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Automatic determination of stream networks from DEMs by using road network data to locate culverts

Ville Mäkinen, Juha Oksanen and Tapani Sarjakoski

Department of Geoinformatics and Cartography, Finnish Geospatial Research Institute FGI, National Land Survey of Finland, Masala, Finland

ABSTRACT
Determining stream networks automatically from digital elevation models is an issue that is actively being studied. The quality of elevation models has increased over time, but many hydrologically critical features, such as culverts, are often missing from the elevation data. To analyze the surficial water flow, one must either prepare a special elevation model or post-process an already-existing model.

This study builds on the traditional, well-established method of determining the stream network from digital elevation models. We have extended the traditional method by locating culverts automatically, using road network data as an input. We show, by comparison to the reference data, that the culverts being most relevant for the stream network can be found with good accuracy. We demonstrate that by including the automatically located culverts in the automatic stream network determination, the quality of the generated network can be noticeably improved.

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KEYWORDS
Hydrologic analysis; digital elevation or terrain models; algorithm development

1. Introduction
Stream networks are required in several geospatial analyses and applications. Examples include drainage basin delineation, rainfall runoff and climate modeling, flow statistics, and flood risk analyses (Young et al. 2000, Turcotte et al. 2001, Olivera et al. 2002, Yuan et al. 2005, Bell et al. 2007). They are an important part in estimating the transport of surface materials such as nutrients and pesticides (Wilson and Gallant 2000, Ator et al. 2004).

Field surveys are the most reliable way to determine the stream network, but they are expensive and slow and, therefore, cannot be used for extensive areas. Inspecting the stereo imagery using a stereo workstation is faster, but it is still a manual process. In addition, vegetation hides many features on the ground, limiting the accuracy of this approach. Stream networks can also be determined automatically from digital elevation models (DEM) (O’Callaghan and Mark 1984, Jenson and Domingue 1988, Tarboton et al. 1991). The development and the increased use of airborne laser scanning (Light Detection and Ranging, LIDAR) measurements have improved the quality and the resolution of the available DEMs, making the automated process more attractive (da Paz et al. 2008, Barber and Shortridge 2005, Jones et al. 2008, Lang et al. 2012, Petroselli 2012).

CONTACT Ville Mäkinen ville.p.makinen@nls.fi

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The determination of the stream network is traditionally done by first assigning the flow directions for each cell, then performing the flow accumulation analysis, and finally selecting in the stream network the cells that have a flow accumulation value higher than a predefined value (O’Callaghan and Mark 1984, Jenson and Domingue 1988). DEMs usually contain depressions, that is, areas of which the water cannot flow out. Their local minima are called pits (O’Callaghan and Mark 1984, Lindsay 2016). Shallow depressions may occur in the terrain naturally or artificially, for example, because of errors in the data. In high-resolution DEMs, small roads and ditches are visible, but stream channels under the bridges and through the culverts are not represented. This means that roads act as long, low dams, resulting in large depressions, especially in low-relief areas. Separate data on culverts and bridges may be available, but in general one cannot assume this to be the case.

The stream network determination requires a DEM without pits to produce a meaningful network. In some cases, the pits may have already been removed at the time the DEM was generated (Hutchinson 1989). Otherwise, the pits must be removed by post-processing the DEM with one of the many algorithms developed for the task by a) filling the depressions (Jenson and Domingue 1988), b) by carving through ridges around depressions (Soille et al. 2003, Lindsay and Dhun 2015), or c) by combining both approaches (Morris and Heerdegen 1988, Martz and Garbrecht 1998, Soille 2004, Poggio and Soille 2012, Lindsay 2016). For stream network determination, the most suitable method to remove the depressions is the carving algorithm (Soille et al. 2003).

By design, the carving algorithm often carves along the stream channels that are visible in the DEM. Obstacles in the channel usually do not cause serious errors in the determined streams. Roads, on the other hand, may have significant effects on the locations of the determined streams, and they can even cause errors in the topology of the generated network (Figure 1).

To improve the quality of automatically determined high-resolution stream networks, we have developed a method that corrects the network by placing culverts into automatically determined locations. In addition to a DEM, a road network data is also used as input. This inclusion is justified because the roads are artificial constructs, and comprehensive data sets can be expected to be available. There is often at least rudimentary stream data available as well. However, to avoid circular reasoning, stream data that is already available is not included in the method directly. We present our evaluation of the method’s performance by determining the stream network for a test area for which we have reference data available, and we show that by applying our method we can improve the quality of the extracted network.

