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Arc-Malstrøm: A 1D hydrologic screening method for stormwater assessments based on geometric networks

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ABSTRACT

A method is presented to perform a first screening of high-resolution digital terrain models to detect the extents and capacities of local landscape sinks. When identified their capacities and rain volumes provided from their local catchments during a rainstorm are saved as attributes for the pour points. Next, the downstream paths from the pour points are saved as junctions and edges in a geometric network leading to a final calculation of the accumulated spillover in the topologic data structure determined by a custom trace tool. Although the screening method is based on a representation of the overland surface in a 1D network not involving any hydrodynamic components, it is well suited to provide a quick first overview of a landscape's overall drainage basins, the location of sinks, their contributing watersheds and the accumulated downstream flow when the sinks spill over. The exemplified study assumes Hortonian flow and a uniform rain event, but if spatial variations in precipitation or infiltration capacities are available the local sinks' catchment level, they may easily be added to the workflow to produce first risk map approximations for residential areas threatened by future stormwater incidents.

1. Background

For decades, raster based modeling software has been available to transform the raw terrain models cell by cell into flow pattern predictions by analyzing the elevation values saved as large matrices in the computers' memory. The basic computation is a cell-wise search for the steepest downhill gradient simulating a raindrop's path. However, the software was designed in times when elevation models had very coarse resolutions of, typically, 30 or 10 m, and computers had significantly less RAM. Consequently, working on today's elevation data of 40 cm resolution runs into historical limits of memory usage and file size, as a 40 cm raster has 625 times more cells per km² than a 10 m raster. Therefore, for each square kilometer it is now a matter of processing 6,250,000 cells instead of formerly 10,000.

Software developers (Yildirim, Watson, Tarboton & Wallace, 2015; Barnes, 2016) have addressed these limits and begun to handle very large and very detailed elevation data. Meanwhile, this raises the question whether it is actually necessary to work on very detailed raster representations solely throughout the computations, or if supplementing data representations might be worth considering easing computing. If only the basic raster flow computations must be carried out with high precision, and all preceding processing steps could be carried out based on much

more simple and less data heavy vector data representations, many problems may be solved.

2. Introduction

Leading commercial GIS vendors like Esri and GeoMedia (formerly Intergraph) and open source GIS products like GRASS, SAGA and PC-Raster have had the necessary building blocks for years to calculate flow directions, flow accumulations, delineate watersheds and identify sinks using raster-based tools. As a service to Esri's users a free extension, ArcHydro, even provides data model recommendations and applications to set up stream networks and enable time series measurements from gauges (Maidment, 2004) being efficient in studies of drainage systems at regional levels.

Parallel to the GIS vendors' developments several commercial software producers anchored in the engineering business have focused specifically on numerical hydrologic and hydraulic modeling in order to predict flood inundations in rural and urban landscapes. Among these contesters are PIHMGIS (Bhatt et al., 2014), ISIS & DIVAST (Lin et al., 2006), SWMM (Chen et al., 2009), LISFLOOD-FP (Bates and De Roo, 2000), SCALGO (2017), InfoWorks ICM from Innowyze (Boulos and Niraula, 2016), Sobek by Deltares and the MIKE software series from

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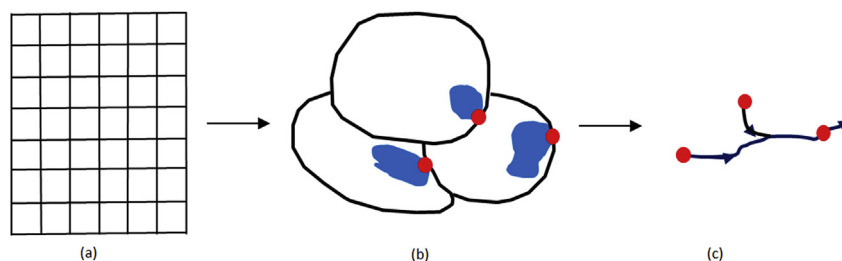


Fig. 1. From elevation values in cells (a) to sinks, catchments and pour points as vector features (b) and further into junctions and edges in a geometric network (c).

DHIGROUP – the latter compared in a study by Vanderkimpen et al. (2009). Such software is typically designed to be much more focused on 2D modeling of hydraulic water infrastructures based on locations of drains/man holes, sewer pipe dimensions, gradients, valves et cetera. The systems may also incorporate detailed information about various soil types' extents, their saturated or unsaturated hydraulic conductivities, groundwater bodies, impervious surfaces and so forth. Moreover, situations due to clogging of debris during rainstorms can be predicted and incorporated into the modeling (Leitão et al., 2016; Pina et al., 2016).

Many local and regional planners have interests in surface based runoff flood modeling aiming at foreseeing stormwater consequences but sometimes at a coarser and more overall level than the commercial software is aiming at in order to perform basic runoff screenings, merely.

This opens up for discussions about suitable levels of detail and if the raster-based data representation is still efficient in stormwater modelings in times where recent LiDAR based terrain models may cause the conventional modeling setups to choke. If the landscape instead could be broken down into local sinks, their catchments and descriptions of flow paths in between those and downscaled into points, lines and polygons, the morphological water traps and carriers could be demarcated, processed and stored more efficiently. Next, if those units were organized as junction and edge features in a geometric network, a complete hierarchical (topological) hydrologic overview of the downhill water flow from sink to sink is nailed enabling calculations of water volumes stored locally in the sinks or carried along when spilling over, see Fig. 1.

The proposed method's workflow and the tools involved to perform a runoff screening are basic and adoptable for users with access to a high-level geographic information system able to handle and process raster, vector and geometric network based data representations. From a strict point of view, the method proposed is applicable, only, when surface runoff is predominantly 1D as seen especially in many not-developed sewerless cities. However, the method is applicable in permafrost regions, also, when assessing sudden impacts of melted snow while the ground remains frozen, and surface infiltration is absent (Johansson, 2016). In warmer regimes it is applicable, too, in stormwater situations when infiltration rates are so low that they may be ignored in order to provide a first overview of the hydrologic situation for rural and urban catchments before considering detailed 2D flood modellings.

