Received: 7 October 2016 | Accepted: 12 October 2017

DOI: 10.1002/hyp.11385

WILEY

RESEARCH ARTICLE

Evaluating preprocessing methods of digital elevation models for hydrological modelling

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Funding information
Kempe Foundation; VINNOVA; Swedish Energy Agency; EU Interreg program Water management in Baltic Forests (WAMBAF); Lilla Fonden för skogsvetenskaplig forskning, the Future Forest project (Mistra); ForWater Project (Formas)

Abstract

With the introduction of high-resolution digital elevation models, it is possible to use digital terrain analysis to extract small streams. In order to map streams correctly, it is necessary to remove errors and artificial sinks in the digital elevation models. This step is known as preprocessing and will allow water to move across a digital landscape. However, new challenges are introduced with increasing resolution because the effect of anthropogenic artefacts such as road embankments and bridges increases with increased resolution. These are problematic during the preprocessing step because they are elevated above the surrounding landscape and act as artificial dams. The aims of this study were to evaluate the effect of different preprocessing methods such as breaching and filling on digital elevation models with different resolutions (2, 4, 8, and 16 m) and to evaluate which preprocessing methods most accurately route water across road impoundments at actual culvert locations. A unique dataset with over 30,000 field-mapped road culverts was used to assess the accuracy of stream networks derived from digital elevation models using different preprocessing methods. Our results showed that the accuracy of stream networks increases with increasing resolution. Breaching created the most accurate stream networks on all resolutions, whereas filling was the least accurate. Burning streams from the topographic map across roads from the topographic map increased the accuracy for all methods and resolutions. In addition, the impact in terms of change in area and absolute volume between original and preprocessed digital elevation models was smaller for breaching than for filling. With the appropriate methods, it is possible to extract accurate stream networks from high-resolution digital elevation models with extensive road networks, thus providing forest managers with stream networks that can be used when planning operations in wet areas or areas near streams to prevent rutting, sediment transport, and mercury export.

KEYWORDS

breaching, culverts, digital elevation model, LiDAR, preprocessing, roads

1 | INTRODUCTION

In order to facilitate protection of surface waters, the first step is to map streams and lakes so protection can be incorporated in everyday land-use planning and management. Today's maps are often created from aerial photos; therefore, only streams distinguishable from aerial photos are displayed on current maps, which generate a bias towards larger streams. Also, because of canopy cover in forested landscapes, small forest streams are especially poorly mapped (Bishop et al., 2008; Kuglerová, Ågren, Jansson, & Laudon, 2014; Montgomery & Foufoula-Georgiou, 1993). In addition, streams that are present on current maps do not always form an integrated drainage network and do not change with seasons (Ågren, Lidberg, & Ring, 2015). Unless a stream is network based, it is not possible to trace water from each stream segment to the outlet of a catchment, and thus, managers are faced with a puzzle of different stream segments. Seasonal variations are also important because the length of stream networks changes dynamically between high and low flows (Ågren et al., 2015; Blyth & Rodda, 1973; Jones, 2000).

Recent advances in remote sensing and digital terrain analysis have paved the way for new techniques and better understanding of forest hydrology (Creed, Sass, Wolniewicz, & Devito, 2008; Murphy, Ogilvie, Castonguay et al., 2008; Ågren, Lidberg, Strömgren, Ogilvie, & Arp, 2014; Laudon et al., 2016). The better understanding of forest hydrology is partly due to the availability of better hydrological maps derived from high-resolution digital elevation models (DEMs) generated from Light Detection And Ranging (LiDAR; Murphy, Ogilvie, Castonguay et al., 2008). Early DEMs were created from photogrammetry, whereas modern DEMs are often derived from LiDAR point clouds and can have resolutions of less than 0.5 m × 0.5 m (a grid resolution of 0.5 m × 0.5 m will, from now on, be written as 0.5 m; Reutebuch, McGaughey, Andersen, & Carson, 2003). The amount of country-wide LiDAR datasets is rapidly increasing, and some examples of countries with a national DEM created from LiDAR are as follows: Denmark (Danish Geodata Agency), Finland (National Land Survey of Finland), and Sweden (Swedish Mapping, Cadastral and Land Registration Authority). These new DEMs are increasing in popularity amongst managers and are often used to map hydrological features such as stream networks (Vaze & Teng, 2007). Streams extracted from DEMs have three main advantages: First, they form an integrated drainage network (O'Callaghan & Mark, 1984); second, they are highly accurate (Goulden, Hopkinson, Jamieson, & Sterling, 2014) and follow actual channel depression in the DEM (Murphy, Ogilvie, Meng, & Arp, 2008); and third, they can easily be adjusted for seasonal variations and also display where ephemeral streams appear (Ågren et al., 2015).