2. Improved methods for stream network determination

The traditional method to determine the stream network from a DEM consists of three main steps (Figure 2). First, the depressions are removed from the DEM using a carving algorithm (Soille et al. 2003). The carving algorithm simulates a rising flood from the edges of the DEM. It keeps track of the direction from which the flood advances to each cell. When the flood spills into a depression and reaches a pit, the directions are backtracked to the first cell that is lower than the pit, and all the backtracked cells are lowered to the elevation of the pit. In the second step, flow
directions are determined for each cell, using one of the published algorithms (O’Callaghan and Mark 1984, Tarboton 1997). In this work, we are using the D8 algorithm. Finally, the directions are used to perform a flow accumulation analysis, and the cells with an accumulated flow over the threshold value are selected for the stream network.

The carving algorithm will carve the pit from the same direction as the rising flood front first reaches the pit. Roads are problematic because they are continuous constructions that are often elevated from their surroundings, and they can avert the advancing of the flood front. Although, in reality, the water flows through the culverts downstream, from the point of view of the carving algorithm, the culverts control how the flood front advances.

Our aim is to locate culverts and include the additional flow routes into the stream network determination. The inclusion could be achieved in many ways. We have modified the carving algorithm presented in Soille et al. (2003) so that we can include connections between cells not neighboring each other. In this study, we refer to this modification as culvert-aware carving (CA-carving). This extension is used to simulate culverts under the roads by declaring a connection between two cells on the opposite sides of roads. If no connections are defined, the CA-carving produces the same results as those produced by the traditional carving (Soille et al. 2003).

One could also add the flow routes provided by the culvert into the DEM simply by carving the cells between the sinks and the sources of the culverts. However, moving or

Figure 1. Streams (blue) determined by the carving algorithm in the vicinity of roads (red). The algorithm fails to find a stream channel from A to B, and the determined stream flows incorrectly through point C. Yellow circles mark the locations of the reference culverts. The background represents the elevation (dark = low, light = high), and the contours are drawn at two meter intervals.
removing culverts later on would be difficult, and the resulting DEM could not be used in applications where the surfaces of the roads are important, for example, in orthorectification.

We have developed two algorithms that inspect the carved DEM and the flow accumulation values with the aim to locate the missing culverts. The road network data is used as supporting data to determine the region where culverts can be placed. If the algorithms find new culverts, they are added to the system, the CA-carving is repeated, and the flow accumulation values are recalculated. This procedure is repeated until no more culverts are found and added. We refer to the resulting iterative process to determine stream networks (Figure 3) as a culvert-search method. A comparison to the flowchart of the traditional method (Figure 2) shows that, if there are no culverts to start with, our method performs the traditional process at the beginning of the first iteration. The two algorithms used to find and place the culverts are discussed in the following chapters. The source code and the data used are available at https://github.com/vpmakinen/ijgis_ca_carving.

2.1. Carving path analysis algorithm

If a stream channel is blocked by a continuous object like a road, the carving algorithm may find an alternative route to the other side of the road (Figure 1). In such cases, the DEM may need to be carved considerably (from A to C in Figure 1). A long, continuous carving that substantially lowers the elevation of the cells suggests that the actual

![Figure 2](image-url). The flow chart of the traditional method to determine stream networks from DEMs.
channel is somewhere else. The carving path analysis algorithm (PAA) developed in this study examines the performed carvings to locate some of the missing culverts. To explain its rationale, we must first understand how the carving algorithm works.

A one-dimensional example of a carving is shown in Figure 4, where the cells at positions C and D are pits. A pit can be a starting point of a carved path, in which case all the cells on the path are lowered to the elevation of the pit (C). Another possibility is that the pit is located on a carved path starting from another pit. In that case, the pit is first removed by carving, but later further lowered like any other cell (D).

The PAA examines the carved paths produced by the CA-carving algorithm and searches for the pits that require considerable carving to be removed. For such pits, the PAA follows the carving paths starting from the pits and tries to place culverts in suitable locations under the roads.

We define the removal cost for each pit that is a starting point of a carving by following the flow directions from the pit cell to the first cell that has not been carved. The removal cost of the pit is the sum of the elevation differences of the original and the carved DEM along the path (multiplied by the cell area). The cost is essentially the volume of the terrain that needs to be carved out. A similar definition has been presented by Soille (2004). Mathematically, the cost $S_i$ to remove a pit $i$ with a carving following a path $P_i$ is defined as

$$S_i = A \sum_{c \in P_i} (\text{DEM}[c] - \text{DEM}_{\text{carved}}[c]),$$

where $c$ represents the coordinates of the cells on the carved path $P_i$, and $A$ is the area of one cell. For example, in Figure 4, cell C is a pit with removal costs of 19. If a pit is on a path of another carving, it is skipped over at this point (Figure 4, cell D).