January 2016 a LiDAR based terrain model with a spatial resolution as low as 40 cm was released as part of the Danish government's digital

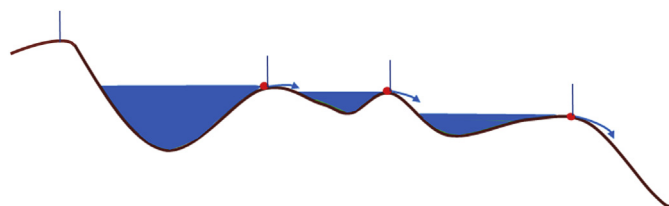


Fig. 2. 2D cross-section of a landscape with sinks (blue) supplied with runoff from their local catchments (delineated at the vertical bars) and from upstream sinks spilling over at their pour points (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

policy making all authoritative base maps public available (Agency for Digitization, 2012). This means that everybody can access and process a raster-based elevation model for Denmark (covering approx. 42, 000 km²) where the average elevation is within a vertical accuracy of 5 cm (The Danish Geodata Agency (2015)). Models of such high precision makes it possible to predict very accurate runoff patterns even along seasonal plough furrows on farmlands in studies of local erosion. In urban areas, the high level of detail reveals ponding along roadways and bike lanes that is of interest to the authorities responsible for maintaining the infrastructures. In addition, delineations of local catchments along paved roads' centerlines forcing the runoff along curbsides into gutters and drains can be evaluated vs. the locations and the capacities for already established manholes or drains.

This article presents the setup of a simple, lumped, 1D rainfall-runoff model to screen any rural or urban land surface for local sinks and their contributing catchments. Unlike Chen et al. (2009); Zhang and Pan (2014) and Maksimović et al. (2009) that carry out the entire hydrologic modeling in the raster domain, this study converts selected information to features in a geometric network providing a quick overview about where and how much water is trapped in local sinks and how much is transported further downstream as spill-over. This means that when the basic overview is provided at the sink-level including the overland path flows, the modeling of various rain event scenarios are carried out in the geometric network that is much less computer demanding than raster processing. Therefore, also unlike previous works there is no need for resampling of large-scale high-resolution DEMs and identifications of a few major sinks, only, to keep the computation times and disc storage requirements at reasonable levels. Furthermore, the advantage of incorporating the geometric network data model in stormwater screening scenarios is that it provides fast searches and displays of connected downstream paths identifying the straight flow towards the outlet and/or the upstream paths, sinks and catchments from any network junction due to the data model's inherent topologic data structure.

Principally, all sinks deeper than an elevation model's vertical accuracy may be detected successfully in order to provide information about locations of even shallow puddles that may lead to dangerous traffic situations in urban environments – for example on rainy days along bike lanes when bicyclists manoeuvres irresponsibly in order to avoid splashes. So, in the current study focusing on urban landscape represented by an elevation model with the before mentioned spatial resolution and vertical accuracy, the extents and capacities of all local sinks with depths ≥ 5 cm are identified no matter their two-dimensional extents and volumes. To divert the surface runoff around buildings and eliminating their volumes if located in sinks, building footprints (as polygons) are added to the terrain surface, too. Optionally, the cells from a surface elevation model within the buildings' footprints may substitute terrain cells in the DEM to model runoffs more accurately for rooftops.

3. Methods and data

In order to keep the data processing in the raster environment at a minimum, the landscape's local sinks and their contributing catchments are used as the representative basic hydrologic units ahead each

describing a well-delineated local drainage basin (Huggett and Cheesman, 2002). As each sink per se is supplied with overland flow from one catchment, only, the sink's water holding capacity vs. the catchments area can be determined assuming Hortonian surface flow conditions (Horton, 1933) as the precipitation amount (the local FillUp value) at which the sink will spill-over at its pour point. If more precipitation is added to the sink from its catchment, excess water spills over, leaves the local catchment, and enters the next downstream catchment and its sink as sketched in the landscape cross section, Fig. 2.

Consequently, a landscape can be broken down into and be represented by sinks, catchments and the flow paths interconnecting them to describe the entire surface hydrology – assuming that the entire runoff during Hortonian conditions takes place on the surface without involving any groundwater component, sewer systems et cetera. If that information is organized in a hierarchical (topologic) network for a regional watershed, the nested flow is under control.

The screening method presented is based on functionality in ArcGIS Desktop ver. 10.5.1 (Esri, 2017) having the necessary components to work on raster, vector and geometric network representations of the real world.¹ However, the entire method may be adopted in other GIS environments, also, having similar building blocks.

3.1. Raster processing

To build the information for the geometric network, the terrain model must first be raster processed based on the following sub-steps:

- a) Delimitation of the regional catchment(s) covering the entire study area in question,
- b) Addition of building footprints to the terrain surface,²
- c) Identification of local sinks deeper than the tolerance level for the terrain elevation model used, their pour point locations and capacities (volumes when filled to the pour point levels),
- d) Delineation of the local sinks' catchments,
- e) Derivation of the downstream flow paths from each sink's pour point.

3.2. Vector processing

Raster to vector conversions of:

- f) Sinks and catchments into polygon features,
- g) Pour points into point features,
- h) Flow paths into polyline features.

Next,

- i) Spatial joins of the sinks' and their matching catchment attribute values to the pour points allowing for easy computations of the rain volumes entering the sinks from their local catchments at various uniform or distributed precipitation events.

3.3. Geometric network processing

- j) Assembling of a geometric network defining the sinks' (now represented by the pour points) topological relationships (their internal hierarchy) where the pour point features represent the junctions and the polylines the downstream edges connecting the junctions,

¹ As a note to interested users a model developed for ArcGIS Desktop ver. 10.3.1 to derive local sinks, their catchments and determination of FillUp values can be downloaded from Esri's LearnArcGIS.com site (keywords: cloudburst, flooding).

