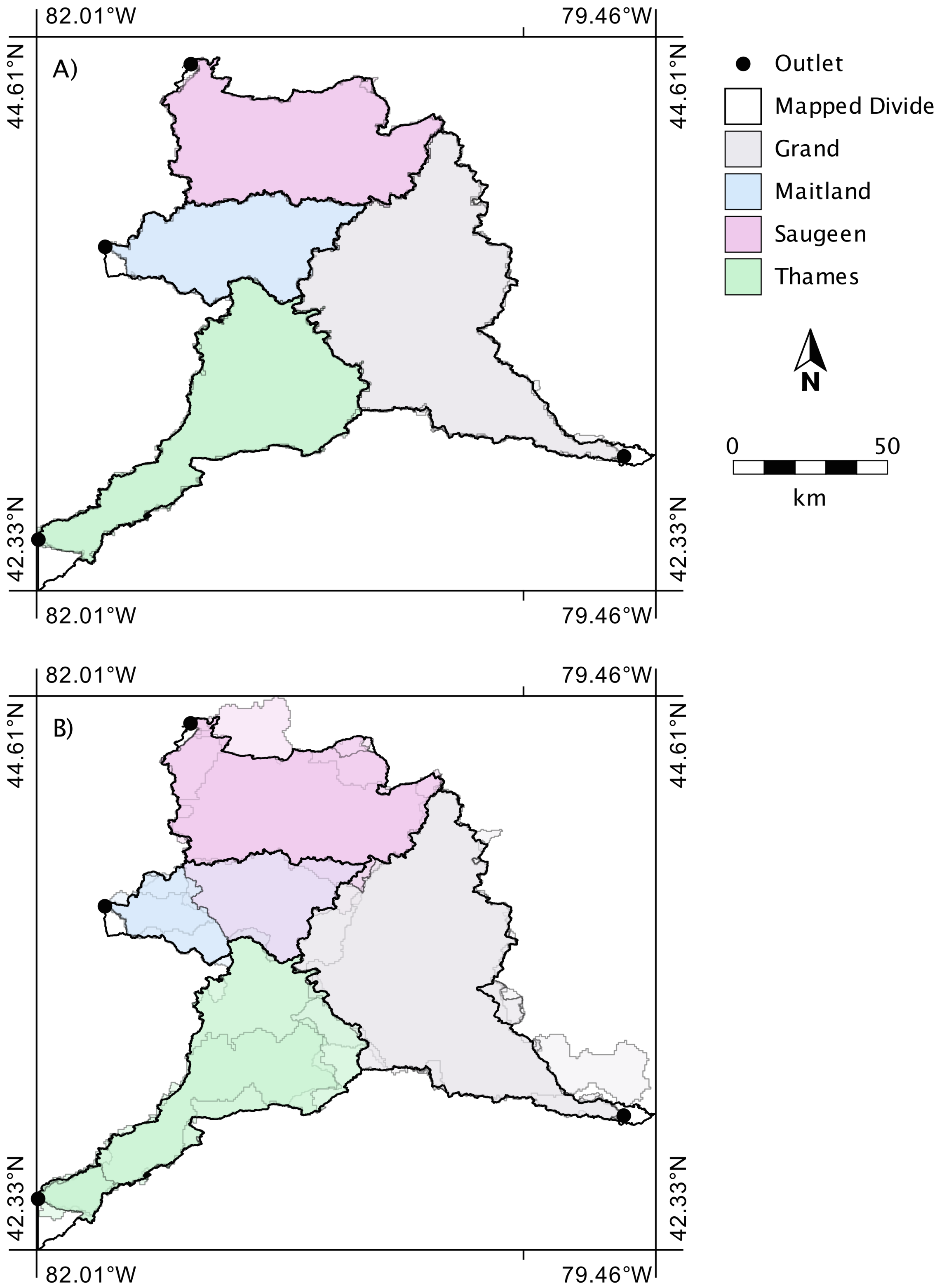

Figure 5: Extracted watershed divides for four major inland watersheds of southwestern Ontario derived using the A) *TopologicalBreachBurn* and B) *FillBurn* methods. The watersheds extracted from all five DEMs are transparently overlaid. The official mapped watershed boundaries are also shown for comparison.

palette is scaled to its unique range of values, they share the common characteristics that lighter colors correspond to areas of high flow accumulation (associated with valley bottoms and streams) and darker areas corresponds to low values, which are typically situated near drainage divides. It is apparent from inspection of the drainage patterns in Fig. 6 that the *TopologicalBreachBurn* method produces flow lines that are largely consistent with the stream network (Fig. 6A) even at the coarser resolution of the GTOPO-30 DEM (Fig. 6D). Although the areas of high flow accumulation in the *FillBurn* derived grids (Fig. 6C and Fig. 6E) coincided with streams, there are many locations where the effects of artifact stream capture have strongly impacted the drainage patterns (see white triangles). In some cases, the *FillBurn* algorithm has produced flow lines that are inconsistent with the topology of the mapped stream network, connecting streams inappropriately. This is particularly apparent for the GTOPO-30 DEM (Fig. 6E). Also notice how the tight meandering of the lower lengths of the Grand River are better represented in the *TopologicalBreachBurn* GMTED-7.5 grid (Fig. 6B) compared with the erroneous meander cutoffs produced by the *FillBurn* method (Fig. 6C).

