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The accuracy of drainage network delineation as a function of environmental factors: A case study in Central and Northern Sweden

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Abstract

Drainage networks delineated from Digital Elevation Models (DEMs), are the basis for the modelling of geomorphological and hydrological processes, biogeochemical cycling, and water resources management. Besides providing effective models of water flows, automatically extracted drainage networks based on topography can diverge from reality to varying degrees. The variability of such disagreement within catchments has rarely been examined as a function of the heterogeneity of land cover, soil type, and slope in the catchment of interest. This research gap might not only substantially limit our knowledge of the uncertainty of hydrological prediction, but can also cause problems for users attempting to use the data at a local scale. Using 1:100000 scale land cover maps, Quaternary deposits maps, and 2 m resolution DEMs, it is found that the accuracy of delineated drainage networks tends to be lower in areas with denser vegetation, lower hydraulic conductivity, and higher erodibility. The findings of this study could serve as a guide for the more thoughtful usage of delineated drainage networks in environmental planning, and in the uncertainty analysis of hydrological and biochemical predictions. Therefore, this study makes a first attempt at filling the knowledge gap described above.

KEYWORDS

accuracy, catchments, digital elevation models, drainage network, land cover, slope, soil type, variability

1 | INTRODUCTION

The drainage network, along which water and sediments are transported to the outlet of a drainage basin, and its derived hydrologic features and descriptors, for example, Specific Catchment Area (SCA) (Wilson & Gallant, 2000), drainage density (Horton, 1932) and stream order (Strahler, 1957), are the main inputs for analyzing geomorphometric features of valley development (Oguchi, 1997; Vogel, 2000), predicting soil erosion (Wischmeier & Smith, 1958),

estimating runoff from rainfall (Clark et al., 2008; Quinn, Beven, Chevallier, & Planchon, 1991), and managing water resources (Gorelick, 1983; Rossetto et al., 2018; Thomas, Joseph, Thirivikramji, & Abe, 2011). With the increasing availability of high quality Digital Elevation Models (DEMs), automated extraction of drainage networks from DEMs has been an effective alternative to time-consuming manual mapping from topographic maps (Holmgren, 1994; O'Callaghan & Mark, 1984; Tarboton, 1997; Wang, 2014; Zhou, Pilesjö, & Chen, 2011). However, it is common to observe that there is some

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degree of disagreement between an extracted drainage network and the landscape which that drainage network models.

Since the most widespread methods of automatic drainage network delineation are based solely on the topography modelled in a DEM, a large number of previous studies focus only on the complexity of the topography and its representation, for example, the scale and resolution of the source DEM, which can lead to some variability of agreement between the resulting extracted drainage network and the actual landscape (Ariza-Villaverde, Jiménez-Hornero, & De Ravé, 2015; Tang, Hui, Josef, & Liu, 2001). Nevertheless, the hydrologic performance of the actual landscape is not only affected by its topography, but also by its land cover, soil type, etc. It is well known that the infiltration rate of soil, the water content in different soils and drainage channels, etc., strongly influence runoff pattern (Dietrich, Wilson, Montgomery, McKean, & Bauer, 1992; O'Callaghan & Mark, 1984; Veihmeyer & Hendrickson, 1931). Runoff regimes could also change between different land covers, for example, forest and grass, due to differences in evaporation and water uptake by roots (Feddes et al., 2001; Penman, 1956). In addition to these factors, the quality of a DEM is likely to be a function of the land cover types and terrain characteristics present at that location (Adams & Chandler, 2002; M. E. Hodgson et al., 2005). Therefore, the degree to which delineated drainage networks may, in some locations, be a poor representation of reality is not only related to topography, but is also related to the heterogeneity of environmental factors such as land cover and soil type. Although there might be many other factors influencing the accuracy of delineated drainage networks, in this paper we focus on investigating three key environmental factors, namely slope, land cover, and soil type.

Although some previous studies have also observed that vegetation, soil type, and topography may have effects on the results of drainage network delineation (Vogt, Colombo, & Bertolo, 2003), those studies did not explain how and to what extent the accuracy of drainage network delineation may vary among different land cover, soil type, and slope conditions. Lacking such knowledge, it is difficult to assess the quality of a delineated drainage network at a local scale and its effect on, for example, the degree of uncertainty in biogeochemical process modelling (Jenson & Domingue, 1988; Jolly, 1982). Most of the time, researchers have focused on the explanation of how heterogeneous environmental factors intuitively lead to the uncertainty of hydrological and biogeochemical modelling, but have ignored the fact that unrealistic flow estimation (as a result of inaccurate drainage network delineation) due to local conditions could be one of the principle explanations for the magnitude of uncertainty in hydrological and biogeochemical predictions (Chaves & Nearing, 1991). Therefore, hydrological and biogeochemical models should not only be calibrated in terms of the characteristics of topography, land cover, and slope (Strömqvist, Arheimer, Dahné, Donnelly, & Lindström, 2012), but also be calibrated based on the quality of flow estimation data associated with these characteristics (Beven, 1993).

In addition, even though the variability of the disagreement between derived drainage networks and the reality they represent has

been observed within a catchment, most studies still have provided only a description of the overall accuracy of the delineated drainage networks for the catchment as a whole. Thus, it is impossible to assess the quality of a delineated drainage network at a local scale, in specific portions of a catchment, and this shortcoming substantially limits the ability to communicate detailed information about the data quality of a delineated drainage network to its users (Johnston & Timlin, 2000). This will further cause problems for water resources management, for example, irrigation system design in farming planning (Bhattacharya & Michael, 2006; Karásek, Tlapáková, & Podhrázská, 2015; Molle et al., 2007; Young, Smart, & Harding, 2004).

This paper studies the variability of the quality of delineated drainage networks as a function of key environmental factors within catchments, and also explores the underlying mechanisms for these variabilities. Understanding the significance of the potential effects of environmental conditions on the variability of the accuracy of drainage network delineation is often limited, mainly due to the lack of field data that are required to evaluate the accuracy of the delineated drainage network. Field data are often unavailable due to the high cost of manual collection in the field, or of manual digitalization from high resolution satellite images. In this study, 30,000 control points, surveyed in 10 catchments in central and northern Sweden were used to quantify the agreement between the delineated drainage network and flow conditions in the landscape. Additional ancillary data, namely 1:100000 scale land cover, 1:100000 scale Quaternary deposits maps, and 2 m resolution DEMs, were used to extract the information about land cover, soil type, and slope in the study area.

2 | MATERIALS AND METHODS

The workflow of this study is presented in Figure 1. Further details about data and processes are explained below.

2.1 | Study site

Ten catchments in Central and Northern Sweden were included in this study: Delångersån (199,300 ha), Gavleån (245,800 ha), Gnarpån (22,900 ha), Hamrångeån (51,800 ha), Harmångersån (119,600 ha), Krycklan (6,800 ha), Ninån (19,700 ha), Norrlanån (31,900 ha), Skarjaån (32,900 ha), and Testeboån (111,100 ha) (Figure 2). In these catchments, the elevation generally decreases from Northwest to Southeast. Krycklan is a tributary to the Vindeln River that ultimately enters the Baltic Sea, and the other nine catchments are directly connected to the Baltic Sea.