Figure 3. The main loop of the culvert-search method. The DEM and the road network data are immutable, but the culverts are added during the iterations. The Path Analysis Algorithm (PAA) and Intersection Inspection Algorithm (IIA) are used to find and adjust the location of the culverts.
From the pits for which the removal cost is calculated, we include for further analysis the ones that fulfill the following conditions: The removal cost must be above a predefined threshold $p_{\text{COST}}$, and the carving must exceed another predefined threshold $p_{\text{MIN,CARV}}$ at least on one cell on the carving path. The first condition is set because we are only interested in notable carvings. The second condition is established because, in low-relief areas, even a shallow pit may require a long carving to be removed. Especially in marsh areas, long carving paths, onto which the cells are only lowered by a small amount, are common.

Figure 4. A one-dimensional example of a carving to remove pits. In (a) road B prevents cell C from flowing to cell A, and a considerable carving is performed from C to E. The numerical values on the surface indicate the carving costs, and the shaded area around cell B shows the culvert insertion area. In (b) the inserted culvert allows the flow from C to A, and only minor carving is required to remove the depression at D.
The included pits can be located anywhere in the area under analysis. Especially, many of them might be located in places other than the vicinity of the roads where we are trying to place culverts. However, carving paths can sometimes originate far away from the roads and later come close to or even cross a road. If an included pit is too far away from a road, we follow the flow directions to the next cell. The removal cost for this cell (the numerical values in Figure 4) is defined as the cost of the previous cell minus the carving of this cell. With this definition, we can handle cases where the carving path starts far away from a road and initially consists of only negligible carvings (e.g., if the pit is located in a marsh area), and only later consists of substantial carvings that constitute the majority of the carving cost. If the cost decreases under the threshold, we move on to the next included pit. Otherwise, the process is repeated until the distance of the cell from any road is below a threshold value $p_{ROAD}$.

When we encounter a cell that is within the threshold distance from a road, we use it as a potential location for a sink of a new culvert. Using that cell as a starting point, we perform an A* (A-star, Hart et al. (1968)) search to find all the cells that we can reach by carving with the cost of that cell. If we can reach a cell with a lower elevation than the starting cell and that is on the other side of a road, we select it to be the source of the culvert. For example, in Figure 4, the cell at location A can be reached from pit C with a carving cost of only 7, compared to the 19 needed to carve to location E. If there are previously inserted culverts closer than $p_{DIST}$ to the new culvert, we again follow the flow directions to the next cell and perform the same steps as before. Otherwise, we add the new culvert to the system and move on to the next included pit. We ignore the rest of the carving path, as it is possible that it can disappear in the following iteration and is therefore invalid input data for placing other culverts. The algorithm is presented as a flow chart in Figure 5.

2.2. Road–stream intersection inspection algorithm

It is possible that the elevation of a road does not differ considerably from its surrounding area. If an automatically determined stream crosses a road at such a location, the removal cost may not exceed the threshold value, and therefore no culvert is placed.

We assume that after the PAA has found all the culverts it can, the rest of the intersections of the roads and the determined streams are often close to the reference culvert locations. The carving algorithm carves a DEM through the road at the location where the elevation of the road deck is (locally) at its lowest value, because that is the location where the simulated flood spills over the road. However, the location of the culvert does not necessarily need to be at that location. A more probable location is the point with the lowest elevation at the side of the road from where the water is flowing over the road. This minimizes the size of the puddle that forms next to the road.

The intersection inspection algorithm (IIA), also developed in this study, starts by collecting all the road cells that have the flow accumulation value over a predefined threshold $p_{FLOW}$, in other words, all the cells where the roads and relevant streams intersect. From each of those cells, it backtracks the stream until it encounters a cell that is not on a road. Then, all the cells that can be reached from this cell, without going higher than the elevation of the cell at the road and stream intersection, are selected.
This procedure can also be expressed as selecting all the cells that would be submerged in the puddle that forms on the upstream side of the road before spilling over it. From the selected cells, we first exclude the ones that are too far away from roads and then select the one with the lowest elevation. This cell is used as the culvert sink. Then for the source of the culvert, we select the closest cell on the other side of the road that either has a lower elevation value than the sink or, if no such cell is found, the lowest cell in the range of the maximum culvert length. If there are no previous culverts in the vicinity of the new culvert, we add the new one to the system.