Before any hydrological modelling can be applied to a DEM, it needs to be adjusted in order to be hydrologically correct (Jenson & Domingue, 1988; O'Callaghan & Mark, 1984). Water can only move downhill in a DEM, which means that sinks need to be removed to allow water to continue towards the outlet. Sinks are defined as areas surrounded by cells with higher elevations, which prevent water from moving further (Jenson & Domingue, 1988; Lindsay, 2015; Martz & Garbrecht, 1998; O'Callaghan & Mark, 1984; Zhang & Montgomery, 1994). They can be real depressions in the landscape or artefacts from urban features such as bridges. Thus, preprocessing of DEMs is important, especially because any errors in the input data will be amplified with each subsequent calculation (Kenward, Lettenmaier, Wood, & Fielding, 2000; Wise, 2000). There are two commonly used methods to handle sinks: filling (O'Callaghan & Mark, 1984; Wang & Liu, 2006) and breaching (Martz & Garbrecht, 1998; Martz & Garbrecht, 1999; Rieger, 1993). A fill algorithm examines the cells surrounding a sink and increases the elevation of the sink cells to match the lowest outlet cell (Planchon & Darboux, 2002; Wang & Liu, 2006). A breaching algorithm instead lowers the elevation of cells along a path between the lowest cell in the sink and the outlet of the sink (Martz & Garbrecht, 1998).

There are a number of studies that show how different preprocessing methods affect a DEM. Lindsay and Creed (2005) analysed the impact of the removal of artefact sinks from a 5-m DEM and found that methods combining filling and breaching had the least impact on the spatial and statistical distribution of terrain attributes. Poggio and Soille (2012) analysed the effect of preprocessing methods on stream networks and concluded that a combination of breaching and filling produced the most accurate stream network on a 30-m DEM. Lindsay (2015) demonstrated a flexible hybrid breaching–filling sink removal method on six large DEMs with resolutions of 30 and 90 m and concluded that the hybrid method performed similar to the highly efficient fill algorithm by (Wang & Liu, 2006) in terms of processing time. Preprocessing of high-resolution (<2 m) DEM introduces new challenges. There are mainly two problems associated with increasing the resolution of DEMs. The first problem is processing time, which increases drastically when the resolution increases and thus the number of data points increases (Barnes, Lehman, & Mulla, 2014; Qin & Zhan, 2012). The second problem is that features such as road–stream intersections become detectable, and, because roads are slightly elevated above surrounding terrain, they often appear to block the streams they cross. In reality, water may be draining underneath the road in a culvert or bridge (Shortridge, 2005).

Higher resolution also produces more detailed hydrographic features such as stream networks (Dehvari & Heck, 2013; Goulden et al., 2014; Vaze & Teng, 2007; Yang et al., 2014) but does not improve the detection of large features such as wetlands (Creed, Sanford, Beall, Molot, & Dillon, 2003) or topographic wetness index (Ågren et al., 2014). LiDAR is also sensitive to noise from low-lying vegetation and saturated soil surfaces, which need to be dealt with during the preprocessing (Goulden et al., 2014; Gyasi-Agyei, Willgoose, & Troch, 1995). An important advantage of high-resolution data is that it may contain information of forest ditching and similar small-scale features that impact drainage.

In the small country of Sweden, more than 210,000 km are forest roads built to extract timber from 227,000 km^2 of forested land. That equals roughly to 1 km of roads for every square kilometre of forest landscape. Ågren et al. (2015) mapped stream networks from a high-resolution DEM and found 2–5 km of streams per square kilometre of forested land, depending on season. This highlights the importance of handling sinks caused by road embankments correctly during the preprocessing stage; otherwise, the resulting hydrologically modelled maps will contain misplaced streams. The location of culverts needs to be incorporated into DEMs to prevent this error (Goulden et al., 2014; Shortridge, 2005). It can be done by breaching a path across roads if their locations are known, but this is rarely the case, and mapping culverts in the field is both time-consuming and costly. Much previous work has focused on coarser resolution DEM without small-scale anthropogenic features such as roads (Lindsay, 2015; Poggio & Soille, 2012); however, recent studies have addressed this problem (Lindsay & Dhun, 2015; Schwanghart, Groom, Kuhn, & Heckrath, 2013) using high-resolution data on small geographical areas.

In this study, we focus on digital terrain analysis to extract streams from DEMs with a range of different resolutions, in watersheds containing a large number of small-scale anthropogenic artefacts, which are mostly roads. The first research question in this study is, "Which preprocessing methods most accurately route water across road impoundments at actual culvert locations?" For this purpose, a large field inventory has been conducted in northern and central Sweden, where over 30,000 road culverts in 10 watersheds have been located and mapped manually. This is a unique dataset and a rare opportunity to evaluate the performance of preprocessing methods with focus on road impoundments.

We assume that one wants to enforce continuous flow to the outlet without losing important information from the original DEM. The second research question in this study is therefore, "How much of the landscape is affected by the different preprocessing methods?" Here, we evaluate area changed and the difference in absolute volume between original DEMs and preprocessed DEMs.

2 | MATERIALS AND METHODS

2.1 | Study sites

This study consists of nine large catchments in central Sweden (Gävleån, 2,458 km^2; Delångersån, 1,993 km^2; Harmångersån, 1,196 km^2; Testeboån, 1,111 km^2; Hamrångeån, 518 km^2; Skarjaån, 329 km^2; Norrlanån, 319 km^2; Gnarpsån, 229 km^2; and Ninån, 197 km^2) and one intermediate-sized catchment in northern Sweden (Krycklan, 68 km^2). When combined, the catchments cover 8,350 km^2, of which 82.3% are forested land, 8.7% are lakes and rivers, 6% are open land, 3.8% are agricultural land, and 0.3% are urban areas. The quaternary deposits in the catchments are dominated by till. All the large catchments have their outlets in the Baltic Sea, whereas Krycklan is a subcatchment to Vindeln River (Figure 1).