Two-metre resolution DEMs were used to estimate slope in ArcGIS 10.1 software (Burrough, 1986) and to extract the drainage networks for the study area. The DEMs, provided by the Swedish Mapping, Cadastral and Land Registration Authority, were generated from airborne LiDAR point cloud data with a point density of 0.5–1.0

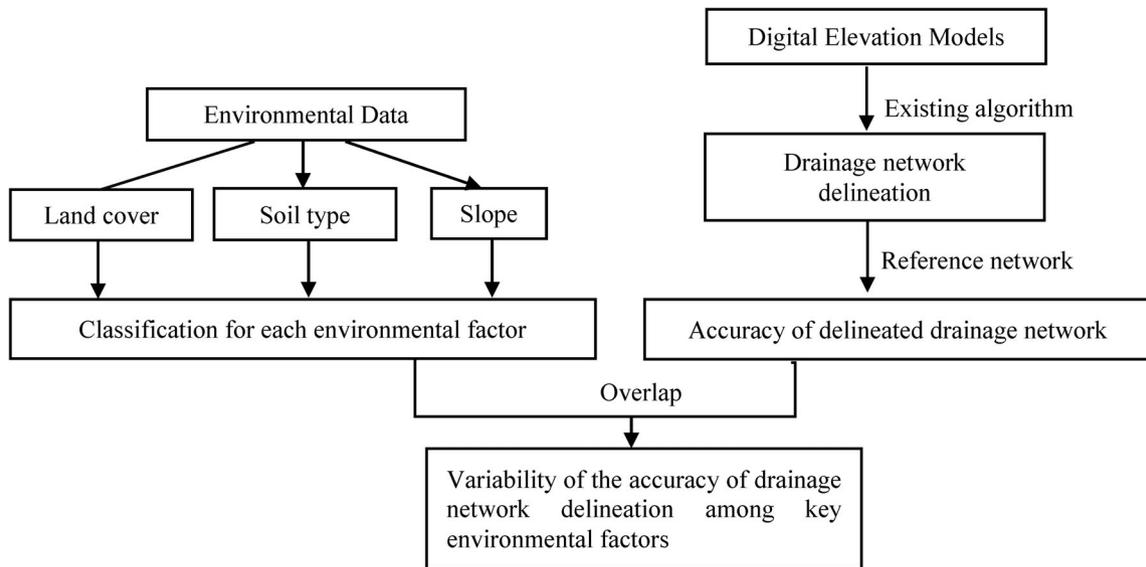


FIGURE 1 Workflow used to assess the variability of accuracy of drainage network delineation as a function of key environmental factors

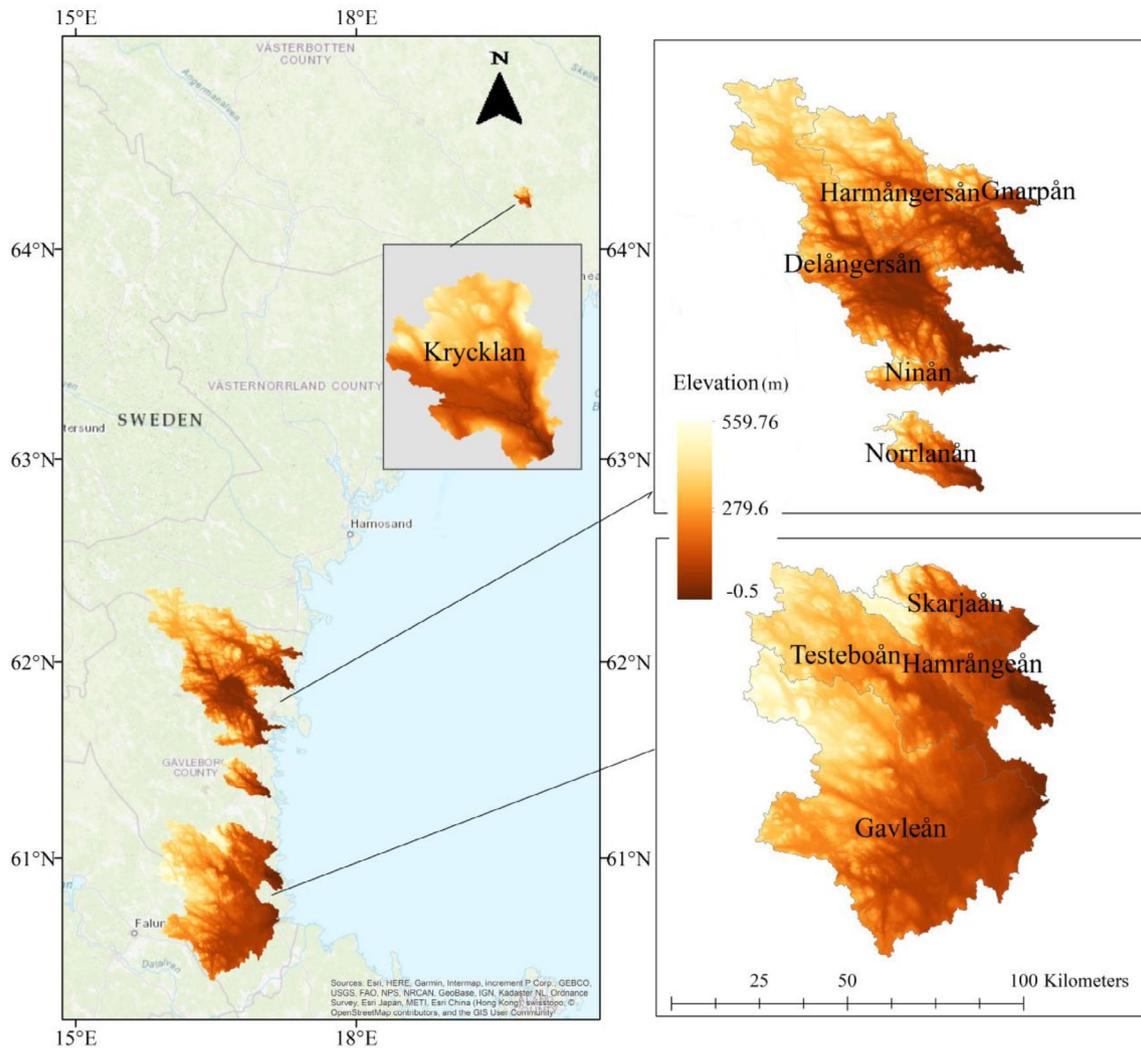


FIGURE 2 Digital elevation model-based topographic maps of the 10 catchments. One of the study areas is located 60 km inland in Northern Sweden, while the other nine areas are located along the coast of Central Sweden