The IIA does not search for alternative routes for the streams to cross roads, but it only adjusts the location of the crossing. Therefore, we apply it only if the PAA cannot

Figure 5. The flow chart for the PAA, the algorithm to place culverts based on the road network data and on the amount of carving required to perform for the original DEM.
find any new culverts. Adjusting the locations does not usually cause drastic changes to a stream network. But nevertheless, it serves as a sound method for improving the locations of the culverts and thus the quality of the determined stream network.

### 2.3. Handling of placement failures

There are situations where both the PAA and the IIA fail to place culverts. For example, small service roads in forests are often barely elevated from the surrounding terrain. In such cases, only minor carvings are performed, and it is possible that the threshold values to execute the PAA are not reached. The smallest roads may not have ditches along them. This causes problems for the IIA because it seeks out cells with lower elevation near the roads.

One possible solution would be to exclude such roads from the input data. This may often be the best option because the road data may contain roads that do not have any ditches, and the surficial water may flow over them. However, the available road classification might be unsuitable for appropriate exclusion. Therefore, in this study, we must be prepared to deal with the fact that after some iterations, we will find locations where roads and determined streams will intersect, but neither of the culvert placing algorithms are able to place new culverts. In such cases, we simply place culverts at the intersections without any further heuristics.

### 2.4. Handling of consistency of the generated network

Inserting a culvert affects the flow accumulation values of some of the cells that are at a lower elevation, sometimes considerably. We take this into consideration by ignoring the rest of a carving path if a culvert is placed on it, as the rest of the carving path may become redundant after the culvert is placed. Another option would be to start a new iteration after each culvert placement, but since the carving and the flow accumulation analysis are the two slowest parts of the process, it is not a feasible approach. In addition, the culverts inserted in the same iteration must be at least a predefined distance $p_{DIST,ITER}$ away from each other. These conditions exist to reduce the number of unnecessary culverts. When both the PAA and the IIA can no longer find new culverts, we perform a final check and remove all the culverts that do not have water flowing through them.

### 2.5. Handling of the edges of processing area

The borders of the analysis area require special attention. In the stream network determination, we first encounter them when we set the flow directions for the cells at the edges of the area. Because these cells have less than eight neighbors and the D8 algorithm cannot be applied, we simply set the flow directions outwards from the area.

Because of the finite analysis area, the flow accumulation values of the cells near the perimeter are probably underestimated. As a result, some of the cells are incorrectly excluded from the stream network because their flow accumulation values do not exceed the threshold. To tackle this issue, we define a buffer zone for the analysis area. We assign flow directions and perform the flow accumulation for the whole area,
but we exclude the buffer zone from the culvert placing process because the flow accumulation values are too unreliable.

Lakes that are clipped off by the boundary of the analysis area are especially problematic because they most likely end up flowing out of the analysis area. If in reality the lake drains into a stream inside the analysis area, the flow accumulation of that stream is severely underestimated and may lead to erroneous topology of the stream network. To prevent this, we inserted virtual dams along the perimeter of the analysis area where we know that lakes in fact drain in other directions.

### 2.6. Limitations of the method

Our method attempts to locate underground structures that are not directly visible in DEMs. However, determining more extensive and complicated structures, such as underground rain water drain systems, is out of scope.

In our study’s DEM, the lakes show up as nearly flat areas and are often difficult, if not impossible, to distinguish from low-relief terrain, for example, marsh areas. In our analysis, we treat the lakes as any other terrain, aside from inserting artificial dams at some locations where the lakes are cut off by the border of the analysis area. Only in the visualizations have we masked the lakes with polygons, as the determined stream network is neither meaningful nor interesting at those locations.

### 3. Performance evaluation

#### 3.1. Test area and data

Our test area is 4.5km × 7.0km and located in Espoo, southern Finland (Figure 6). There is a residential area at the top center of the test area, with large paved areas and rain water drain system, that is excluded from the verification of the results. We performed field surveys on the area in the spring of 2016 and located 184 culverts by a Real-Time Kinematic (RTK) Global Positioning System (GPS) device. We performed an additional survey during the spring of 2018 when the snow was melting and classified 28 of the culverts that are located under the main roads as relevant, using the amount of water flowing through them as the classification criterion.