The added complexity of the *TopologicalBreachBurn* method, compared with the other stream burning methods, does add to the computation time needed to process DEMs. However, the tool was found to be sufficiently efficient to allow for the processing of large DEM rasters. For example, the large SRTM-1 DEM, with nearly 115,000,000 grid cells, was processed on a system with a 3.0 GHz processor and 64 GB of 1866 MHz DDR3 memory in 16.64 min. For comparison, the *FillBurn* tool processed the same data in 2.10 min. The rasterization step, which must be performed twice, was the most computationally intensive component of the *TopologicalBreachBurn* method. Future efforts could be made to parallelize this stream rasterization process.

5. Discussion

So often with stream burning, the practice is to take the best available hydrography data and to combine this information with a lower resolution DEM. It has long been recognized in the field of geographic information science that combining multiple data sets of widely varying spatial scale can cause significant problems (Goodchild, 2011). In the case of stream burning, the mismatch between the scales of the two data sources can yield unintended topological errors in modeled drainage patterns (Turcotte et al., 2001). This work has demonstrated how distilling the stream network to its essential form to better match the scale of the DEM and how incorporating information about the stream network's topology directly into the stream burning process can lead to improved results and provide a more robust solution across widely varying DEM resolutions. The *TopologicalBreachBurn* method identifies a hierarchy of streams within a vector hydrography network based on a measure of stream size (TUCL). This hierarchy forms the basis in the method for prioritizing flow within larger streams and for pruning the hydrography to a restricted network of essential features, with a level of detail that best matches the scale of the DEM. In doing so, the *TopologicalBreachBurn* method explicitly aims to minimize the impact that erroneous stream capture caused by artifact stream adjacency and collisions has on the DEM-modeled drainage patterns.

The results of the case study showed that while traditional stream burning methods provide