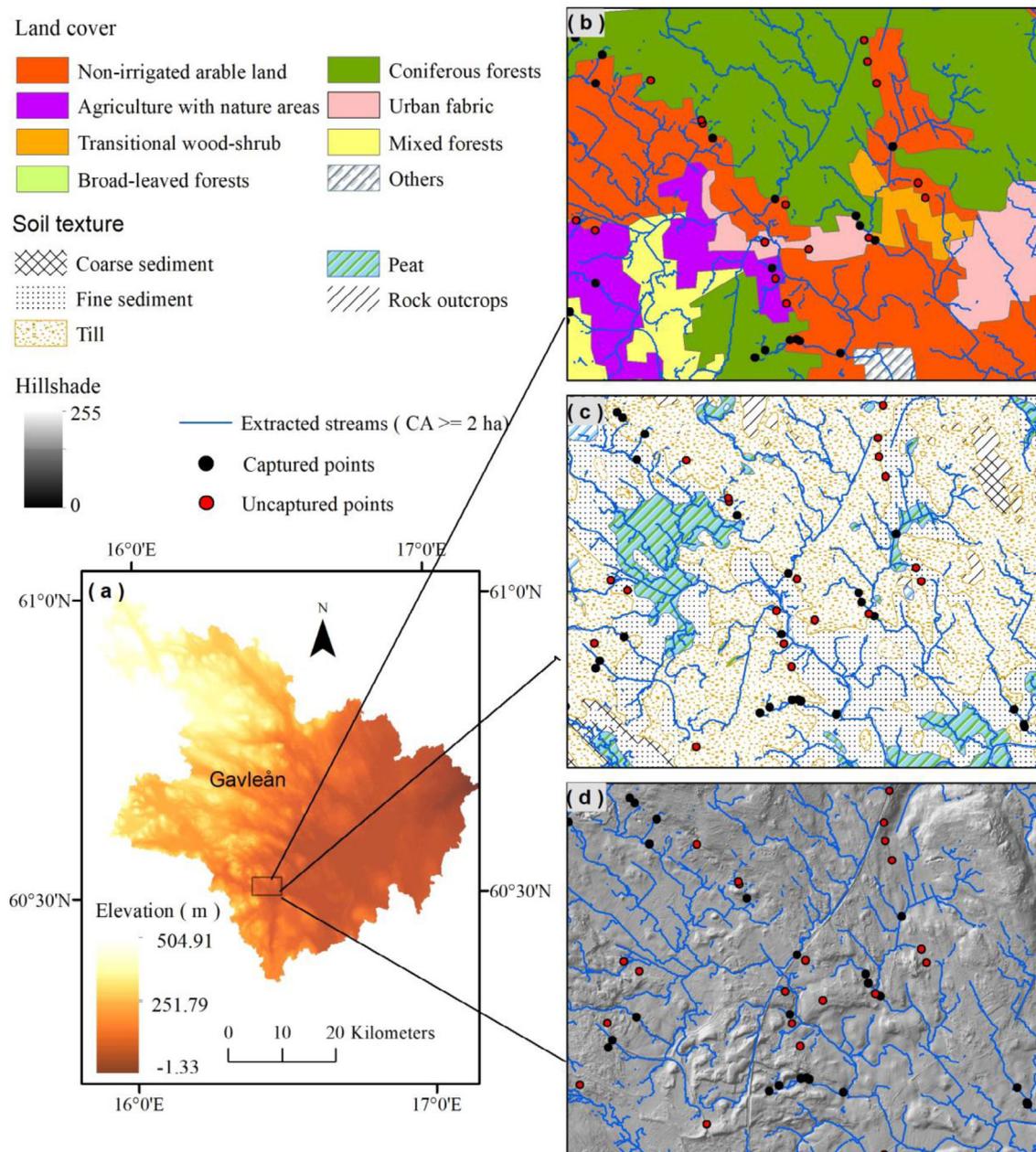


FIGURE 3 Delineated drainage network within the Gavleån catchment. (a) digital elevation model, (b) land cover map, (c) soil texture map, and (d) hillshade map with sun elevation angle of 45° and sun azimuth angle of 315° . Blue lines indicate streams that are extracted by the LCP&TFM algorithm with a constant threshold of contributing area (CA) (i.e., 2 ha). Black and red dots indicate control points that are captured and not captured by the extracted streams, respectively

point/m², an average horizontal accuracy of 0.4 m (using the SWEREF99TM coordinate system), and a vertical accuracy of 0.1 m. The scanning of the study area was conducted during optimal conditions, after leaf fall and before snow cover in the late autumn of 2010. A Triangulated Irregular Network (TIN) was generated from the ground elevation data of the LiDAR signals and converted to a $2\text{ m} \times 2\text{ m}$ gridded DEM by linear interpolation (Worboys & Duckham, 2004), with an average elevation error of 0.5 m (Ågren, Lidberg, & Ring, 2015).

2.2 | Data

2.2.1 | Control points of reference drainage network

Roads often appear to block streams that they cross, and to prevent this from happening, culverts are constructed to allow water to drain underneath the road (Barber & Shortridge, 2005). In the study area, most culverts were constructed following the natural streams over

which roads cross. One should note that when designing a culvert that will move streamflow under a road, usually the degree to which the channel and flowpath are modified from their original course is minimized to the extent possible, due to the considerations to minimize the chance of undermining the road and the cost of material and labour. A few culverts were built to prevent ephemeral flooding over roads due to snow melt in spring. Each culvert has an “inlet” side and an “outlet” side, and this study considered only the inlets to the culverts as “control points” (Figure 3). These inlets correspond to the position of a “real stream” created by hydrological processes related to, for example, infiltration, precipitation, evaporation, and topography.

A culvert survey was conducted in Krycklan catchment between June 29 and July 25, 2013. Through the use of a handheld GPS receiver, culvert locations were mapped with a horizontal accuracy of less than 10 m. Additionally, a DEM (0.5 m horizontal resolution) and an orthophoto (17 cm resolution) were used to manually adjust the locations of the mapped culverts in order to increase their precision. For the other nine catchments, the culvert surveys were carried out during the snow free period of 2014, again using GPS receivers with a horizontal accuracy of 0.3 m, in collaboration with the Swedish Forest Agency. Approximately 30,000 culverts in total were mapped through field surveys. The culvert data are available by contacting the Krycklan Catchment Study (<https://www.slu.se/Krycklan>). In order to examine how the spatial pattern of road culverts is distributed on the drainage network, the average nearest neighbour ratio was calculated (Ebdon, 1991). The average nearest neighbour ratio of road culverts was found to be 0.42. In comparison, a set of random points was generated (with the same total number as the number of road culverts) that were randomly distributed along the drainage network, and the average nearest neighbour ratio was found to be 0.69 for this set of points. Both sets of points (i.e., road culverts and the random distribution of the same number of points on the drainage network) exhibit a moderate, but significant, level of clustering, as indicated by their average nearest neighbour ratios of less than 1 and both p value of 0.000. Thus, from the point of view of the degree to which the locations are clustered, there is little difference between using road culverts and a randomly distributed set of points on the drainage network. Visual inspection reveals that the clustering is mainly present around convergence points where lower order streams meet higher order streams. In addition, from Table 1, it is seen that road culverts are almost stratified to be proportional the abundance of the various conditions in the landscape (i.e., if the cells coincident with the stream network are 70% coniferous forest, then ~70% of culvert samples should be in locations with coniferous forest, etc.). All things considered, it is appropriate to the use of road culverts data as ground points of stream networks.