A culvert survey was conducted in Krycklan during June 29 to 25 July 25, 2013, where culvert locations were mapped using a handheld GPS with a horizontal accuracy < 10 m. These culverts were manually adjusted using a 0.5-m DEM and a 17-cm Orto photo in order to increase the precision. The culvert surveys of the larger catchments were conducted in collaboration with the Swedish Forest Agency during the snow-free periods of 2014–2015 using a handheld GPS with a horizontal accuracy of 0.3 m. A total of 30,883 culverts were mapped during the field surveys. Densely populated urban areas with underground drainage systems were excluded from the survey (0.3% of the combined area). This study uses the Swedish National DEM generated by the Swedish Mapping, Cadastral and Land Registration Authority using LiDAR. This DEM has a cell resolution of 2 m and was generated from a point cloud with a point density of 0.5–1 points/m^2 with horizontal and vertical errors of 0.1 and 0.3 m, respectively. This DEM was resampled using nearest-neighbour interpolation to 4-, 8-, and 16-m DEMs.

The preprocessing methods that have been evaluated can be sorted into three categories: algorithms that fill sinks, algorithms that breach sinks, and algorithms that utilize a combination of both filling and breaching to remove sinks. In this study, we focus on efficient algorithms capable of handling large DEMs (~1,000 km^2 at 2-m resolution). The following is a short introduction to the evaluated algorithms. Each method is given a short name in this study (in italics), and all methods are summarized in Table 1.

2.2 | Fill algorithms (also known as incremental methods)

Wang and Liu (2006) introduced the priority flood algorithm, which examines each cell on the basis of its spill elevation, starting from the edge cells, and visiting cells from lowest order using a priority queue. This algorithm was modified to work with larger LiDAR DEMs and implemented in SAGA

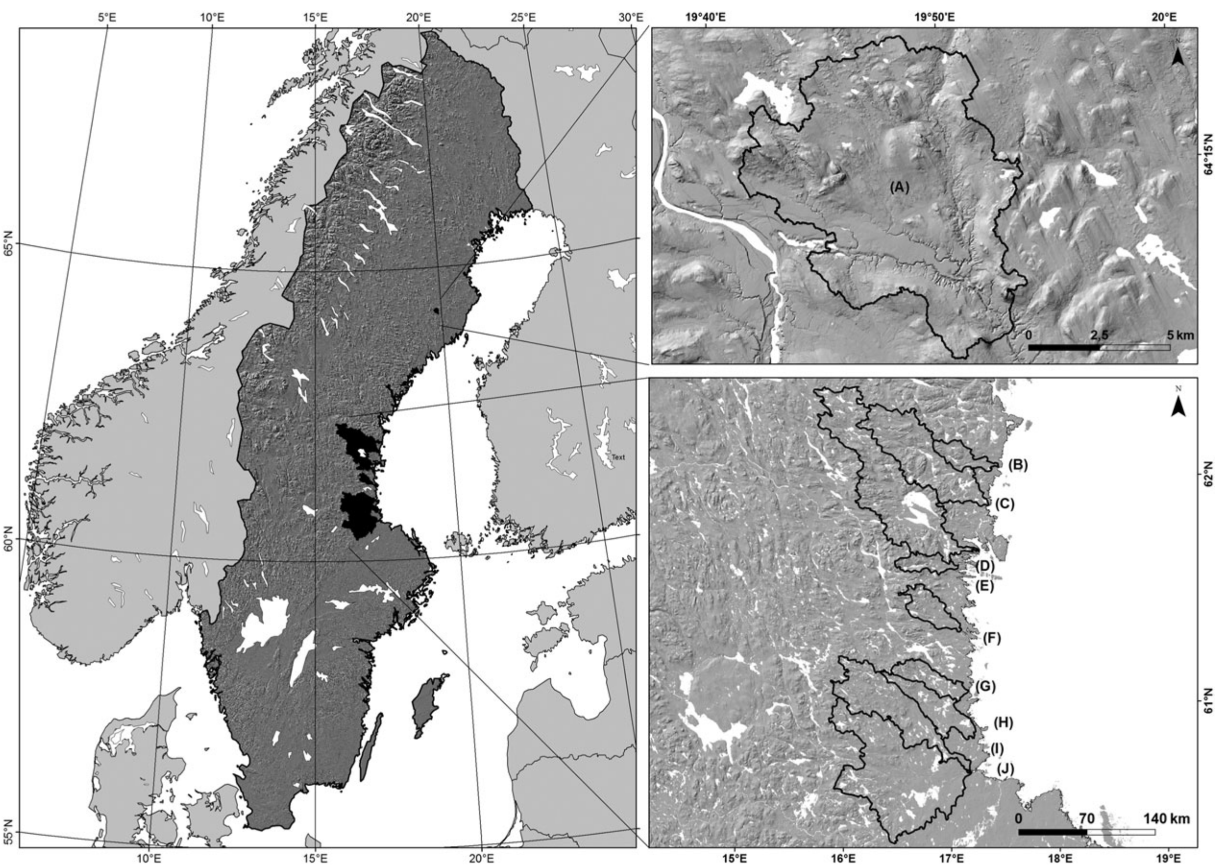

FIGURE 1 The nine large catchments are located along the coast of central Sweden, whereas the small catchment is 60 km inland in northern Sweden. (A) Krycklan, (B) Gnarpsån, (C) Harmångersån, (D) Delångersån, (E) Nianån, (F) Norralanån, (G) Skårjån, (H) Hamrångeån, (I) Testeboån, and (J) Gåvleån