² Preferably, the buildings should be added as 3D geometries ensuring that roof tops act as true topographic drainage divides. If footprints for walls, monuments etc. are available, they may be added as well.

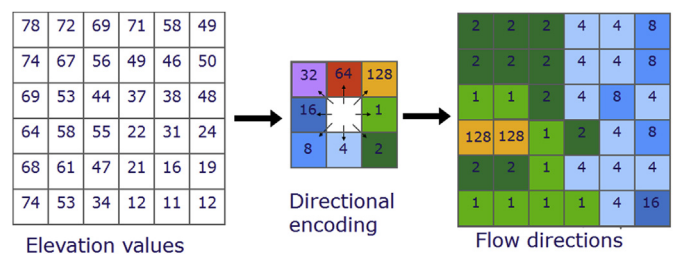


Fig. 3. Derived flow directions from an integer elevation raster (adopted from Esri, 2017).

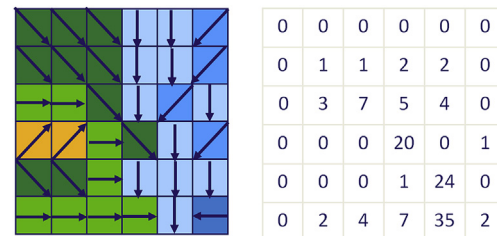


Fig. 4. Flow accumulation values (adopted from Esri, 2017).

- k) Execution of a custom trace tool traversing the entire network and accumulating the spillover from sink to sink at a specific rain event assuming that all sinks are empty before the event,
- l) Display of the sinks' spillover vis-à-vis the accumulated downstream water loads along the flow paths (edges).

4. Theory

Unless mentioned the theories behind the GIS processing tools all refer to the help documentation for ArcGIS Desktop ver. 10.5.1 (Esri, 2017).

4.1. Flow direction

The flow direction approach still used to determine water movements on terrain surfaces were originally documented by Greenlee (1987) and Jensen and Domingue (1988). As each squared cell in a raster contains an elevation value, flow patterns are derived from a search for the steepest downhill slope gradient when evaluating a center cell's elevation value vs. the surrounding 8 neighbors within a moving 3 × 3 window, also named the “8N approach” (Baker and Cai, 1992). The flow direction is determined for the center cell by the direction of the steepest descent calculated as the change in z-value divided by the distance, see Fig. 3.

4.2. Drainage basin and catchment delineation

The input flow direction raster is analyzed to identify all sets of connected cells belonging to the same drainage basin. The drainage basins are delineated by locating the pour points along the edges of the terrain model (where water would pour out of the raster) as well as the sinks, and then identifying the contributing area above each pour point. To keep track of which sink that belongs to a specific catchment, the same unique integer value is assigned to both entities. When identifying the catchment for a specific sink, the catchment is derived from a search for the upstream contributing area.

4.3. Flow accumulation

The flow direction raster is also used to generate a flow accumulation raster that cell-wise examines and stores the number of cells flowing into each downslope cell, see Fig. 4. Thus, the flow accumulation value

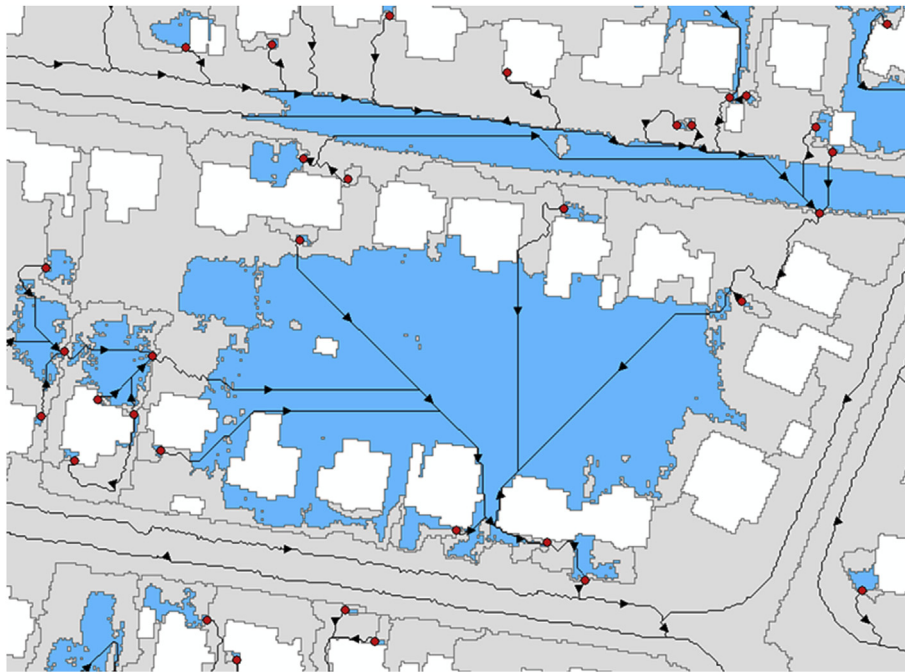


Fig. 5. Cells grouped into sinks (blue), sink catchments (grey), sink pour points (red), and flow paths (black w/directional arrows) in between buildings (white) in a residential area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

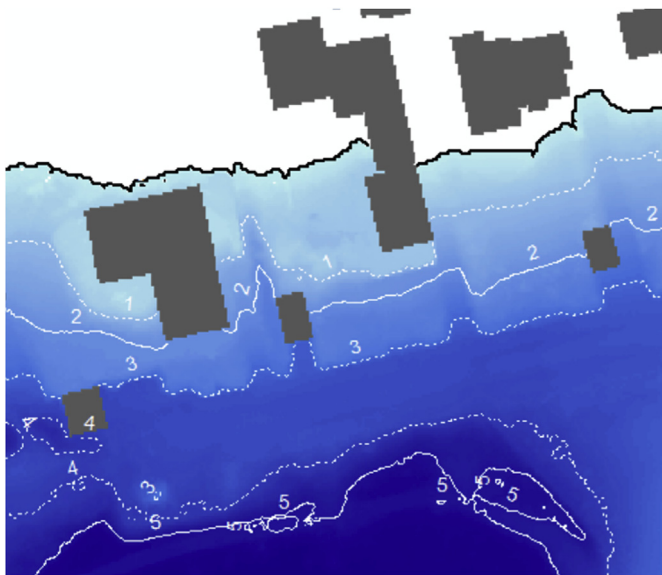


Fig. 6. Local blue spot map with contoured water depths in meters and critically located buildings (dark grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

multiplied by the squared cell resolution and the precipitation value tells the amount of water that passes through a cell under Hortonian flow conditions.