2.2.2 | Quaternary deposits map

The Quaternary deposits map (jordarter-25-100-tusen) created by the Swedish Geological Survey shows the surface and near surface

TABLE 1 Percentage of various conditions along stream networks and around road culverts

Land cover	Stream network (%)	Road culverts (%)
Urban fabric	0.5	2
Agriculture with natural areas	0.4	0.9
Non-irrigated arable land	6.6	10.1
Coniferous forest	79.1	70.5
Transitional woodland-shrub	9.1	9.8
Mixed forest	3.9	5.5
Broad-leaved forest	0.4	1.2
Soil type	Stream network (%)	Road culverts (%)
Coarse sediment	14.0	12.8
Fine sediment	7.2	10.8
Till	60.9	71.3
Peat	14.8	3.3
Rock outcrops	3.1	1.8
Slope	Stream network (%)	Road culverts (%)
0–6	57.9%	50.6%
6–18	41.7%	49%
>18	0.4%	0.4%

distribution of different soil types in a scaleranging between 1: 25000 and 1:100000. Spatial accuracy of the position of soil type features in this map is, in general, better than 100 m. The map is assumed to be accurate enough to be used (Bjoernbom, 1985) in order to investigate if soil type can influence the accuracy of a delineated drainage network.

Most of the Quaternary deposits in Sweden were formed very recently, during and after the latest glaciation. The Quaternary deposits were categorized by their hydrological function into five main categories: These are till, peat, coarse sediments, fine sediments, and rock outcrops (Figure 3) (Ågren et al., 2014). Coarse sediments (cohesionless soils) include material such as glacial and postglacial fine sand, glacial and postglacial silt, and postglacial sand and gravel, whereas fine sediments (cohesive soils) contain, for example, glacial and postglacial fine clay, clay, silty clay, and mud. The content of till may vary from pure clay to mixtures of clay, sand, gravel, etc. Across the whole study area, 7% of the surface is coarse sediment, 5% is fine sediment, 60.7% is till, 9% is peat, and 8.3% is rock outcrops. The remaining 10% of the land area shown in the Quaternary deposits maps is water, mainly in the form of glacial ice, and this portion of the landscape is not considered in this study.

2.2.3 | Land cover map

The COOrdination of INformation on the Environment (CORINE) Land Cover (CLC) inventory consists of an inventory of land cover in

TABLE 3 The proportion of classes of slope present within land covers in the Gavleån catchment

Slope	Land cover						
	Urban fabric	Agriculture with natural areas	Non-irrigated arable land	Coniferous forest	Transitional woodland-shrub	Mixed forest	Broad-leaved forest
0°–3°	0.42	0.53	0.50	0.28	0.23	0.33	0.39
3°–6°	0.27	0.25	0.25	0.27	0.28	0.28	0.27
6°–9°	0.13	0.10	0.12	0.18	0.19	0.16	0.14
9°–12°	0.07	0.05	0.06	0.11	0.12	0.10	0.08
12°–15°	0.04	0.03	0.03	0.07	0.08	0.06	0.05
15°–18°	0.03	0.02	0.02	0.04	0.05	0.03	0.03
18°–27°	0.03	0.02	0.02	0.04	0.04	0.03	0.03
>27°	0.01	0.00	0.00	0.01	0.01	0.01	0.01
Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0

TABLE 4 The proportion of classes of slope within soil textures in the Gavleån catchment

Slope	Soil texture				
	Coarse sediments	Fine sediments	Till	Peat	Rock outcrops
0°–3°	0.37	0.54	0.21	0.65	0.09
3°–6°	0.28	0.27	0.27	0.25	0.17
6°–9°	0.15	0.1	as0.2	0.06	0.18
9°–12°	0.08	0.04	0.13	0.02	0.16
12°–15°	0.05	0.02	0.08	0.01	0.13
15°–18°	0.03	0.01	0.05	0.01	0.1
18°–27°	0.03	0.02	0.05	0	0.13
> 27°	0.01	0	0.01	0	0.04
Total	1.0	1.0	1.0	1.0	1.0

raster by setting a threshold that is usually a constant value for the minimum contributing area that is needed to form and maintain a channel. Points/cells in the DEM with the minimum contributing area are located where streams initiate, that is, stream heads.

There are two main categories of drainage network delineation algorithms, that is, Single Flow Direction (SFD) algorithms and Multiple Flow Direction (MFD) algorithms. The main difference between these two kinds of algorithms is that, for each grid cell, water flows to only one downslope cell, along the steepest slope, for SFD algorithms, whereas it is distributed to one or more downslope cells for MFD algorithms. SFD algorithms work well on convergent surfaces (O'Callaghan & Mark, 1984), while MFD algorithms produce more realistic results on divergent surfaces (Holmgren, 1994). When implementing such algorithms, the pre-processing of DEMs is required to remove spurious sinks (Hutchinson, 1989). However, the most widespread methods for sink removal not only alter the elevation data in the DEMs, but also remove all real sinks, for example, lakes, resulting in potential inconsistency between the altered terrain and the original surface, and this can result in unrealistic

drainage network delineation (Jenson & Domingue, 1988; Lindsay & Creed, 2005; Martz & Garbrecht, 1999). The Least Cost Path (LCP) algorithm provides an alternative approach to traditional sink removal, by determining flow through unaltered terrain and out of any sinks that are present. However, the original LCP method was designed for either converging or diverging flow patterns, but not both at the same time. The Triangular Form-based Multiple flow (TFM) algorithm (Pilesjö & Hasan, 2014) is sensitive to terrain form, and is able to effectively represent both diverging and converging flow patterns. However, in its original form, it requires sink removal. By combining the advantages of the LCP algorithm and the TFM algorithm, the resulting combined LCP&TFM algorithm (Yan et al., 2018) could not only estimate flow out of sinks without changing any elevation data, but can also effectively represent both converging and diverging flow patterns. The combined algorithm has been proven to improve the accuracy of delineated drainage networks, as compared to commonly used algorithms. Therefore, this algorithm has been selected and implemented in this study to delineate drainage networks.

The characteristics of extracted drainage network depend extensively on the selected threshold of contributing area, equal to the minimum contributing area (Ozulu & Gökğöz, 2018). One appropriate way to determine an effective threshold of contributing area is to carry out a field survey. Stream heads, with a contributing area ranging between 2 and 16 ha, were observed in the study area during varying hydrological conditions from 2013 to 2014 (Ågren et al., 2015). The value of 2 ha was chosen as the minimum contributing area to extract drainage networks in this study as it is likely to identify all possible drainage networks based on field survey.

2.4 | Calculation of the accuracy of drainage network extraction

The accuracy of the delineated drainage network reported below is calculated for each class of the three identified environmental factors, and the classification of each of the environmental factors is described in Section 2.5. From a constant and reasonable value selected for the threshold of contributing area, a drainage network can be extracted. Generally, the accuracy can be assessed by the number of control points intersecting the extracted drainage network, divided by the total number of control points (culverts) present within the catchment.