TABLE 1 The evaluated methods are summarized on the left, using the same name as the main text

Name	Description	Program
Fill	Fill with flat increment[a]	Whitebox GAT
BR fill	BR[b] + Fill with flat increment[a]	Whitebox GAT
LCAT breach	Least cost auxiliary topography	TopoToolbox
BR LCAT breach	BR[b] + Least cost auxiliary topography	TopoToolbox
Complete breach	Complete breaching mode[c]	GoSpatial
BR complete breach	BR[b] + Complete breaching mode[c]	GoSpatial
Constrained breach	Constrained breaching mode[d]	GoSpatial
BR constrained breach	BR[b] + Constrained breaching mode[d]	GoSpatial
Selective breach	Selective breaching mode[e]	GoSpatial
BR selective breach	BR[b] + Selective breaching mode[e]	GoSpatial

Note. The descriptions show how each method was run and is further explained below. The programs used to run each method are displayed on the right.

[a]Flat increment = Flats were given the arbitrary slope of 0.001°.

[b]BR = Streams were burned across roads with a maximum length of 50 m.

[c]Complete breaching mode = All sinks were resolved by breaching.

[d]Constrained breaching mode = 2 m max depth, 50 grid cells length followed by internal breaching and fill.

[e]Selective breaching mode = 2 m max depth, 50 grid cells length followed by fill.

GIS 2.2 and Whitebox GAT 3.4 and can be set to add a small elevation increment to flat area cells to impose a flow direction. An increment of 0.001° was chosen for this study and will be referred to as *fill*.

2.3 | Breaching algorithms (also known as decremental methods)

The first breaching methods were introduced by Martz and Garbrecht (1998) and Rieger (1993, 1998) and worked by identifying and breaching the lowest outflow in a sink if specific criteria of depth and breach length were meet. Studies by Soille (2004), Schwanghart and Kuhn (2010), and Schwanghart et al. (2013) propose breach algorithms based on the least cost auxiliary topography. This algorithm is included in MATLAB TopoToolbox R2013b and will be referred to as *LCAT breach*. An even more efficient breaching algorithm was introduced by Lindsay (2015) and is available in a small program called GoSpatial. This method will be referred to as *complete breach*.

2.4 | Hybrid algorithms (incremental and decremental combined)

GoSpatial also offers the possibility to combine breaching and filling into a hybrid solution using a priority flood algorithm where sinks can be resolved by *selective* or *constrained* breaching. Constrained breach and selective breach was run with a maximum breach length of 50 grid cells and maximum breach depth of 2 m. This means that sinks that would require a breaching path of more than 50 grid cells or sinks deeper than 2 m will be filled instead of breached. The main difference between constrained and selective breach is that selective breaching does not breach sinks that do not meet the criteria above, whereas constrained breaching creates a partial breach up to the above-defined criteria in order to reduce the interior sink size (Lindsay, 2015). For example, constrained breaching will breach a channel of 50 m before applying fill, whereas selective breaching will stop and fill without breaching that specific sink.

There is also an option to burn a known stream network into a DEM. Unfortunately, forest hydrology is often poorly mapped, and only streams distinguishable from aerial photos are displayed on current maps, which makes stream burning questionable (Lindsay & Dhun, 2015). Even so, it is still reasonable to assume that the location of a stream–road crossing would be easier to distinguish from aerial photos because of the opening in the canopy along roads, making these locations more reliable. Therefore, streams from existing maps were burned into the DEM where they crossed a road, and only a short distance (maximum 50 m) that would correspond to the distance necessary to burn across the largest road embankments in the catchments. This step was done using the tool "burn streams at roads" in Whitebox GAT and will be referred to as "BR." Here we applied (*fill*, *complete breach*, *selective breach*, *constrained breach*, and *LCAT*) separately to the stream–road-burned DEM. Methods where the stream–road intersections were burned into the DEM have "BR" added to the name to clarify this (*BR fill*, *BR complete breach*, *BR constrained breach*, *BR selective breach*, and *BR LCAT*).