4.4. Sinks

A sink is a landscape depression without a water outlet until the so called pour point level is reached. Sinks may be detected directly from LiDAR data sets as suggested by Liu and Wang (2008), but may more easily be identified using standard GIS tools by first identifying the most low-lying cell within a depression without a downhill flow direction. Next, through an iterative process, the water level is raised within the

depression until water spills over at the so-called pour point located at the most low-lying location along the sink's upper edge, see Fig. 5. In practice, once a sink is detected, its pour point can be located from a search for the cell within the sink having the highest flow accumulation value. To eliminate all minor and questionable depressions from the analysis the sinks with depths greater than the used elevation model's vertical accuracy are saved, only, and all others are filled to their horizontal pour point levels.

If the original elevation model is compared with the filled model on a cell-by-cell basis, the local depth difference can be calculated providing a so-called blue spot map, see Fig. 6. When summarizing the depth values for cells within each sink and multiplying them by the cells' squared spatial resolution, a sink's total capacity (volume) is determined. Subsequently, the sinks can be converted to individual polygons and assigned attribute values describing their capacities and maximum depths.

4.5. Flow paths from sink to sink

Once identified the further downhill movement of water spilled over at the sinks' pour points can be traced by using ArcGIS' Cost Path tool to identify the least cost downstream flow route by looking up the flow directions cell by cell in the flow direction raster. The output is a one-pixel wide raster stream network that can be converted to downstream oriented polylines using the Stream to Feature tool.

4.6. Nested flows, geometric networks and spillover calculations

Geometric networks is a data representation consisting of a set of connected edges and junctions along with connectivity rules used to represent and model the behavior of common real world network infrastructures (Young, 2001; Zeiler, 2010) having specific flow directions like found in gas and water pipeline utility systems. Once established it is possible to perform upstream or downstream tracing operations in the network very efficiently due to the full topological overview (Mitchell, 2012). Although obvious and straightforward to use on stream networks, too, only very few references are found on this topic except Palacios-Vélez et al. (1998) who studied kinematic waves in analysis of surface runoff and computation order, and Wagler (2014) who describes a

Table 1
Sinks from Fig. 7 and their attribute values after a rain event of 30 mm.

SinkID	Capacity, liters	CatchmentArea, m ²	CatchmentContribution, liters	ActualVolume, liters	% of capacity	Spill-over, liters
A	200	1000	30	30	15	0
B	70	4000	120	70	100	50
C	100	8667	260	100	100	210
D	50	3000	90	50	100	40
E	20	0,333	10	20	100	80
F	30	2667	80	30	100	50
G	40	1333	40	40	100	290

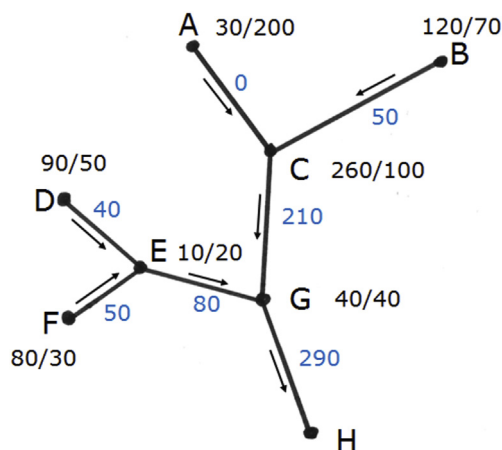


Fig. 7. Logical representation of a geometric network component where sinks are assigned IDs A-H. The numbers xxx/yyy represents the runoff contribution, xxx, from the local catchment to a sink, and the sinks capacities, yyy. The blue numbers represent the spillover values carried downstream. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Steady soil infiltration rates. Adapted from Hillel (1998).

Soil type	Steady infiltration rate, mm/hr
Sand	20+
Sandy loam	10–20
Loam	5–10
Clay	1–5

combinatorial algorithm to locate the maximum flow in a network. When the junctions and edges are added as the network's basic features, the geometry is build. If errors occur caused by either disconnected junctions or so called loops where circular flows (in flat regions) create circuits, they must be corrected in order for the network to perform a correct flow tracing (see Table 1).

To describe how the accumulated nested flow is determined, a logical geometric network example is presented in Fig. 7, where sinks are junctions and streams are edges with flow directions pointing downstream. Junction A represents a sink with a capacity of 200 volumetric units, but the sink's local catchment contributes with 30 units, only, resulting in no spillover towards junction C. The sink at junction B has a capacity of 70 but a delivery of 120 volumetric units from its local catchment, so 50 units spillover is transported downstream to the sink represented by junction C. That sink has a capacity of 100, but 260 units are supplied from its local catchment providing a spillover of 160. Moreover, (0 +) 50 units must be added from upstream spillover at junctions A and B resulting in a total of 50 + 160 units transported towards junction G. However, the water balance for that sink must await the results from the spillover at junctions D, E and F before it can be estimated and so forth. Table 2 shows the balance for a rain event of

30 mm where the entire rain volume is turned into Hortonian flow. Thus, the rain volume entering a local sink from its local catchment equals the CatchmentArea * RainVolume.