Due to errors in GPS measurements, and/or the difficulty of locating inaccessible control points, the locations of control points in field are not always absolutely correct. For instance, control points may be located along side of a stream, rather than at its centre because of inaccessibility. Therefore, for this analysis, there is an “acceptable distance” between the extracted drainage network and measured control points (culverts). Thus, the accuracy (T) can be calculated by the number of control points (culverts) that are within the acceptable distance away from the extracted drainage network (N_{fitted}) divided by the total number of control points (culverts) present in the catchment (N_{total}), as in Equation 1:

$$T = N_{fitted} / N_{total} \quad (1)$$

In the study area, most streams are less than 10 m wide. For example, if a stream is 10 m wide and a control point was located erroneously along the side of the stream, the horizontal position error of this control point is 5 m (if ignoring possible error in GPS positioning). Therefore, the potential error in the locations of control points is larger than 5 m. However, since it is hard to set an optimal value for this acceptable distance, several values of likely acceptable spatial mismatch, that is, 10, 15, 20, 25, and 30 m were used for calculating the accuracy, respectively.

2.5 | Extraction and classification of environmental factors

As water moves down to the river mouth of a basin, upslope hydrological processes may, to some extent, impact the water

downslope, but usually do not control the downslope processes since these can vary greatly with changing land cover, soil texture, or terrain as water flows downhill. Sometimes, the impact of upslope areas on downslope flow is very weak. For instance, there might be large and dense streams in upslope areas but these streams may be gone when reaching downslope areas due to rapid absorption of water by soils. In addition, the upslope processes may not affect the accuracy of drainage network extraction on downslope surfaces. The accuracy might be very low in the case of upslope flat terrain, but contrastingly high in the case of downslope steep terrain. Thus, it seems that local environmental factors can have a larger influence on the actual position of a stream than upslope environmental factors do. It means that, for example, locally dominant land cover, rather than upslope dominant land cover, should be considered when assessing the accuracy of drainage network delineation at a local scale.

Since the accuracy of drainage network extraction is assessed in this study based on the positions of control points, the identified environmental factors, that is, soil texture, land cover, and slope, are extracted within a local window surrounding each control point. The locally dominant slope, land cover, and soil texture are obtained using a window of size 50 m. The maximum width of most streams is 10 m, and large roads above these wide streams can have a significant influence on the derivation of local environmental conditions for each control point if the window size is set too small. Thus, by assuming a road of 10 m × 10 m as a center cell, and by using a 5 × 5 window of such cells (i.e., 50 m × 50 m), is a reasonable approach to reduce the effects of roads and to ensure that the environmental factors are derived at an appropriate local scale. The locally dominant slope is expressed by the average slope, while the locally dominant land cover and soil type are indicated by the land cover and soil type that occupy more than 50% of the total area of each local window, respectively. It is quite rare that a local window for a control point contains more than two types of land cover or soil texture. As there are fewer than seven valid cells, the calculation of slope will not be performed in the ArcGIS 10.2 that is used for slope calculation as mentioned above. Windows containing one or more cells with null values were skipped as well for the calculation of the average slope. In total, there were 34 such windows out of a total of 29,262.

To find the variation of the accuracy of drainage network extraction among environmental factors, it is necessary to make a classification of each factor. As described above, the study area consists of seven main land cover classes and five main types of soil texture. Slope is the only factor left to be classified. The range of slope is from 0° to 90° but there is no general classification key for slope, since it is usually classified to meet certain requirements or parameters of landscape components (Wilson & Gallant, 2000). Thus, in this study, slope is equally grouped into 180 classes, 90 classes, 45 classes, 30 classes, and 18 classes, respectively. This implies that the range of each slope class (i.e., the bin size of slope) is 0.5°, 1°, 2°, 3°, and 5°, respectively.

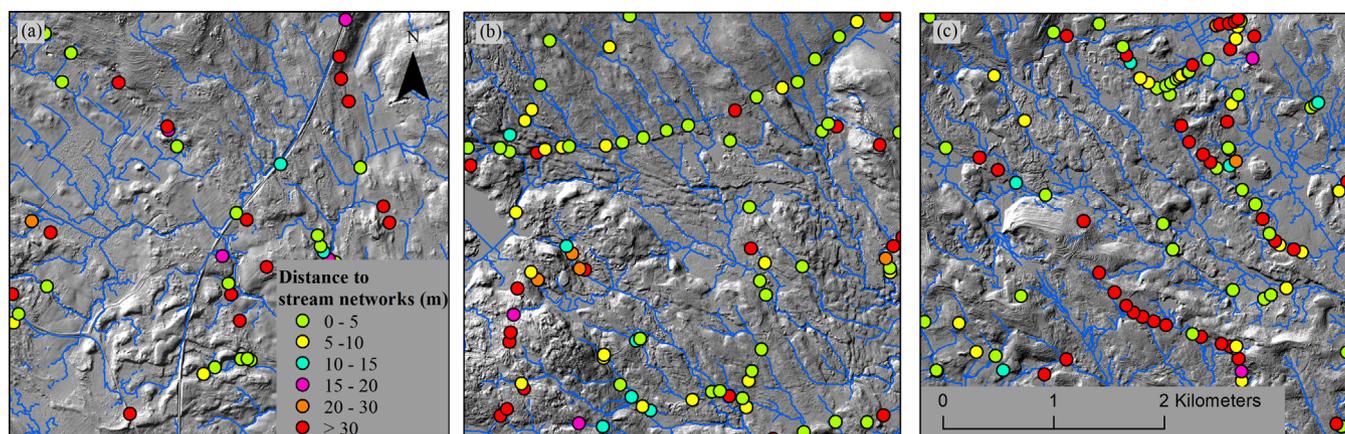


FIGURE 4 Distance of culverts to delineated drainage network in three small regions of the study area

3 | RESULTS

From the methodology previously described, we aimed at studying the variability of the accuracy of a delineated drainage network. Figure 3 shows a portion of the study area, including the distribution of its land cover, soil and topography as well as a delineated drainage network together with control points (culverts). Figure 4 indicates the ranges of the accuracy of drainage network delineation based on the distance of culverts to delineated drainage network in three small regions of the study area. For each control point, the locally dominant land cover, soil texture, and slope were extracted, and the number of control points within each class of land cover, soil texture, and slope was counted, as shown in Table 5. Since some control points were skipped (as explained above), there are differences in the total number of control points considered for each of the three environmental variables (Table 5). The statistics indicate that the local average slope of control points ranges from 0° to 27° , mainly varying between 3° to 12° . In addition, most control points are locally dominated by coniferous forest and till. Results describing the variability of the accuracy of drainage network extraction for each environmental variable are presented in Figures 5 through 7.

3.1 | Variability of the quality of drainage network delineation with respect to soil textures and land covers

Due to the range of acceptable distances considered in Section 2.4, the accuracy of drainage network extraction for each type of soil texture and land cover was calculated based on the described values. Figures 5 and 6 show the main results for all classes of soil texture and land cover, respectively.

The overall accuracy of drainage network extraction was highest for peat lands (as high as 0.88, see Figure 5). There was a slightly lower accuracy for coarse sediments, and lower still for till and fine sediments. Rock outcrops displayed far lower accuracy (lower than 0.6) (Figure 5). In addition, the highest overall accuracy of drainage

network extraction was for transitional woodland and shrub (as high as 0.76), followed by coniferous forest, mixed forest, broad-leaved forest or non-irrigated arable land, urban fabric, and agriculture with natural areas (no higher than 0.5) (Figure 6). Note that culverts sampled in peat soils were undersampled (Table 1) but had the highest accuracy of drainage network delineation compared to other soil types. In contrast, culverts in urban and agricultural areas were over-sampled (Table 1) but had the lowest accuracy of drainage network delineation. This further demonstrated that the lower accuracy of drainage network delineation for a specific land cover, soil type or slope class is not related to fewer samples of culverts.