2.5 | Evaluation

Field mapping an entire stream network is not an easy task, and stream networks are tricky to compare in a reliable way (Molloy & Stepinski, 2007). Instead of comparing the entire stream network, we focus on locations where streams intersect roads. Our unique dataset of field-mapped culvert locations allows us to investigate if the modelled stream network crosses the road at the correct locations, that is, where the stream drains underneath the road in a culvert. For this assessment, stream networks were extracted from each preprocessed DEM using the flow routing algorithm Deterministic-8 (O'Callaghan & Mark, 1984) and a flow initiation threshold or accumulated area (Tarboton, Bras, & Rodriguez-Iturbe, 1991) of 0.02 km^2 (2 ha), which represents spring flood on the basis of field observations of stream initiation in the northernmost study catchment (the Krycklan catchment; Ågren et al., 2015). This means that culverts located in areas near a water divide, before a stream has been initiated, will not be intersected by this stream network. A lower flow initiation threshold would produce a more extensive stream network and intersect more of the field-mapped culverts, but we decided that it would be more relevant to use a realistic flow initiation. A stream–road intersection was only considered to be accurate if a stream passed within 10 m of both ends of a culvert. The 10-m search radius was chosen to avoid nearby culverts at road intersections and similar locations.

2.6 | Effects of preprocessing methods on DEMs

Preprocessed DEMs were compared to original DEMs in order to analyse how preprocessing methods changed the DEM. This comparison included area changed and absolute volume changed, which are commonly used to assess the impact of preprocessing methods (Lindsay & Creed, 2005; Poggio & Soille, 2012). Absolute volume change is the sum of the absolute height difference for all cells in the catchment before and after the preprocessing multiplied by the total number of cells (Equation 1).

$$\mathrm{Abs(volume)} = a \sum_{i=1}^{N} \left(z_{i,\mathrm{orig}} - z_{i,\mathrm{proc}} \right). \quad (1)$$

a is the area of a raster cell, $z_{i,\mathrm{orig}}$ is the elevation for raster cell i in the original DEM, $z_{i,\mathrm{proc}}$ is the elevation for raster cell i in the preprocessed DEM, and N is the number of raster cells in the DEM.

LiDAR is absorbed by water, so elevation data in these surfaces were interpolated from surrounding terrain during the DEM creation. They were also flattened using lake and river polygons from a topographical map and given an arbitrary slope towards the coast. These areas were excluded from the evaluation of preprocessing methods impact on the DEMs.

3 | RESULT

3.1 | Correct stream–road crossings

Stream networks from all preprocessed DEMs were intersected with over 30,000 field-mapped road culverts, and the number of correct