Our DEM was generated from the aerial LIDAR point cloud data (NLS LIDAR data 2017) of the National Land Survey of Finland (NLS). We first constructed a triangulated irregular network (TIN) from the ground points and then created a raster of 1mx1m resolution by linear interpolation. The lower limit of the point density of the LIDAR data is only 0.5/m², which means that at some locations the resolution of the raster is higher than the data can support. On the other hand, even higher resolution would be required to be able to distinguish the smallest streams and ditches that we are interested in. Therefore, the 1-meter resolution was a good compromise. The road data was taken from the Topographic Database (2017) of the NLS.
Figure 6. The overview of the test area. Surveyed roads are drawn with bold black lines, and smaller roads that were not included in the survey with thinner black lines. Surveyed culverts are drawn with yellow circles. The residential area is marked with a light red rectangle, and the manually added dams at the edge with dark red. Coordinate system: ETRS-TM35FIN, units in m.
3.2. Methods for measuring the performance of the algorithms

We will analyze the performance of our algorithm by comparing the locations of the inserted culverts to the reference ones. We will determine the placement error for each inserted culvert in the following manner: First we calculate the distance of each inserted culvert to each reference culvert and mark each reference and inserted culvert as unprocessed. Then we iteratively select the pair with the shortest distance whose both culverts are unprocessed, set the error for the inserted culvert as the distance of the pair, and mark both the reference and inserted culvert as processed. If there are more inserted culverts than reference culverts, the remaining inserted culvert will be assigned a very large error.

With the placement errors defined for the inserted culverts, we can count how many of them can be classified as correctly placed by choosing a threshold value for the placement error. Then we can calculate the traditional precision and recall values (Manning et al. 2008):

\[
\text{precision} = \frac{\text{number of correctly placed culverts}}{\text{number of inserted culverts}},
\]

\[
\text{recall} = \frac{\text{number of correctly placed culverts}}{\text{number of reference culverts}}.
\]

We define two subsets of the inserted culverts into which we include only the culverts located near the main roads for which the additional field survey was performed. Additional requirement is that the simulated catchment area of the culverts must exceed 0.01km\(^2\) for the first subset and 0.1km\(^2\) for the second. We will calculate the precision and recall also by using these subsets of the data to study if more prominent culverts are found with different accuracy. Finally, we will compare the actual generated stream networks generated with and without the inserted culverts and study the effect of the inserted culverts.

3.3. Parameter sensitivity analysis

The algorithm depends on six parameters, which have been explained in Sections 2.1, 2.2, and 2.4, and tabulated in Table 1. To understand how the results depend on them and to make sure that we choose reasonable values for them, we will perform a parameter sensitivity analysis. We set the minimum distance of the inserted culverts to 10m because in the test area there are culverts within that distance of each other. The maximum

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Description</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_{\text{FLOW}})</td>
<td>Flow accumulation threshold</td>
<td>(0.001), 0.01, (0.1)</td>
<td>km(^2)</td>
</tr>
<tr>
<td>(p_{\text{COST}})</td>
<td>Pit removal cost threshold</td>
<td>(1), (5), 10, 20</td>
<td>m(^3)</td>
</tr>
<tr>
<td>(p_{\text{MIN,CARV}})</td>
<td>Min. carving threshold</td>
<td>0.25, 0.5, 1, 2</td>
<td>m</td>
</tr>
<tr>
<td>(p_{\text{DIST,ITER}})</td>
<td>Min. culvert distance (same iter.)</td>
<td>(10), 50, 200</td>
<td>m</td>
</tr>
<tr>
<td>(p_{\text{DIST}})</td>
<td>Min. culvert distance (previous iters.)</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>(p_{\text{ROAD}})</td>
<td>Max. sink/source dist. to roads</td>
<td>20</td>
<td>m</td>
</tr>
</tbody>
</table>
distance of the culverts from the roads we set to 20m. This value was chosen because the road data we use contains only the center lines, and on wide road segments the sinks and sources of the culverts can thus be far away from the center lines. For the other four parameters, we choose a range of values and run the algorithm with each combination. The parameter values are reported in Table 1.

In the sensitivity analysis, we use the harmonic mean of the precision and recall, also known as the balanced F measure (Manning et al. 2008), as the metric:

$$F = \frac{2 \times \text{precision} \times \text{recall}}{\text{precision} + \text{recall}}.$$  \hspace{1cm} (4)

We will refer to this as the F-score. Because the precision and recall, and thus the F-score, depend on the placement error threshold, we will investigate the graphs of the F-score with respect to the threshold (F-graphs). This allows us to see the effect of the threshold on the results and choose a reasonable value for the threshold in the final assessment.