Concerning the acceptable distance of between 10 and 15 m, there was a major increase in accuracy for all classes of soil texture and land cover, while between 15 and 30 m, there was a steady and very slowly increasing accuracy (Figures 5 and 6). Thus, in this study, 15 m can be considered to be the optimal acceptable distance to be used when validating the accuracy of the extracted drainage network.

3.2 | Variability of the quality of drainage network delineation with respect to slope

The number of control points that the extracted drainage network succeeded in capturing was obtained for each class/bin of slope, and then its accuracy was calculated in each class. Since the accuracy did not change much as acceptable distance increased (as described above), a value of 15 m for the acceptable distance was used here. After testing varying numbers of bins of slope, it was observed that with bin sizes of 3° , there was an increase in accuracy between 0° and 6° (Figure 7). Then, the accuracy remained more or less stable between 6° and 18° . Between 18° and 21° , there was a slight decrease in accuracy. Between 21° and 27° , it seemed that the accuracy generally increased. However, the number of control points between 21° and 27° was very small (less than 30), and thus it was not statistically significant. Therefore, the increase observed between 21° and 27° is not discussed further. In short, as slope increases, the

TABLE 5 Statistics of the number of culverts locally dominated by each class of land cover, soil texture, and slope for the whole study area

	Land cover							Total
	Urban fabric	Agriculture with natural areas	Non-irrigated arable land	Coniferous forest	Transitional woodland-shrub	Mixed forest	Broad-leaved forest	
No. of culverts	595	258	2,967	20,648	2,878	1,597	327	29,262
	Soil texture					Total		
	Coarse sediment	Fine sediment	Till	Peat	Rock outcrops			
No. of culverts	3,738	3,148	20,764	955	516	29,121		
	Slope							
	0°–3°	3°–6°	6°–9°	9°–12°	12°–15°	15°–18°	18°–27°	
No. of culverts	1,469	13,326	9,723	3,454	900	239	117	29,228

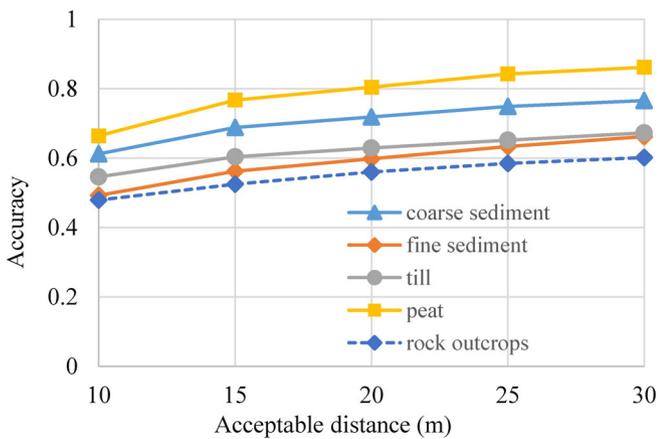


FIGURE 5 The accuracy of drainage network extraction for each class of soil texture ($n = 29,121$)

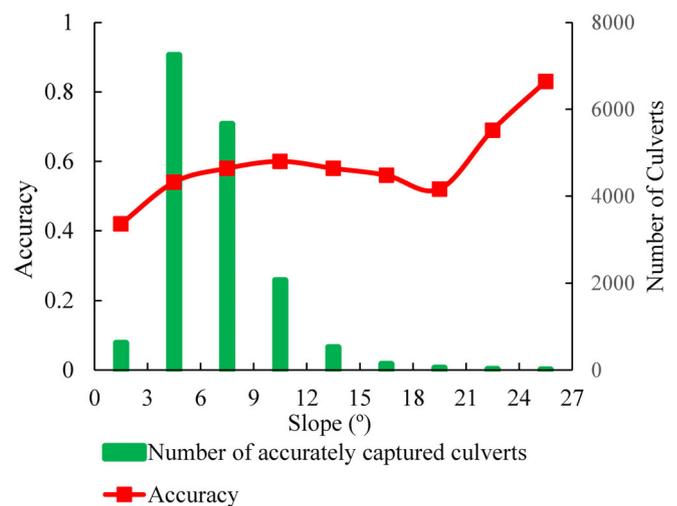


FIGURE 7 Accuracy of drainage network extraction and the number of successfully captured culverts for each bin of slope

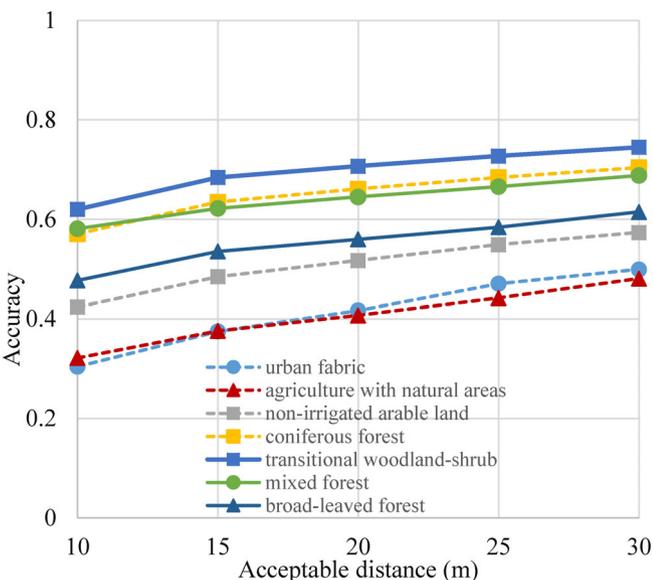


FIGURE 6 The accuracy of drainage network extraction for each land cover type ($n = 29,262$)

relationship between the accuracy of drainage network extraction and slope changes from positive to nearly zero, and then to negative.

4 | DISCUSSION

4.1 | The effect of individual environmental factors on the quality of drainage network delineation

4.1.1 | Land cover

The results suggests that in forests, the accuracy of drainage network extraction decreases as vegetation cover increases, which was also suggested by Thommeret, Bailly, and Puech (2010). This may be due to errors in the DEMs. A high error of LiDAR-derived elevation was shown in heavily vegetated land cover in leaf-off conditions (Kraus & Pfeifer, 1998) and leaf-on conditions (M. E. Hodgson, Jensen, Schmidt, Schill, & Davis, 2003). The elevation error is highest in deciduous

forest land cover, which appears to be consistent with other studies, regardless of leaf conditions (M. E. Hodgson et al., 2005). M. E. Hodgson et al. (2005) also found that land cover with taller canopy vegetation exhibited the largest errors of LiDAR-derived elevation. Apart from forested areas, the artefacts shown in urban fabric (e.g., buildings and roads) and large water bodies surrounding agricultural land with natural areas, to a large extent decrease the accuracy of extracted drainage networks. It might be the case that artefacts such as buildings and roads create large spurious sinks in the DEM (Lidberg et al., 2017), and large water bodies create large flat areas, both resulting in unrealistic drainage network estimation (O'Callaghan & Mark, 1984; Yamazaki et al., 2012).