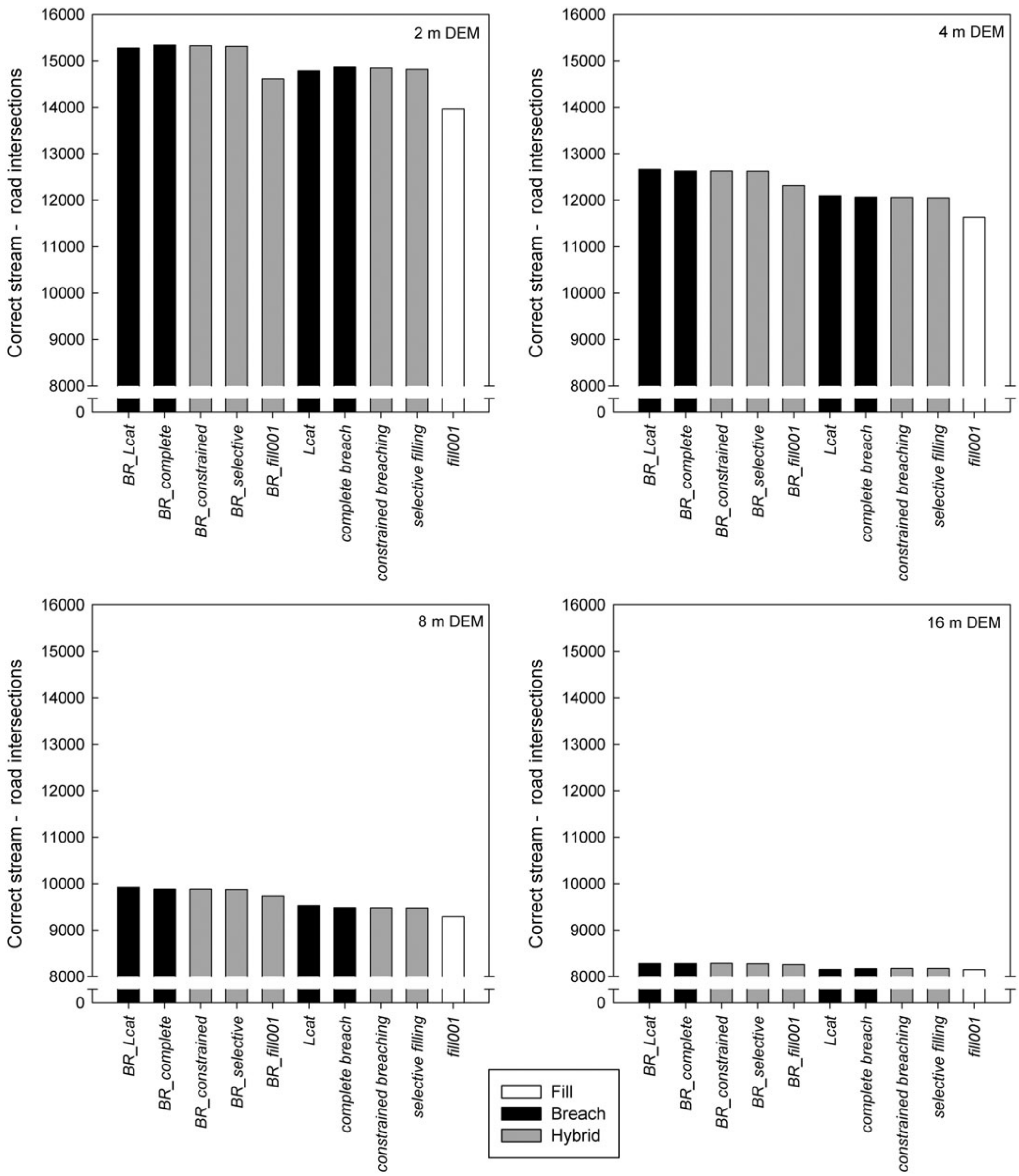

FIGURE 2 The accuracy of topographically derived stream networks increases with increasing digital elevation model (DEM) resolution. Preprocessing methods that prioritize breaching over filling lead to more accurate stream networks on all DEM resolutions

stream–road crossings was used to evaluate accuracy of each method. The accuracy of topographically derived stream networks increased with increasing DEM resolution. Stream networks from the 2-m DEM intersected roughly twice the number of culverts as stream networks from the 16-m DEM. Further, preprocessing methods that prioritized breaching over filling lead to more accurate stream networks on all DEM resolutions (Figure 2). The difference between breaching and filling increased with increasing resolution. Burning streams from the topographic map across roads from the topographic map (*BR*), before applying a complete preprocessing method, increased the number of correct stream–road crossings for all methods, especially for filling. This step was sensitive to scale, and the effect increased with increasing DEM resolution. The least cost auxiliary topography breaching method (*BR LCAT*) intersected most culverts on all DEM resolutions, which means that stream networks extracted from the 2-m DEM preprocessed by *BR LCAT* were most accurate in this study. *BR complete breach*, *BR constrained breach*, and *BR selective breach* also performed well, whereas *fill* had the least amount of correct stream–road crossings on all resolutions.

3.2 | Preprocessing effects on DEMs

The impact of each method was defined by changes in DEM area and absolute volume between the original DEMs and the preprocessed DEMs. Methods that prioritized breach over fill made the least changes, to both area and absolute volume (Figure 3). This was the case for all resolutions. All methods changed larger areas on higher resolution DEMs, especially fill. The difference in area changed between methods that prioritize breaching and methods that prioritize filling also increased with increasing DEM resolution. Burning streams from the topographic map across roads from the topographic map (BR), before applying another preprocess method, reduced the change in area for all methods on the 2- and 4-m DEMs but had little effect on the 8- and 16-m DEMs. Changes to absolute volume decreased with increasing resolution for pure breaching methods, whereas hybrid and filling methods made the most changes to absolute volume on the 2-m DEM. *BR LCAT* and *LCAT* made the least changes on DEM area, whereas *BR complete breach* and *complete breach* made the least changes to absolute volume regardless of DEM resolution. *Fill* and *BR fill* had the biggest impact on both area and absolute volume on all resolutions.

