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## Research Article

# Applying Remote Sensing to Determine the Percent Imperviousness for Urban Drainage Modelling

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## Abstract

**Background and Objective:** Urban areas have become more vulnerable to flooding due to decreased imperviousness in cities and more severe rain events. Sewer modelling is used to examine urban drainage systems and their performance in case of severe rain. Accurate data for impervious surfaces is a key input factor to obtain valuable models. In this study, the use of data acquired automatically by remote sensing techniques is investigated as an alternative to other electronic databases and is manually interpreted to obtain information on the surface conditions. **Materials and Methods:** The study is carried out in a neighbourhood of Copenhagen and the sewer system is modelled by the commercial software MIKE URBAN 2014. Airborne images with 20 cm resolution and 4-band orthophotos were analyzed by following an object-oriented approach and used as input for calculating the percent imperviousness. **Results:** The results show that different types of impervious areas are determined with different accuracy. Road area coverage is underestimated, building coverage is classified accurately and the area of other impervious surfaces is over estimated. When applying the achieved classification and using this to determine the imperviousness, the sewer system is accurately modelled despite the inaccuracies in the area coverage.

**Conclusion:** This study validates the automatic classification of areas using airborne images. The methodology, however, should be optimized with respect to road surfaces and some specific pervious surfaces.

**Key words:** Percent imperviousness, remote sensing, aerial photos, object-oriented image analysis, MIKE URBAN, computed pipe flow, urban drainage

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**Data Availability:** All relevant data are within the paper and its supporting information files.

## INTRODUCTION

To prevent the hydrological impacts associated with urbanization<sup>1</sup>, it is crucial for environmental science and urban drainage engineering, among other fields, to be able to estimate and map impervious surfaces in urban catchments. Impervious surface data (and by association, runoff) is an indicator and a key input factor in hydrological models<sup>2</sup>, water quality estimation<sup>3</sup> and urban drainage modelling<sup>4</sup>. Consequently, there is a need for impervious surface data in our society<sup>5</sup>. To obtain imperviousness data for urban drainage modelling, a detailed characterization of the examined urban area must be performed. Traditionally, digital image analysis and classification have been done using either simple manual interpretation or automatic operation at the pixel level, where the digital number of each pixel is assessed individually<sup>6</sup>.

However, with the invention of object-oriented image analysis, it is possible to interactively classify objects into a pre-defined set of classes. The great advantage of this method is that it uses not only the spectral response of the surface (e.g., water, forests, buildings) but also information about the variance and texture inside the object as well as relations with its neighbours to classify objects.

Conventional mapping techniques in intricate urban areas are often expensive and time consuming when the examined area is large. The automatic analysis and classification of aerial photos and satellite images, i.e., remote sensing (RS), offers an alternative for mapping urban areas, which not only saves time and reduces costs but also reduces the dependency on visual interpretation.

The use of RS for classification and thereby calculation of the percent imperviousness was first shown at the beginning of the 21st century. More mature digital processing techniques have become available<sup>5</sup> and remote sensors have become more suitable for detecting and estimating impervious surfaces. Since then, the RS of impervious surfaces has become one of the most dynamic fields in RS<sup>5</sup>. As a result, over the past decade, several authors have evaluated the feasibility of quantifying and detecting different impervious surfaces by using satellite or airborne images together with image classification techniques<sup>4,7-9</sup>. All these authors used multi-spectral and high-resolution sensors. The RS of urban impervious surfaces demands a high spatial and multi-spectral resolution to be able to discern features in such complex environments<sup>5</sup>. The minimum spatial resolution required for urban environments is half the diameter of the smallest object of interest<sup>5,10</sup>. Impervious features such as buildings (perimeter, area, height and property line) and roads (width) are generally detectable with a minimum spatial resolution of

0.25-0.5 m<sup>5,10</sup>. For lower spatial resolutions, GIS data can be integrated with satellite or airborne images to minimize misclassifications and improve accuracy<sup>8</sup>.

Many different image classification methods can be used to automatically categorize the pixels of the RS images into land use types. The approach used to classify an urban land cover depends on the nature of the analyzed data, the available computational resources and the intended application of the classified data<sup>11</sup>.

In this study, the terminology "object-oriented" is used, however, object-based and object-oriented approaches are not necessarily distinguished in the literature. The difference is explained in a few studies to depend on the workflow for object classification<sup>6</sup>.

Elgy<sup>12</sup> compares statistical methods (maximum likelihood method and sequential maximum a posterior) based on the per-pixel classification approach and a more object-oriented method (segmenting the image into approximately homogeneous polygons using a Mar-Hildreth edge detector) to automatically classify the impervious surfaces and use them for urban drainage applications. Thomas *et al.*<sup>4</sup> uses three classification approaches to automatically assess impervious urban classes for urban drainage applications. The first classification method is a purely per-pixel based algorithm. The second method uses the per-pixel results and modifies them by applying a series of spatial models to clarify ambiguous spectral classes based on contextual clues. Their third method is an object-oriented approach.