4.1.2 | Soil texture

The accuracy of drainage network extraction varying with soil types might be positively related to hydraulic conductivity, as a function of soil texture. The overall accuracy of drainage network extraction is found to be the highest for peat lands. There is slightly lower accuracy for coarse sediments, and even lower for fine sediments. The accuracy for fine sediment is close to that found for till. Rock outcrops have the lowest accuracy. Coincidentally, peat can have higher hydraulic conductivity than coarse sediments, for example, fine sand and silt (Bear, 1972). The hydraulic conductivity of coarse sediments is higher than that of fine sediments (e.g., clay) or bedrock aquifers, because of the high porosity and permeability of coarse sediments. Fine sediments' hydraulic conductivity may not vary much from that of till, since till consists of clay, or mixtures of clay, sand, etc. Rock outcrops have the lowest hydraulic conductivity due to impermeable bedrocks, for example, metavolcanic rocks. In addition, Prosser and Abernethy (1996) showed that areas with high soil saturation due to high soil transmissivity displayed more accurate delineated channel network. Soil transmissivity is the integral of saturated hydraulic conductivity over the depth of the soil profile. Hydrological processes in areas with coarse sediments are usually less complicated than those with fine sediments due to larger pores and lower tortuosity facilitating rapid water flow (Childs & Collis-George, 1950; Vogel, 2000). The longer duration of water staying in the soil, the more likely activities/interactions among water, air, soil etc. The assumption behind hydrology-based flow algorithms to delineate drainage networks solely from elevation data is that water flows downslope under the effect of gravity. However, the complexity of water flowing through fine sediments might make the assumption inappropriate which increases the uncertainty of flow path estimation using hydrology-based algorithms, that is, increases the chance of lowering the accuracy of drainage network delineation.

4.1.3 | Slope

It has been argued that drainage networks tend to be more accurate when extracted from steep surfaces than from flat surfaces, since flat

terrain may decrease the accuracy of delineated drainage networks due to uncertainty in flow direction (Martz & Garbrecht, 1999; Turcotte, Fortin, Rousseau, Massicotte, & Villeneuve, 2001). However, the results of this study show that the steepness of terrain does not always contribute positively to the accuracy of drainage network extraction, and instead reaches a "plateau" between 6° and 18° , and decreases in erodible areas with slopes between 18° and 21° . On the other hand, the results might suggest that the quality of a delineated drainage network is lower in erodible areas, while higher in relative flat terrain. This has also been observed in many previous studies. For example, Thommeret et al. (2010) presented a method combining terrain parameters with a hydrology-based algorithm to extract drainage network in the badlands where areas are highly eroded and vegetation is either sparse or absent. It showed that main channels were well delineated where terrain is quite flat, however, drainage networks delineated on higher slopes were less accurate, and were either over-detected or under-detected when compared to reference drainage networks. There are other studies showing similar results, where derived drainage networks were more accurate on valley floors than on higher slopes (Shen & Sheng, 2012; Sofia et al., 2011). Drainage channels are usually formed where water can easily converge, that is, in areas with low and relatively flat terrain, making them easier to detect. In eroded areas, it is less likely for a stream to be formed, and because some ephemeral flow occurs there, due to for example, snowmelt, it is very hard to identify these channels correctly solely from topographic models.

4.2 | Interactive environmental factors' co-effects on the quality of delineated drainage networks

Although the quality of delineated drainage networks was discussed and explained for individual soil texture, slope, and land cover factors, some results were difficult to explain by considering these factors on a purely individual basis. For example, rock outcrops with the lowest hydraulic conductivity, located in steep slopes between 6° and 18° (Table 4) have the lowest accuracy of delineated drainage network among different soil types. Similarly, peat lands with the highest hydraulic conductivity, located upon slopes of less than 3° (Table 4) have the highest accuracy of delineated drainage network, when compared to other soil types. This could be because rock outcrops are usually present on erodible terrain on the top of small hills, close to headwater areas where the ephemeral flow due to snowmelt in spring is difficult for the flow algorithm to detect. Peat lands are often distributed within perennial drainage channels which are easier to detect, although the terrain is rather flat.

In short, the accuracy of the delineated drainage network is high in areas with moderately steep terrain (e.g., slope $<18^\circ$), less vegetation, and high hydraulic conductivity. Vogt et al. (2003) showed that in areas with high drainage density, that is, steeper slope, less vegetation, higher rock erodibility, and low soil transmissivity (transmissivity is positively related to hydraulic conductivity), drainage network delineation is more accurate than in the areas with lower drainage density.

By comparing the results from Vogt et al. (2003) with our findings, both agree that in areas with moderately steep slopes (i.e., not too flat) and less vegetation, the accuracy of the drainage network tends to be higher. However, in our study, we found that low soil transmissivity does not contribute to an increase in the accuracy of drainage network delineation while high soil transmissivity does. The missing identification of artificial ditches in the vicinity of agriculture lands, where soil transmissivity is high due to permeable rocks or soils, is probably the reason why the quality of delineated drainage network was low in areas with high soil transmissivity in Vogt et al. (2003).

4.3 | Limitations

4.3.1 | Drainage network delineation method

In this study, the drainage network is extracted by the combined LCP&TFM algorithm (Yan et al., 2018). The accuracy of drainage network delineation is affected by the lateral errors in derived drainage network, that is, the performance of the flow algorithm used. The combined LCP&TFM algorithm has been demonstrated to perform better than other commonly used hydrology-based algorithms. Still, it is likely that the resulting variability of accuracy in drainage network extraction would vary according to the flow algorithm used. However, most hydrology-based algorithms are able to detect main drainage channels in a satisfactory way, although there is some variation in the resulting values of contributing area (Desmet & Govers, 1996; Yan et al., 2018).

Studying the variability of the performance of flow algorithms for drainage network delineation among different landscapes within a catchment is an indirect way to explore the effects of environmental factors on the accuracy of drainage network delineation. Low accuracy of delineated drainage network is often found in flat areas (Martz & Garbrecht, 1999). Therefore, the use of ancillary data such as lake and river networks is recommended to help correct unrealistic flow estimation over flat surfaces using flow algorithms (Hutchinson, 1989; Yamazaki et al., 2012). However, such problem of drainage network delineation on flat surfaces, for example, plains, might not exist if drainage networks were delineated by, for example, morphology-based algorithms using high resolution satellite images (Montgomery & Dietrich, 1992; Peucker & Douglas, 1975; Tribe, 1992). Thus, the results of this study are limited to drainage network delineation using hydrology-based algorithms. However, hydrology-based algorithms are preferable to those morphology-based algorithms since they are able to detect continuous stream network as well as estimate flow direction for each cell which is essential for watershed hydrological modelling.