The above accumulated nested flow calculation in geometric networks is not implemented as a standard tool in ArcGIS Desktop. Therefore, a custom trace tool was designed and programmed in C# and .NET in Microsoft's Visual Studio based on functions, interfaces and classes available in ArcObjects for ArcGIS Desktop. As downstream edges may merge in between junctions defined by the pour points, so called orphan junctions are inserted at edge intersections, see Fig. 7. At each true junction, a sink's Capacity is considered versus the incoming RainVolume to evaluate if a spillover is present. Otherwise, the Spillover value is assigned the absolute value of the Capacity minus the RainVolume. If not the Spillover value is set to zero. Additionally, the sinks' actual water contents are expressed as an ActualVolume value always being in the range 0 to Capacity, which later may be turned into an ActualVolume percentage value.

Next, the edge pointing downstream from a junction is assigned the Spillover value as a so-called Weight value. So, at the next downstream junction this weight represents the conveyed water volume entering the local sink. As mentioned earlier streams from two (or more) sinks may merge before entering the next downstream sink. If that is the case, the downstream edge from the orphan junction will be assigned the conveyed value accumulated from the weights of its two upstream edges.

Hortonian flow was defined by Horton (1933) as the tendency of water to flow horizontally across land surfaces, when rainfall exceeds infiltration and depression storage capacity. Such conditions may actually occur during stormwater situations - in Danish named cloudbursts according to the Danish Meteorological Agency (DMI, 2016) when precipitation amounts exceed 15 mm in 30 min causing only small fractions of the precipitation to infiltrate the soil if dominated by clay. Also, if the drains letting the water into sewer systems somehow are blocked and more or less inefficient, Hortonian flow conditions may occur.

According to Hillel (1998) the soil's steady infiltration rate is as presented in Table 2, but a soil's wet conditions prior to a rainfall determines how fast the infiltration rate declines before reaching the steady level. If field capacity is present, steady rates will occur, but if the soil is dry, the values may be 2–5 times higher.

5. Results and discussion

To demonstrate the method's outcome on a high-resolution dataset a 40 cm resolution terrain model for a drainage basin of 8 km² located in an urban area 10 km north of Copenhagen City in Gentofte Municipality, Denmark, was used. The region was shaped during the Weichsel glaciation ending approx. 15,000 years ago and is slightly undulating with elevation ranges between -3 and 57 m. The dominating soil type is morainic clay (covering 71%) in the highest lying parts of the landscape, glaciofluvial sandy deposits in meltwater valleys (12%), marine sand (1%) in the coastal region and organic rich deposits (16%) formed in valley bottoms and isolated dead-ice sinks (Bornebusch and Milthers, 1935), see Fig. 8. A few ponds are present in between the residential areas, but no open streams are visible. However, the overall drainage system shows one single outlet into Øresund - the sound between Denmark and Sweden.

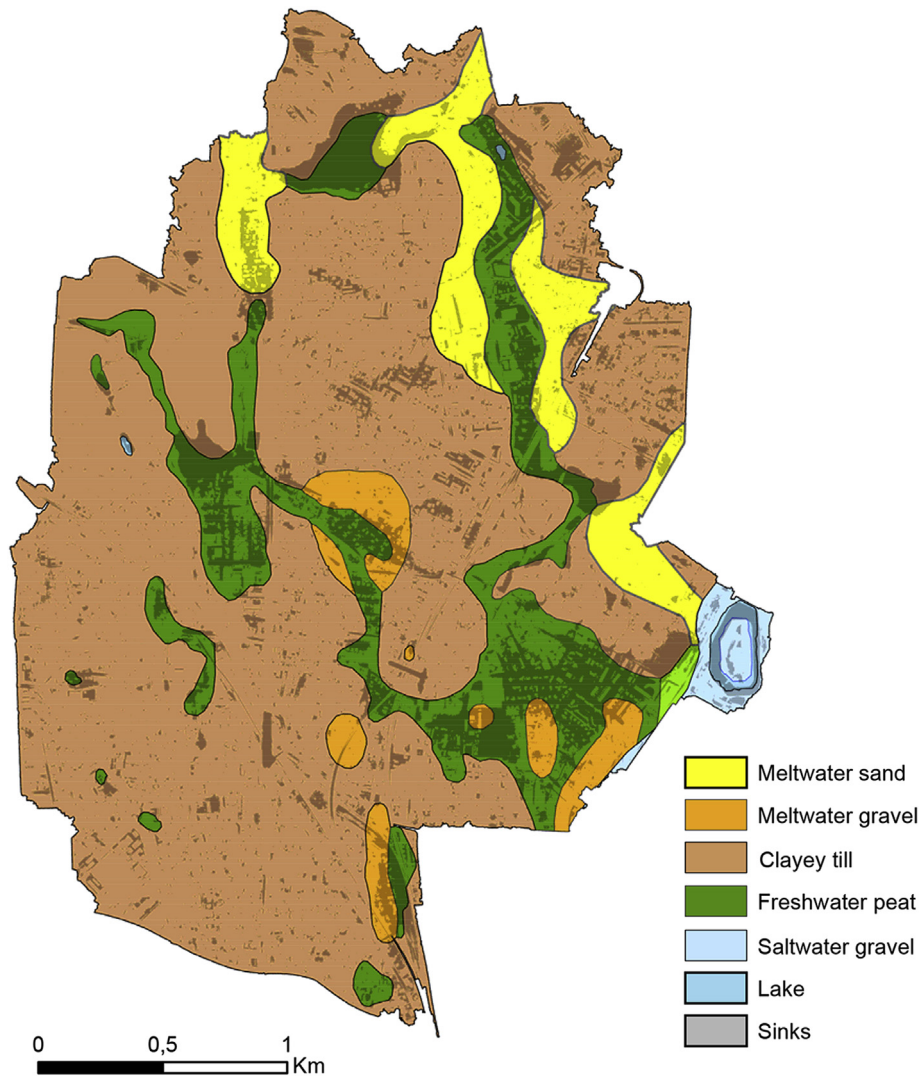


Fig. 8. GEUS' geologic subsurface map, 1:25,000 superimposed with detected sinks.