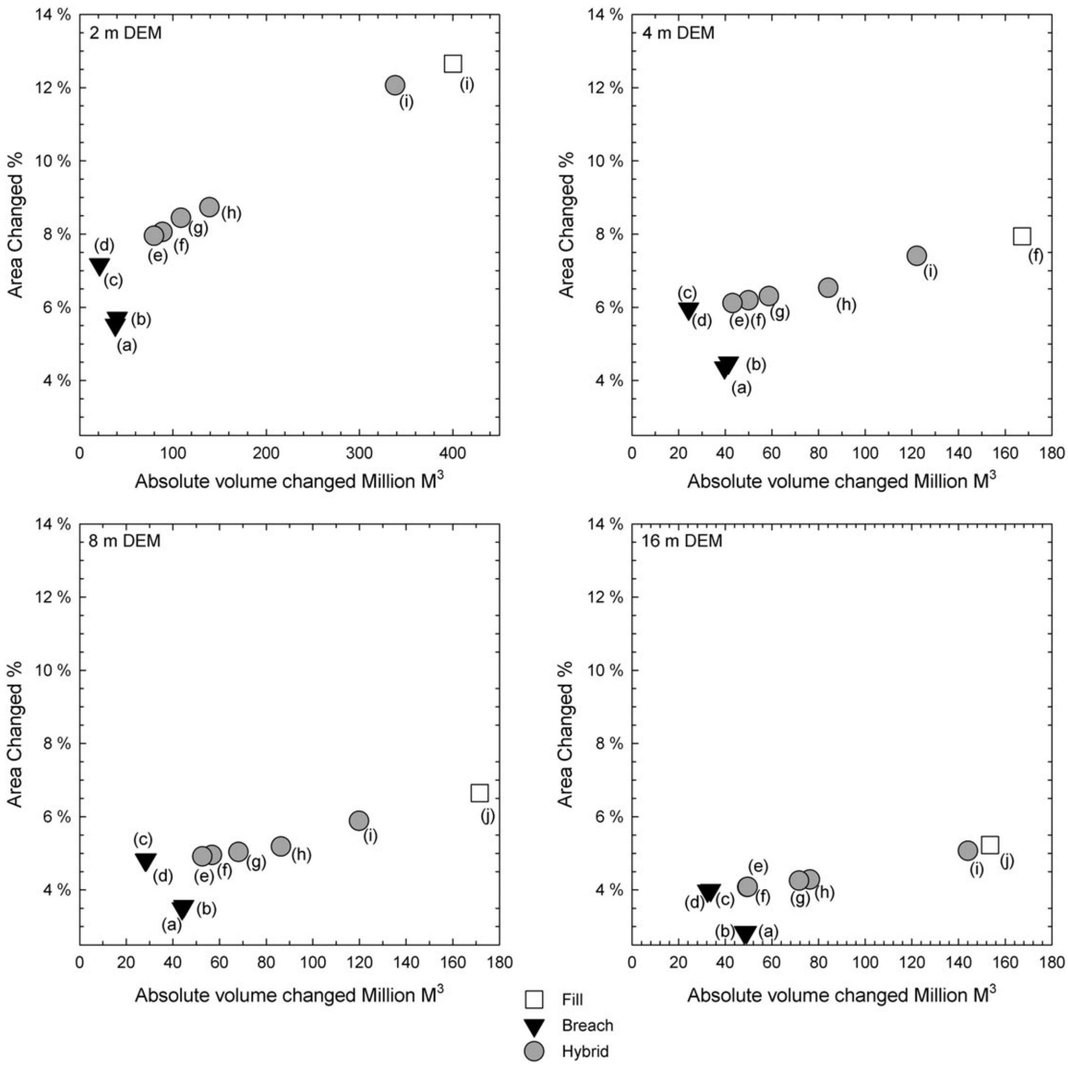

FIGURE 3 Change in absolute volume of the digital elevation models in Million M^3 against changed area in percent of total area. (a) BR LCAT, (b) LCAT, (c) BR complete breach, (d) complete breach, (e) BR constrained, (f) constrained, (g) BR selective, (h) selective breach (i) BR fill, and (j) fill

4 | DISCUSSION

In this study, we assessed different methods to preprocess DEMs of varying resolutions by analysing the number of field-mapped culverts intersected by extracted stream networks. The effect of each preprocessing method was assessed by area changed, and absolute volume changed, from the original DEMs. Our results showed that the least cost auxiliary topography method proposed by Schwanghart and Kuhn (2010) and Schwanghart et al. (2013) (*LCAT*) was the most accurate in terms of number of culverts intersected, regardless of DEM resolution. We also found that the accuracy increased when streams from the topographic map were burned across roads from the topographical map, before applying a complete preprocessing method. In this study, a stream–road intersection was only considered to be accurate if a stream passed within 10 m of both ends of a culvert. Using a 10-m search radius for all resolutions allows for a more direct comparison between resolutions, but it can potentially cause some issues with the 8- and 16-m DEMs because the nodes of the extracted stream network are located in the centre of the resampled grid cells.

Increasing resolution also increased the accuracy in terms of number of correct stream–road crossings. This is consistent with a study in Canada where Goulden et al. (2014) evaluated stream networks delineated from 1-, 5-, 10-, 15-, and 50-m DEMs and concluded that stream networks from the 1-m DEM produced the highest spatial accuracy. Dehvari and Heck (2013) did a similar study in Canada and observed large differences between 1 m and 10 m DEMs on all topographical and hydrological attributes, suggesting that 10 m might be to course to extract streams in that landscape.

Increasing DEM resolution increased the area affected by preprocessing, especially for methods that prioritize fill. This is likely due to sinks caused by small-scale features, which become visible at higher resolutions. Features such as road embankments could explain increasing differences in area changed, and number of correct stream–road crossings, between breaching and filling at higher resolutions. *BR LCAT* created the most accurate stream network, and it changed 52% less of the study area compared to the classic fill method on the 2-m DEM. This is also consistent with recent findings. Lindsay and Dhun (2015) evaluated preprocessing algorithms on a 1-m DEM in a landscape dominated by agriculture and found that breaching changed an area 86.5% smaller than filling. This is consistent with results from a study on a 30-m DEM by Poggio and Soille (2012). Some of the difference in impact between filling and breaching can be attributed to flat areas in our catchments. If a road crosses the outlet of a flat area, the fill algorithms will fill up the whole area in order to remove the sink, whereas breach algorithms will breach a channel across the road. Burning streams from the topographic map, across roads from the topographic map, reduced the impact on the DEMs and improved the accuracy for all methods but especially for filling methods. This shows just how sensitive filling is to road embankments.

Previous studies have shown that methods that change the DEM less produces more accurate stream networks (Lindsay & Creed, 2005; Poggio & Soille, 2012). This is consistent with our results, but there is no reason why minimizing the impact should be a goal by itself. The aim of any preprocessing method is to create accurate flow directions and by extension accurate stream networks. One of the most important advantages with breaching instead of the filling used here is the behaviour of flow paths upstream of a road embankment. Streams from both methods might cross the road in a correct location, but fill will produce straight parallel streams across the filled area, whereas breach uses the flow path information of the unfilled DEM to the beaching point. This means that filling fails to utilize information about flow directions in the filled areas (Figure 4).