Furthermore, setting a smaller contributing area threshold for drainage network delineation in this study does yield a higher accuracy of delineated drainage network, since more control points are included in this case. For example, if the threshold is set to the extreme, smallest possible value, that is, one single cell, the accuracy of drainage network delineation is 100% because all control points

are included. However, as we know, it is unrealistic that all grid cells are streams. Thus, a smaller threshold could result in unrealistic drainage network delineation. A contributing threshold value of 2 ha was chosen due to the fact that the channel initiation was observed at the points with upslope contributing area ranging from 2 to 16 ha over a year subject to precipitation in the field. The contributing area threshold of 2 ha was found to be able to identify most streams in the study area. Also, culverts that were not captured by the derived drainage network due to the inappropriate contributing area threshold of 2 ha (i.e., insufficient extension of the drainage network in some headwater areas) were rather few, which did not have a big impact on the results we presented here. Nevertheless, there is a limitation in applying a fixed threshold for drainage network delineation, since the upslope contributing areas of stream heads are not always the same, due to the heterogeneity of a variety of factors in the hydrologic environment. Significant efforts have been made to tackle the problem of applying a fixed contributing area threshold for drainage network extraction. For instance, Lin, Chou, Lin, Huang, and Tsai (2006) showed that channel initiation points can be accurately obtained from airborne photographs, coupled with high resolution satellite images for suitable drainage network extraction. Rather than threshold values, geomorphological characteristics computed from DEM were used to extract drainage network (de Azeredo Freitas et al., 2016).

4.3.2 | Data quality of DEM

The accuracy of a delineated drainage networks is undoubtedly dependent on the quality of the DEM used, which could vary with changes in terrain and land cover types (Adams & Chandler, 2002; M. E. Hodgson et al., 2005), as well as with other methodological and technological aspects of the elevation data's collection. As mentioned above, the reason why highly vegetated areas exhibit lower accuracy of drainage network delineation might be that dense vegetation lowers the quality of DEM produced from laser clouds. This finding is expected to be in line with that using DEM data that is generated from other remote-sensing products, for example, satellite images. It is because dense vegetation canopy prevents sensors from detecting ground points. Apart from remote-sensing products, the quality of DEM produced from field observations is also largely affected by denser forests that make field work more difficult. Thus, to ensure the accuracy of delineated drainage networks, the quality of DEMs in such areas needs to be validated.

4.3.3 | Other drivers

In brief, the way that land cover affects the accuracy of drainage network delineation is mainly through affecting the quality of DEM data, and the variability of the accuracy of drainage network delineation over different slopes is mainly related to the performance of flow routing algorithms. Hydraulic conductivity of soils, to some extent, determines the complexity of runoff processes, and seems to be able to

explain the uncertainty of drainage network delineation that is solely based on elevation data. Besides land cover, soil types, and slope, there are also other environmental factors that could make a difference in the accuracy of drainage network delineation, such as vegetation height, as this could affect the quality of DEMs generated from LiDAR-derived point cloud data. However, in this study, we have chosen to test only slope, land cover, and soil type. Broad-leaved forests, where low accuracy of delineated drainage network was observed, occupy less than 1% of the total study area, and thus does not heavily influence the quality of the DEM used in this study. Other environmental factors, for example, precipitation or paleotopographic features (Xiong et al., 2017), could also have impacts on the hydrological network. Topographic position (Fan, Miguez-Macho, Jobbágy, Jackson, & Otero-Casal, 2017) or water stress gradient (Cielo-Filho, Gneri, & Martins, 2007) could indirectly impact the quality of drainage network extraction by influencing tree species/tree community composition at a local scale. Therefore, more factors at varying scales are to be investigated in future work in order to enhance our understanding of the underlying mechanisms that determine the accuracy of drainage network delineation.

4.4 | Applications

A generalized classification system of land cover has been made for widespread use of the system (Anderson, 1976): urban land, agricultural land, rangeland (e.g., shrub), forest land, water, wetland, barren land (e.g., beaches), tundra, perennial snow or ice. Among these general land cover classes, the former six land covers are of interest in the study and are distributed from tropical regions to subarctic regions. In addition, based on the distribution of sizes of the particles within a soil, soil can be categorized into sand, clay, silt, peat, chalk and loam types of soil (J. Hodgson, 1974). Chalky soils often contain large quantities of stones of varying sizes and rock outcrops mentioned in this paper is a kind of chalky soils. The till soil studied in this study is one of loam soil, that is, a mixture of sand, silt and clay. Thus, soil types considered in this study cover a general soil group. Furthermore, slopes in this study area mostly range between 0° and 27° and slope is less than 24° (45%) worldwide at a 5-min scale (i.e., about 9 km at the equator). Thus, the variability of land cover, soil type and slopes considered in this study could represent a large proportion of landscapes over the world. In addition, most of the time, due to the lack of field data of drainage networks, it is hard to evaluate the effects of, for example, land cover, slope, soil texture on the accuracy of delineated drainage networks solely from DEMs. Regarding this problem, the tremendous field survey of 10 catchments in Sweden provides a very precious opportunity to have a deeper look at the issue just mentioned, and the findings of this study are not limited to the study area but can be applied elsewhere in the world.

Based on the results of this study, it is possible to have a general and preliminary evaluation of the potential of drainage network delineation from DEMs using flow algorithms. For example, users of DEM derived drainage networks could have a quick

knowledge of the uncertainty of the data they used at the local scale. On the other hand, users could know that drainage networks derived from broad-leaved forest might be less reliable than that from evergreen forest. With this knowledge, it is possible to quickly pinpoint issues that are related to the data quality of derived drainage networks. Especially for irrigation planning in agricultural managements, the results of our study do not recommend the direct usage of stream network data derived from DEMs using flow algorithms, since the accuracy of drainage network delineation is rather low on those gentle slopes (less than 2.86° or 5%) where agriculture is optimal (Fischer, Van Velthuis, Shah, & Nachtergaele, 2002). Also, for hydrological modellers, this gives a means by which to effectively calibrate the flow path estimation over some problematic areas and to have a more complete view of the uncertainty of runoff simulations over different landscapes. For example, ancillary data is recommended to improve flow estimation when simulating runoff over flood plains where the accuracy of stream networks derived from DEMs is poor.

5 | CONCLUSIONS

In this study, we have found that there is observed variability in the agreement between the extracted drainage networks and the surface waters in the landscape (as represented by the locations of control points) for varying land cover, soil types, and slope within catchments, using 30,000 control points, 1:100,000 scale land cover maps, Quaternary deposits maps, and 2 m resolution DEMs. Results show that areas with transitional woodland shrub, peat soils, and relatively flat terrain (slope between 6° and 18°) have the highest accuracy of drainage network delineation. Dense vegetation cover, low hydraulic conductivity, and steep slopes generally tend to undermine the quality of drainage network delineation. At a local scale, the accuracy of drainage network delineation is likely dependent on the combined effects of land cover, soil type, and slope. The wide variability of land cover, soil type and topographic slope in the study area, makes it possible to apply the findings of this study to most catchments over the world. The knowledge of the variability of the quality of drainage network delineation as a function of these factors should be helpful to guide users of drainage networks for applications in particular locations, and to encourage producers to improve the quality of their drainage network databases.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the public domain: <https://www.slu.se/Krycklan>, <https://www.eea.europa.eu/publications/COR0-landcover>, and <https://www.sgu.se/en/produkter/geological-data/use-data-from-sgu/>. If any problems

with downloading the data from the public domain, the data is available upon reasonable request from the authors.

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