As mentioned in the Method section the elevation model's vertical accuracy is 5 cm, so all sinks with shallower depths were eliminated by filling them up and using the new filled surface as a substitute ahead for the original terrain. Incorporating all sinks with depths ≥ 5 cm in the study may sound as overkill, but as discussed in the [Introduction section](#) it may be very informative for municipalities or governmental authorities maintaining the infrastructures to watch the locations of even minor, shallow water pools along them revealing unintended cavities on asphalt or concrete covers. Of course, it might be advantageous to leave out sinks based on specific capacity thresholds instead of maximum water depths. However, currently, it is only possible to filter out sinks based on depth criteria, but introducing threshold criteria by volume will be considered among other future enhancements.

In total 9653 sinks were kept with capacities ranging from 20 to 414,387,600 L with a mean value of 98,200 L, only, as close to 70% of the sinks have volumes < 1000 L. The local catchment areas vary from 0.32 (2 cells) to 372,056 m² which leads to FillUp values for the sinks ranging from 0.01 to 2000 mm precipitation when assuming Hortonian flow. Many sinks are located in parks, gardens and along infrastructures, but 1736 of them with water volumes > 1000 L are touching residential buildings. This means that if such a sink is filled to a critical level, the building located next to it may potentially get flooded as illustrated in [Fig. 9](#) if sewer systems or other water infrastructures either are over capacity during the stormwater event, not present or ignored because of

the limitations of the current 1D screening setup.

When identified the local sinks and their catchments, their areal delineations and the sinks' capacities are the only data being transferred to the pour points that all hydrologic and hydraulic calculations relate to ahead in the geometric network. The consequences hereof are a number of pros and cons. On the positive side, the data volume is reduced drastically so even very large surface models can be processed and further analyzed very quickly as steady state situations. On the negative side, this is at the expense of the dynamic cell-by-cell modeling capabilities that a full raster model may offer. However, as the purpose of this new approach primarily is about providing the user with a first and basic overview of a land surface's overall runoff conditions during a severe rain event, this is a fully acceptable premise. Meanwhile, also on the positive side it should be considered that all information at the local level about differences in precipitation amounts, variations in soil properties (and differences in hydraulic conditions), surface conditions (imperviousness), gradients and other parameters may be assigned at the local catchment level in order to model very realistic events. Because as mentioned in the Methods and Theory section the runoff contribution at the catchment level may be modified very easily by subtracting the water infiltration from the potential runoff within the catchment. If soil characteristics cross catchment boundaries, an overlay operation may be used to split them.

In this context, it should be remembered that the mapping of soil

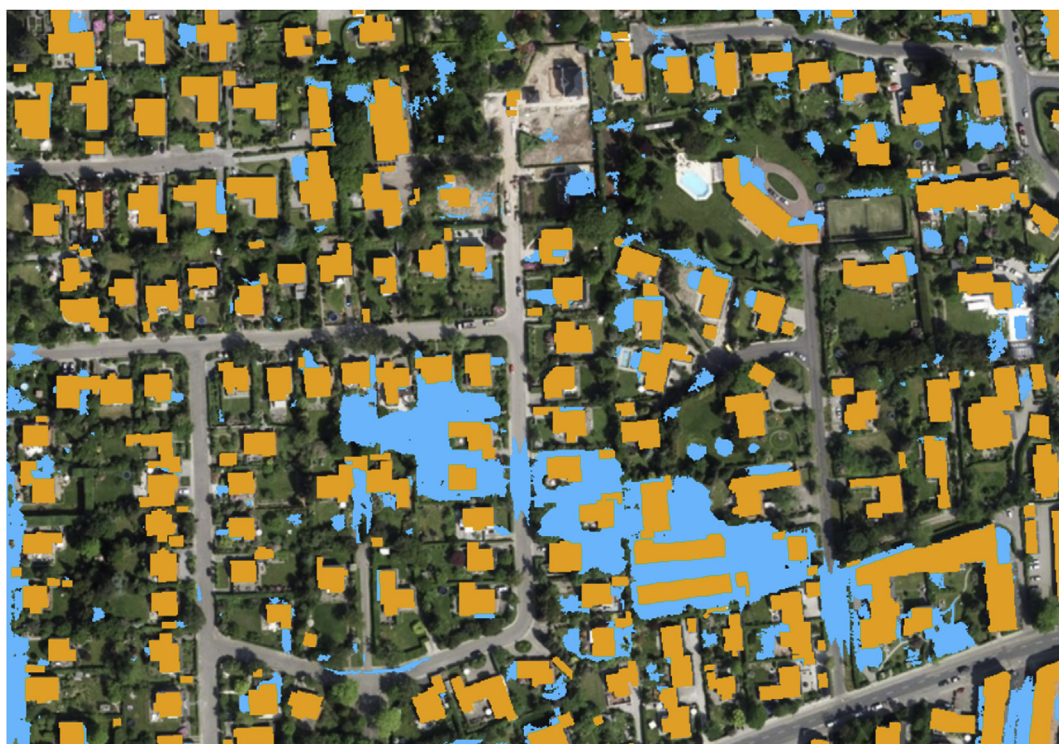


Fig. 9. Residential area with local sinks (blue) and buildings (orange) located more or less critically within or touching them. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