The F-graphs with different parameter combinations differ from each other considerably (Figure 7(a)). First we can eliminate the extreme values of the parameter $p_{\text{FLOW}}$ by grouping the graphs by the parameter and inspecting the aggregated graphs (Figure 7(b)). Similarly,

![Figure 7](image-url)

**Figure 7.** The F-graphs of the algorithm performance, measured with different set of parameters. (a) Results of each combination of parameters plotted with slight transparency for clarity. (b) F-graphs grouped by the parameter $p_{\text{FLOW}}$ where the area between the minimum and maximum values is colored. (c) F-graphs grouped by the parameter $p_{\text{COST}}$ after the parameter $p_{\text{FLOW}}$ is fixed. (d) F-graphs grouped by the parameter $p_{\text{DIST_ITER}}$ with $p_{\text{FLOW}} = 0.01 \text{km}^2$ and $p_{\text{COST}} > 1 \text{m}^3$.
from the remaining values, we can exclude the parameter values $p_{\text{COST}} = 1\text{m}^3$ and $p_{\text{COST}} = 5\text{m}^3$ (Figure 7(c)). Finally, parameter value $p_{\text{DIST,ITER}} = 10\text{m}$ can be excluded (Figure 7(d)).

To conclude, from original 144 possible parameter value combinations, we narrowed the options down to 16. As the F-graphs for these remaining combinations do not differ considerably, we must select one combination for further analysis. The values we selected are written in bold in Table 1. We notice that there is a shoulder in each F-graph near $x = 30\text{m}$ (Figure 7). For further analysis, we define that a culvert is placed in the correct location if it is closer than $30\text{m}$ to the corresponding reference culvert.

### 3.4. Performance of the automatic culvert detection

Using the parameters we chose in the previous section, the automatic stream network determination program inserted 165 culverts under the roads. After these culverts are mapped to the reference ones, as described in Section 3.2, 116 of the inserted culverts are classified as correctly placed. A histogram of the placement errors shows that the majority are placed within $5\text{m}$ of the corresponding reference culvert (Figure 8(a)). The precision and recall values are calculated using equations (2) and (3), and the results are tabulated in the second column of Table 2.

We calculate additional precision and recall values using the subsets of the culverts classified as relevant. From the reference culverts, 28 were classified as relevant. We filter the set of automatically inserted culverts by their drainage areas and obtain subsets with 57 and 22 culverts. The related precision and recall values are also reported in Table 2. With the filter $0.01\text{km}^2$, nearly all of the reference culverts were located. However, we find more than double the amount of culverts compared to the reference data, and the precision decreases. With the stricter $0.1\text{km}^2$, filter the number of reference and inserted culverts are closer to one another and almost all of the inserted culverts are classified as correctly placed. This is reflected in the improved precision values.

Another way to evaluate the performance of the algorithm is to study the qualitative differences of the stream networks determined with and without it. Here, we refer to the stream network determined using the traditional method as $tSN$, and the network determined using the culvert-search method as $csSN$. A comparison of the two networks shows that for the most part they are identical (Figure 9). However, there are some prominent differences, and some of those are highlighted and discussed next.

A common problem in $tSN$ is that it fails to cross roads at appropriate locations. Often a stream is diverted to erroneously follow a road for a considerable distance instead of flowing under the road at the location where the culvert is missing. Examples of such situations are shown in Figure 10(a), 11(a), and 12(a), where the letter A marks the location where a culvert is missing. Adding the missing culvert improves the generated stream network considerably in each case (Figure 10(b), 11(b), and 12(b)).

Sometimes a stream should follow a road but the $tSN$ crosses the road too soon (Figure 12(a,c)). In this case, placing a culvert at the proper location has the opposite
and in csSN the stream follows the road for a longer distance before crossing it in the right location (Figure 12(a,b)).

Figure 8. Placement error of the inserted culverts. In (a) all the reference and inserted culverts are included. In (b) and (c), only the relevant reference culverts are included, and the inserted culverts are filtered with respect to their simulated catchment areas.

Table 2. The number of reference and automatically inserted culverts with different filtering (all = include all points, imp = include only reference culverts classified as relevant, filter = include inserted culverts with catchment area higher than the given value).