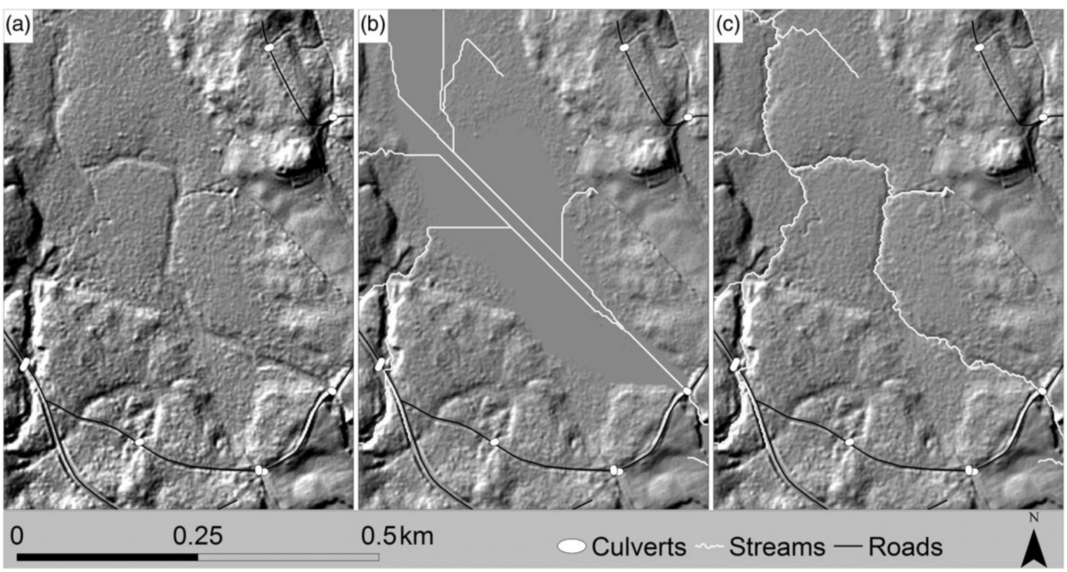

FIGURE 4 One of the most important differences between filling and breaching is not where they cross a road but rather how they affect the upstream flow paths. (a) The road embankment in the bottom right corner is creating a sink at the stream–road intersection. A stream channel is visible in the original digital elevation model. (b) Filling creates a flat area of arbitrary values upstream of the road embankment, which results in parallel and unrealistic stream segments. (c) Breach, on the other hand, manages to utilize the flow path information of the area upstream of the road embankment

However, there are other filling methods such as the one described by Martz and Garbrecht (1998) that impose convergent flow paths away from a higher elevation towards a lower elevation. Selective filling and constrained breaching give the user the option to choose which sinks to fill or breach. Optimally, very deep sinks, such as quarries, should be filled, whereas road embankments and bridges should be breached (Lindsay, 2015). This was especially important on the high-resolution DEMs in this study because our catchments contained a large number of road embankments, which means that there were many sinks that should be solved by breaching. If most sinks were caused by artificial sinks from open mines and quarries, instead of artificial embankments, it is likely that filling would be a preferred method. Selective filling or constrained breaching might be preferable if the DEM contains both deep sinks and road embankments. Selecting appropriate thresholds for maximum breach depth and length can be difficult and will vary with resolution because the origin of sinks changes with resolution.

Road embankments, bridges, and culverts are some of the biggest issue to address in order to create reliable stream networks from high-resolution LiDAR DEMs (Schwanghart et al., 2013). One advantage with high-resolution LiDAR DEMs is that they might contain information about small-scale anthropogenic features such as ditches that can be incorporated in the hydrological models in order to improve the accuracy of stream networks. This would allow us to shed some light on the unknown headwaters described by Bishop et al. (2008). Forest managers could use these stream networks to better plan operations in wet areas near streams in order to prevent rutting (Ågren et al., 2015) and subsequent sediment transport (Kreutzweiser & Capell, 2001) and mercury export (Munthe & Hultberg, 2004).

5 | CONCLUSIONS

The accuracy of stream networks, in terms of correct culvert intersections, increased with increasing DEM resolution. Stream networks extracted from DEMs that had been breached instead of filled created more accurate stream networks on all resolutions and had less impact in terms of change to area and absolute volume. The difference in accuracy between breaching and filling increased with increasing resolution. The accuracy also increased when streams from the topographic map were burned across roads from the topographical map, for all methods and resolutions.

ACKNOWLEDGMENTS

Big thanks to the personnel at the Swedish Forest Agency who conducted the field survey for the five large study catchments. The research was financed by the Swedish Energy Agency, VINNOVA, the Kempe Foundation, the EU Interreg program Water management in Baltic Forests (WAMBAF), Lilla Fonden för skogsvetenskaplig forskning, the Future Forest project (Mistra), and the ForWater Project (Formas). We also like to thank KUA Foundation Gävleborg; County Administrative Board in Gävleborg; Arbetsförmedlingen in Gävleborg; and the Swedish Mapping, Cadastral and Land Registration Authority in Gävleborg.

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How to cite this article: Lidberg W, Nilsson M, Lundmark T, Ågren AM. Evaluating preprocessing methods of digital elevation models for hydrological modelling. *Hydrological Processes*. 2017;31:4660–4668. https://doi.org/10.1002/hyp.11385