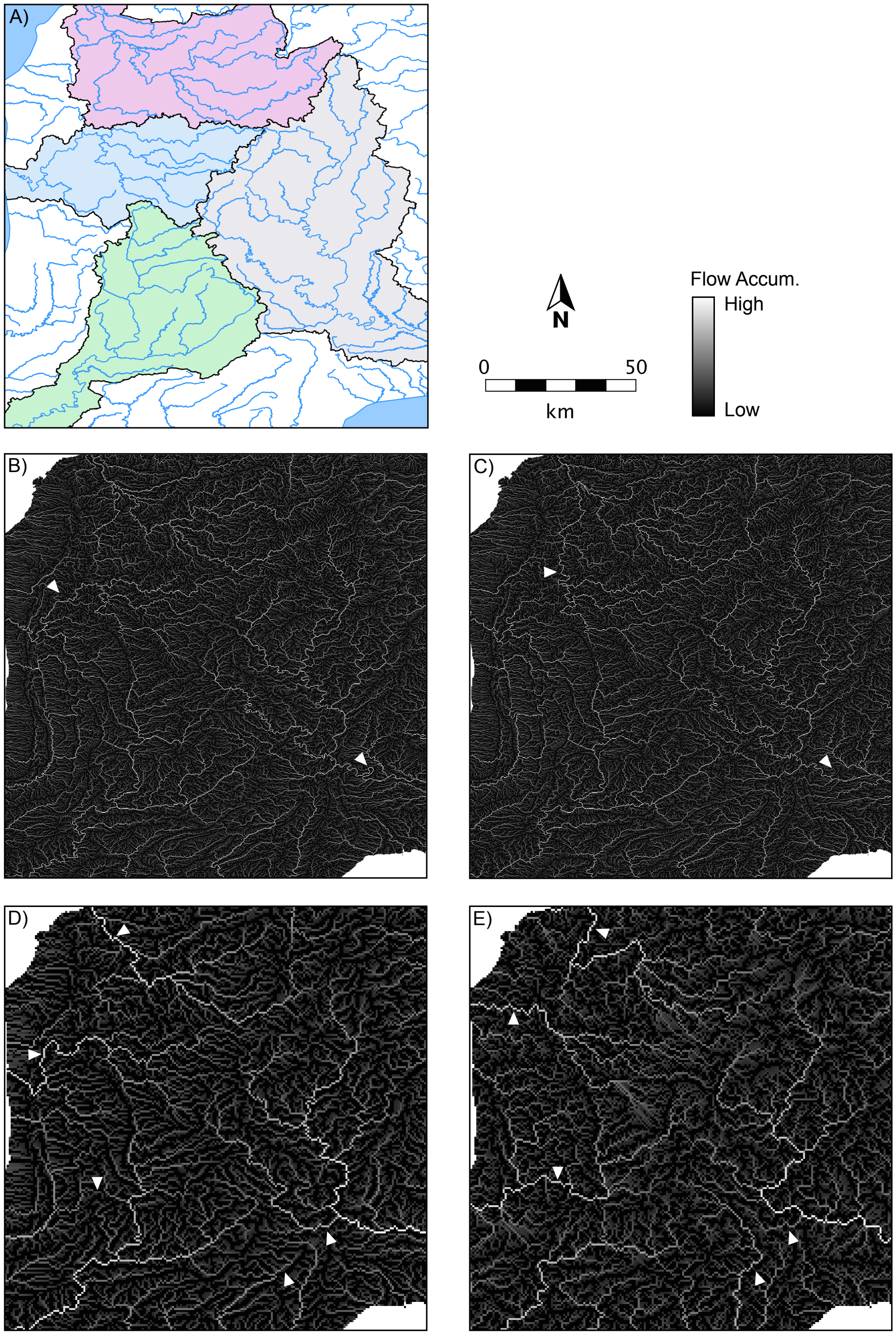

Figure 6: A) A sub-area of the site with overlaid stream network and divides. Flow accumulation rasters derived from the GMTED-7.5 DEM using B) *TopologicalBreachBurn* and C) *FillBurn*, and from the GTOPO-30 DEM also using D) *TopologicalBreachBurn* and E) *FillBurn*. Points of comparison are marked with white triangles.

solutions that are generally consistent with the hydrography, in that flow lines correspond to mapped features, the direction of flow and the connections between stream links can be inaccurate. This situation is worsened as the mismatch between the hydrography and DEM data becomes larger, which can result is significant deviations in regional scale drainage patterns and mapped drainage divides. It has been previously demonstrated that drainage divides extracted from stream-burned DEMs are sensitive to the elevation offset value (Saunders, 1999). The southwestern Ontario DEM data has demonstrated that these errors in watershed boundaries and modeled drainage patterns result from topological errors during the burning process that produce erroneous stream capture. Furthermore, the study showed that a more accurate result can be produced when a stream burning method is designed to explicitly handle stream topology.

Pruning the hydrography layer to match the scale of the DEM only works when the hydrography is more detailed than the DEM. With the widespread availability of fine resolution LiDAR DEMs for use in hydro-geomorphic applications (Lane and Chandler, 2003), it has become increasingly common to observe practitioners apply stream burning to DEMs that are of finer resolution than the available hydrography. For example, many available LiDAR DEMs represent drainage networks more accurately than the photogrammetrically mapped blue-line network printed on most topographic maps, particularly with smaller features in headwater areas (James et al., 2007) and in areas of complex hydrology (Lang et al., 2012). Stream burning with a lower-accuracy hydrography layer is very likely to cause the erroneous parallel streams problem noted by several researchers (Saunders, 1999; Turcotte et al., 2001). Fine resolution DEMs present their own unique challenges for representing drainage patterns, largely resulting from artifact blockages to flow caused by unrepresented culverts beneath embankments in human modified landscapes (Barber and Shortridge, 2005). Several recent studies have focused on developing and testing methods for correcting drainage patterns under these conditions (Duke et al., 2006; Lindsay and Dhun, 2015). One of the main issues with LiDAR DEM based drainage modeling, which may account for why stream burning is sometimes viewed as a viable flow enforcement tool for these data, is that culverts are not present in surface models and so road and rail embankments can result in large artifact dams at road-stream crossings. Thus, an alternative, conservative method, may be to only burn a LiDAR DEM for a short distance upstream/downstream of road crossings, with the intent of removing road embankments while preserving the DEM's representation of drainage features elsewhere. This approach has been implemented as Whitebox GAT plugin tool called *Burn Streams At Roads*, which is available along side the *TopologicalBreachBurn* tool.

6. Conclusions

This paper presented a novel alternative to traditional stream burning methods. The *TopologicalBreachBurn* tool uses TUCL, measured from a vector hydrography layer, to prune the network to a level of detail that matches the raster DEM. This reduces the occurrence of erroneous stream piracy caused by the rasterization of multiple competing stream links to the same DEM grid cell. The algorithm restricts in-channel flow to individual reaches, thereby reducing stream piracy in areas of spurious stream adjacency. In situations where stream collisions do occur, the *TopologicalBreachBurn* method ensures the larger stream (designated by higher TUCL) is given priority, thereby minimizing the impact on regional drainage patterns. Application to a large region within southwestern Ontario and five test DEMs with widely varying grid resolutions demonstrated that, compared with traditional stream burning methods, the *TopologicalBreachBurn* method can produce very accurate drainage patterns and watershed boundaries even at coarser resolutions.

7. Acknowledgements

This work was partially funded through a grant provided by the Natural Sciences and Engineering Research Council of Canada (NSERC; grant number 400317).

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