<table>
<thead>
<tr>
<th>Reference set</th>
<th>All</th>
<th>imp</th>
<th>imp</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference culverts</td>
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<td>28</td>
<td>28</td>
</tr>
<tr>
<td>inserted culverts</td>
<td>165</td>
<td>57</td>
<td>22</td>
</tr>
<tr>
<td>correctly placed culverts</td>
<td>116</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>precision</td>
<td>0.70</td>
<td>0.44</td>
<td>0.86</td>
</tr>
<tr>
<td>recall</td>
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<td>0.89</td>
<td>0.68</td>
</tr>
<tr>
<td>F-score</td>
<td>0.67</td>
<td>0.59</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Figure 9. The stream networks, excluding streams with flow accumulation below 0.1km². Streams found by the traditional method are represented in purple (tSN), the ones by culvert-search method in green (csSN), and matching streams in black. For the most part, the networks are similar, but near the roads (thin black) there are noticeable differences. Coordinate system: ETRS-TM35FIN, units in m.
Inserting a culvert under a road affects the flow accumulation values on both sides of the road. Even if there is only a mild flow through the culvert, it may have a surprisingly large effect on the generated stream network on areas where the flow accumulation values are close to the chosen threshold value. An example of such a case is shown in Figure 10.

**Figure 10.** The automatically determined stream networks, (a) tSN using the traditional method and (b) csSN using the culvert-search method. The black arrows show the flow direction for the most prominent streams. The inserted culverts are drawn with hollow circles and squares, placed using the PAA and the IIA, respectively. The area has low relief, and the artificial channels (small black arrows in (b)) are sometimes missed.

**Figure 11.** The automatically determined stream networks, (a) tSN using the traditional method and (b) csSN using the culvert-search method. Adding the culvert at A clearly improves the topology of the network, as the main stream flows correctly to point B. The culvert at point B is also found, but it does not rectify the subsequent slightly misplaced segment (the correct path is marked with black arrows in b)).

Inserting a culvert under a road affects the flow accumulation values on both sides of the road. Even if there is only a mild flow through the culvert, it may have a surprisingly large effect on the generated stream network on areas where the flow accumulation values are close to the chosen threshold value. An example of such a case is shown in
On flat areas, even a single missing flow route may have a notable effect on the generated network. For example, there are three ponds that are connected in the wrong order in tSN (Figure 9, L1–L3). The flow route from the pond L2 to L1 is blocked, and the erroneous flow order L1 → L3 → L2 is generated. When a culvert is placed between L1 and L2, the CA-carving algorithm manages to carve realistic channels and provide the correct drain order. In another example, a road without culverts creates a drainage divide that separates the two sides of the road hydrologically (Figure 9(a)). When a culvert was inserted (A), the drainage divide moves to north.

In the examples shown above, it can be seen that the improvements of our method are always related to the roads. There are still errors, especially in areas with low relief, after our method has finished inserting culverts and produced the improved stream network (Figure 10(b), 11(b), 12(b) and 13(b), correct streams marked with small black arrows). These errors emerge because the stream channels are too shallow in the DEM, and even minor obstacles in the elevation data may divert the stream away from the real channels.
4. Discussion

A comparison of the results and the reference data gathered from the test area shows that our method improves the quality of the automatically generated stream network. The method depends on a few parameters, and it is possible that they are not completely transferable, which limits the application of the described process to arbitrary areas without some preliminary testing. However, the parameters describe real physical quantities and should be adjustable.

The flow accumulation threshold value $p_{\text{FLOW}}$ had the most significant effects on the results, as it defined how small streams are included in the network. The main streams are included even with a large threshold value. Smaller streams are problematic because, even in field surveys, defining their starting points is highly subjective. With low threshold values, stream segments that are not actual streams are included in the network. Therefore, this parameter cannot have a universally optimal value; it must be adjusted application-wise.

The pit removal cost threshold $p_{\text{COST}}$ and minimum carving threshold $p_{\text{MIN\_CARV}}$ exist to limit the number of performed A* searches in the PAA algorithm. Setting either of them too high effectively disables the PAA, and setting them too low can lead to incorrectly placed or redundant culverts.

The minimum distances to other culverts ($p_{\text{DIST}}$ and $p_{\text{DIST\_ITER}}$) are used to reduce the number of redundant culverts, should the algorithms find any. The maximum distance of the sinks and sources of the culverts from roads $p_{\text{ROAD}}$ exists to enforce the realistic placement of the culverts. Because the road data we used only contains the center lines of the roads, the value of 20m was chosen so that the ditches next to the roads would be included on both narrow and wide roads. Regarding narrow roads, the sinks and sources may be thus located quite far away from the roads, especially in areas with low relief.

Figure 13. The automatically determined stream networks, (a) tSN using the traditional method and (b) csSN using the culvert-search method. The culvert at A directs more flow to the south side of the road, and the resulting network better agrees with the reference data. The location of the crossing is improved at C. The field surveys revealed that right after the culvert at C, the water flows to a rain water drain under the field instead of flowing through it.
A subset of reference culverts was classified according to the amount of water flowing through them. The comparison showed that the more relevant culverts were located with higher accuracy than the average over all the reference data.