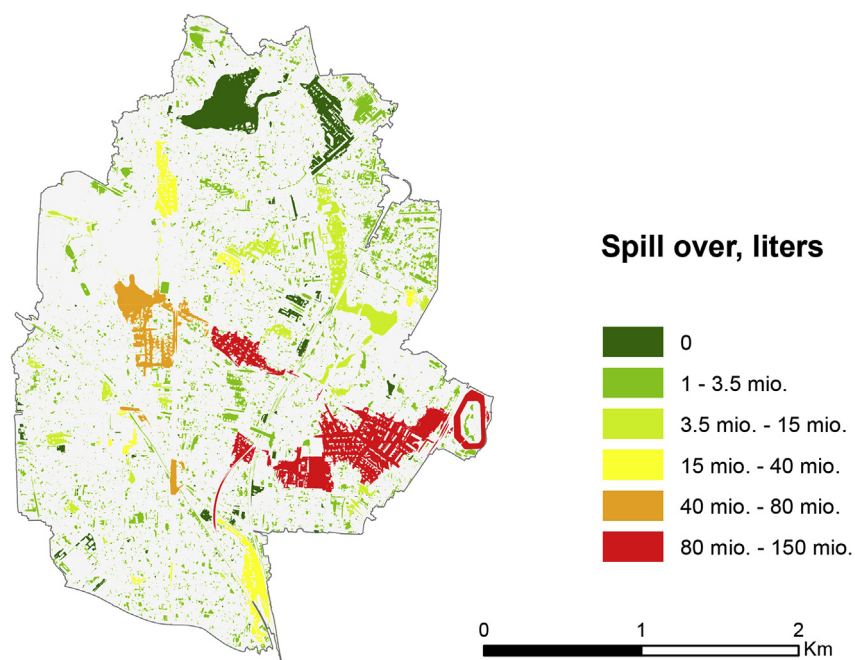


Fig. 10. Sink spillover in liters at a rain event of 30 mm assuming Hortonian flow.

types, groundwater table levels and more underground conditions always are based on field surveys that have led to maps of much lower accuracies than this study's delineation of local surface sinks, their catchments and water ways connecting them. In Denmark, for example, maps on topsoil textural composition were originally sampled at a scale of 1:50,000 based on approximately 1 sample pr. km² (Greve et al., 2007), quaternary soil maps at a scale of 1:25,000 based on (at best) approximately 10–20 samples per km² (GEUS, 1998) and groundwater table maps at best are

predicted at accuracies of 50–100 m (GEUS, 2009). Because the relationship between the soil and the hydraulic soil properties within the study area vs. the location of detailed surface features have not yet been carefully examined based on the before mentioned maps, the soil infiltration has not been evaluated and subtracted at the catchment level. Neither has the various surfaces' imperviousness been taken into consideration although a raster dataset with a cell resolution of 10 m is available from an integration of a land use and land cover map (Aarhus

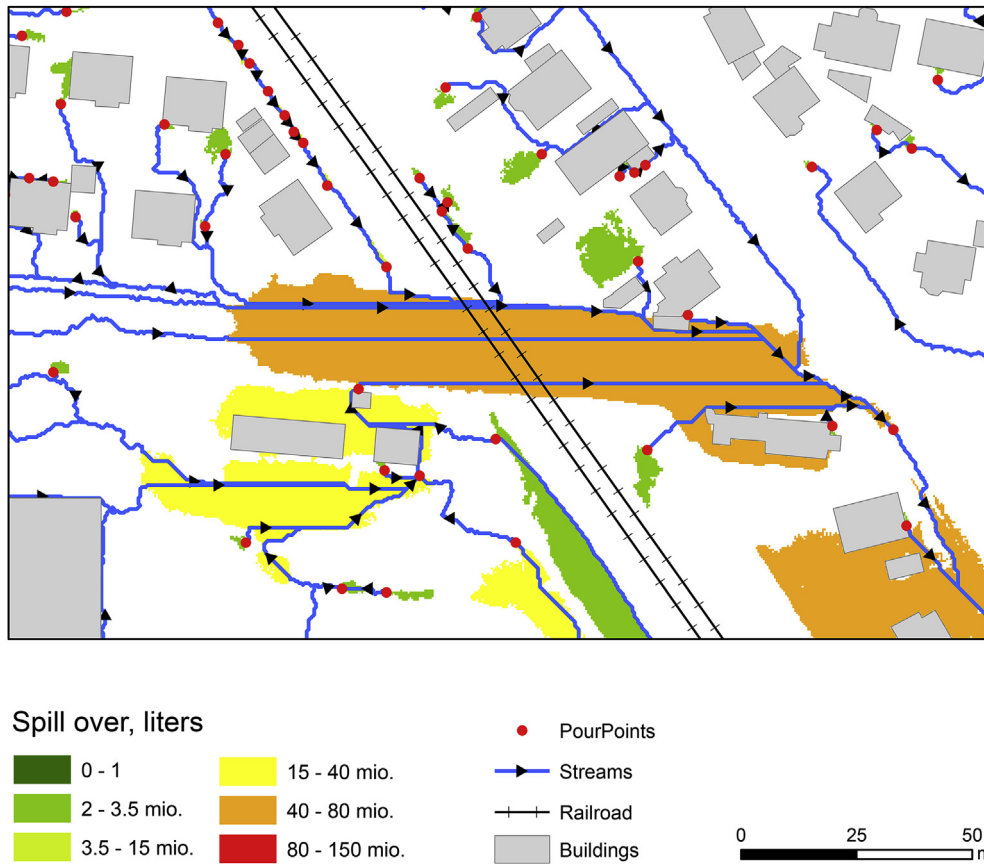


Fig. 11. Detail from Fig. 10 where a large sink located in a railroad underpass with a capacity of 1.95 mio. liters has a spillover of 52.45 mio. liters during a rain event of 30 mm when assuming Hortonian flow. Flow lines across sinks may have peculiar appearances as they indicate flow paths at filled levels.



Fig. 12. Photograph of major sink from Fig. 11.

University, 2012; Jepsen and Levin, 2013). Information about the sewer system's infrastructure is not available, either (although potentially achievable from wastewater and utility companies), so a rough screening has been carried out, only, to determine the overall hydrologic conditions assuming Hortonian flow during a uniform rain event of 30 mm over the entire study area.

The final result from the calculations shows the spillover for every sink, see Fig. 10, a local sink in Fig. 11, its real world location, Fig. 12, and the water loads carried along the flow paths within the major catchment for the study area, Fig. 13. Obviously, bigger and bigger loads of water are transported downstream from the northern region towards east, and a total of 96.7% of the sinks are at capacity, see Fig. 14.