Sometimes a determined stream flows along a road for a long distance. This usually happens with the smallest roads because they are not elevated from the environment and with LIDAR-based elevation data, the undergrowth further elevates the surrounding area in the DEM. In such cases, the algorithms to place culverts get confused and sometimes place culverts in unexpected locations. Using the road data in a vector format to assist the culvert-placing process could result in more accurate placement of the culverts. However, this usually happens with the smallest streams and does not affect the network globally. Similar confusion ensues if there is a discrepancy between the DEM and the road network data, and a road vector is located in a ditch alongside the road. In this study, we did not concentrate on dealing with the uncertainty in the data. For more automatic solutions, it must be taken into account.

Our method relies on the assumption that the water channels are mostly visible in the DEM, and only small corrections are needed. Thus, the method is best suited for sparsely populated areas, where the effects of buildings, paved areas, rain water drains, and so on are local and do not affect the stream network on a large scale. Urban and residential areas with extensive rain water drain systems cannot be analyzed with this method because the drains cannot be seen in the DEM. However, if rain water drain data is available, in theory the sinks and the sources could be included as connections between cells.

The existing carving methods process all the pits in the DEM in an identical manner, and the produced DEMs contain carving paths with a width of one pixel. Often this is a sufficient result, but for some applications it may not be adequate. For example, for hydrodynamical applications the actual width of the channel may be important as well. In addition, for visualization purposes, carved roads are not ideal.

Our method treats the culverts as separate objects. In this way, they can be materialized for each application in a more suitable manner. Additionally, once the algorithm has located the culverts, the rest of the DEM can be processed with any of the previously published carving methods.

Limiting the culvert placement to the vicinity of the roads means that we perform the expensive A* search only on a fraction of the pits in the DEM. This is in contrast to the cost-distance approach (Lindsay and Dhun 2015), where essentially all pit cells are processed, although limiting the search space to the vicinity of roads could probably be similarly applied in their approach.

For analyzing larger areas, more efficient algorithms for the carving and the flow accumulation are required and parallelized implementations may have to be considered.

The presented approach for determining the stream network uses the flow accumulation values of the cells to determine which cells belong to the network. Although adding culverts in the right locations improves the quality, the determined network will never completely match our perception of the real stream network.

5. Conclusions

We have developed two algorithms, the carving path analysis algorithm (PAA) and the intersection inspection algorithm (IIA), which search for probable locations of the culverts
for a given DEM and road network data. We show that if the carving algorithm is modified to use the located culverts, the quality of an automatically determined stream network can be improved. We provide multiple examples of this from our test area.

The next step in the direction of a more universal stream network determination would be to apply machine learning and pattern recognition algorithms to the process of finding channels. A simple approach would be to join the networks determined by the two different methods. Another approach could be to first scan the DEM with pattern recognition and mark the probability of each cell being on a channel. This data could then be used to further guide the carving. Some steps toward a more sophisticated automatic stream network determination have already been taken (Schwanghart et al. 2013). However, further study is needed before the automatic methods can be used reliably in applications and operational systems.

Disclosure statement

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Notes on contributors

Dr. Ville Mäkinen received his Ph.D. degree from the University of Jyväskylä in theoretical physics in 2013. He is currently a senior researcher in the Department of Geoinformatics and Cartography at the Finnish Geospatial Research Institute FGI, which is part of the National Land Survey of Finland (NLS). His research interests include numerical computer simulations on parallel architectures and hydrological analyses.

Professor Juha Oksanen is the Head of the Dept. of Geoinformatics and Cartography at the FGI. He received his M.Sc. and Ph.D. degrees in geography from the University of Helsinki, where he currently also acts as an Adjunct Professor of geoinformatics. His research interests include cartography, geovisualisation, handling of uncertainty and analysis of large spatio-temporal datasets.

Dr. Tapani Sarjakoski serves as a Research Professor at the FGI since the beginning of year 2018. Earlier he was a professor and the Head of the Dept. of Geoinformatics and Cartography at the Finnish Geodetic Institute since 1988. (Finnish Geodetic Institute was merged to the NLS at the beginning of 2015 and continues today its function as Finnish Geospatial Research Institute FGI.) He is an Adjunct Professor in geoinformatics at the University of Helsinki and an Adjunct Professor in photogrammetry at the Aalto University. His current research interests include interface design for geospatial solutions and high-performance geocomputing.

ORCID

Ville Mäkinen http://orcid.org/0000-0002-7887-5646
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