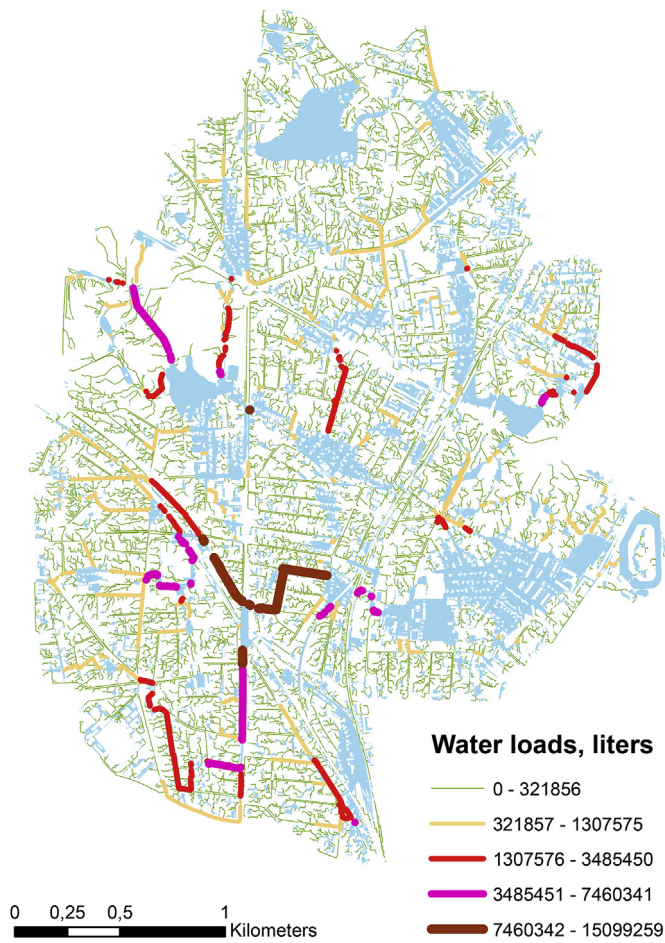


Fig. 13. Water loads along network edges.

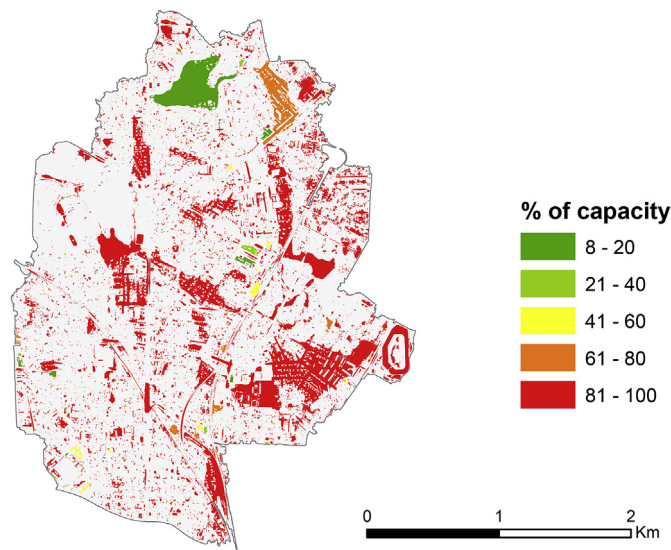


Fig. 14. % filled volume vs. capacity for sinks.

Some of the raster processing steps deriving the flow directions, the flow accumulations, the fill up of sinks and more are time consuming but should be carried out once for all, only. As an indicator the following the efficient processing times and disc storages for the study area's data carried out on a 2.9 GHz, 4 core, 8 logical processors computer with 32 Gb RAM are:

- Identification of hydrologic components in the raster domain: 33 min. Data storage for all relevant input and output rasters (original DHyM, flow directions, flow accumulations, blue spot depths etc.): 1,1 Gb.
- Geometric network establishment: 58 s. Subsequent spillover calculations per rain event scenario: 6 s. Network storage: 3,7 Mb.
- Example of raster vs. vector storage: The blue spots' extents and their local watersheds take up 405 Mb as rasters but 27 Mb, only, as vector polygon feature classes stored in Esri's file geodatabase format.

6. Conclusion

It has been demonstrated how a basic screening of an elevation model for sinks and a preceding conversion from the raster representation into vector features and next into geometric network features enables excellent overviews of the overall hydrologic conditions for a study area on an ordinary desktop computer. The big advantage of having data organized in geometric networks becomes even clearer when working on larger data sets than the one presented here. In principle, geometric networks may contain millions of junctions and edges representing very large and very complex real world hydrologic situations. This opens up for screenings of big regional catchments that are hard to process in raster based model environments, only.

Moreover, the method presented will open up for screenings by new potential groups of planners in local authorities, higher education students and researchers who want to get involved and understand in practice which and where critical landscape factors upstream may be the reasons for severe flood damages downstream. Consequently, this will lead to much more qualified discussions of possible flood precautions and water retention planning initiatives prior to consulting and involving expensive and more sophisticated modeling professionals able to focus on time series studies, detailed impact assessments involving examination of existing sewer systems (if any), implementation of green infrastructures such as constructed wetlands, green walls and more.

The setup presented may easily integrate information about local hydrologic properties of soils and unevenly distributed rain incidents as well taking the lumped model into a distributed setup because the modeling's basic units are the individual sinks and their local catchments. However, it should be remembered that the method presented is merely a method to generate an overview of the overall 1D runoff pattern. Meanwhile, the results from the screening provide great overviews of sinks under or over capacity and where major water corridors are located in stormwater situations. If the sewer system is considered for integration into the current setup, it may be advisable to consider an interface with existing systems already designed to embed hydraulic components into runoff predictions.

Authorship statement

Thomas Balstrøm is the manuscript's primary author who developed and implemented the method described.

David Crawford programmed the geometric network add-in for ArcGIS Desktop and revised the manuscript.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.cageo.2018.04.010>.

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