Khin *et al.*<sup>7</sup> and Yuan and Bauer<sup>13</sup> also mapped impervious surface areas using object-oriented and per-pixel based approaches. Khin *et al.*<sup>7</sup> used 0.5 m resolution, pan sharpened WorldView-2 images to extract the land cover types and derive the hydrologic parameters for an urban drainage model. Yuan and Bauer<sup>13</sup> used Quick bird imagery with a 2.4 m resolution with four multi-spectral bands and a 0.6 m resolution with one panchromatic band.

The mentioned studies conclude that the object-oriented classification approach to assess land cover in urban areas produced results with higher overall accuracy than the classification based on per-pixel images. This is due to the intrinsically complex characteristics of urban areas and the fact that pixels in urban area images are made up of relatively homogeneous patches that are larger in size than individual pixels<sup>11</sup>.

Based on the conclusion that the object-oriented approach is both possible and valid<sup>7,11,13-16</sup>, the objective of this study is to investigate the use of RS for the areal classification and quick estimation of percent imperviousness as the basis for urban sewage modelling.

This study focused on 4 underlying research questions:

- Can impervious information and catchment delineation be accurately obtained by readily available methods, such as the n-object-oriented remote sensing technique using a resolution of 20 cm?
- What causes the significant classification errors that occur when using the remote sensing technique?
- Do the uncertainties and errors in classification and the resulting impervious information cause serious discrepancies and uncertainties in an urban modelling tool (e.g., MIKE URBAN)?
- Do the uncertainties have high impact on the modelling of the runoff and pipe flow?

## MATERIALS AND METHODS

The urban area of Amager Øst (East) in Copenhagen, Denmark, was used as the analysis location. This area was chosen based on the possibility to compare the results with previously made and calibrated MIKE URBAN models for runoff, sewage transport and overflow in the area. The MIKE URBAN modelling software<sup>14</sup> can model runoff from numerous sub-catchments with individual percent imperviousness and sewage transport in a sewage network. This software can simulate flow from catchments to the sewer based on their actual spatial geometry and the corresponding hydrological parameters. The previously developed and calibrated model used for comparison was provided by HOFOR A/S.

**Urban drainage model:** The model used for modelling surface runoff and water transport in a combined sewer system consists of a contributing catchment area of 656 h (areas not connected to the sewer system have been excluded from the model), of which 62% is impervious. The imperviousness information in the previously developed and calibrated model is obtained by the manual interpretation of airborne images. This manual interpretation follows the traditional approach to setting up MIKE URBAN models to determine the percent imperviousness in catchment areas.

The sewer model contains approximately 2,348 links and the pipe length is approximately 131 km, with diameters ranging from 0.25-2 m and approximately 1,948 manholes. The catchment areas in the previously developed model are represented by squares of different dimensions without shape information (MOUSE layout), the model includes 1,648 individual sub-catchments.

Based on airborne images, the imperviousness data were obtained by following an object-oriented classification

approach for multi-spectral and high-resolution airborne images (explained in more detail in the section "Object-oriented classification"). The results from the classification image analysis were compared statistically to previous imperviousness data obtained from GIS data (explained in more detail in the section "Comparison of percent imperviousness").

The obtained imperviousness data were used as the input for modelling runoff, sewage transport and overflow in the urban drainage system of the area using MIKE URBAN, 2014<sup>14</sup>.

The runoff and sewage transport model based on the classification data from RS is also compared to a model provided by HOFOR covering the same area (explained in more detail in the section "Modelling of surface runoff and sewage transport").

**Object-oriented classification:** The percent imperviousness is determined from airborne images using object-oriented image analysis. In the first step (segmentation), the pixels are aggregated into objects with homogeneous spatial or spectral characteristics. In the next step, spectral, textural, shape or contextual criteria are applied. This makes it possible to interactively classify the objects into a pre-defined set of classes. This approach is illustrated in Fig. 1. The impervious mapping method applied here contains both semi-automatic and manual input from image specialists.

The images used to perform the impervious surface mapping analysis included 10 orthophotos from 2008, provided by NIRAS, covering the South-Eastern area of the city of Copenhagen, the district of Amager Øst, Copenhagen, Denmark, on the island of Amager<sup>17</sup>, Denmark. The land use in this area is mainly residential with single-family houses and two- to seven-story buildings. The spatial resolution of the images was 20 cm. The spectral resolution of the images included 4 bands: Red, green, blue (RGB) and near-infrared (NIR).

Interpretation and analysis of the orthophotos were carried out by DHI GRAS, following an object-oriented image analysis approach using the software eCognition, where code for the classification of objects in the images is given. In this case, a step-wise (dichotomous) strategy was used to create a class hierarchy. The first class was defined using specific criteria (applying multi-thresholding algorithms), the second class included everything but the first class and so on. Using this technique, it was possible to (a) set up a simple but structured class hierarchy and (b) avoid unclassified areas falling between the classes. The main classifier in the developed classification code of practice was the normalized differenced vegetation index (NDVI). Therefore, the main

classifier describes the variance in image reflectance between the four spectral bands in the aerial photos and the individual spectral properties of each band.

The orthophotos in this study were categorized into five different classes. Two permeable classes (vegetation and water) and three impervious classes (roads, buildings and other types of impervious surfaces). The spatial resolution (20 cm) seems to be effective to discern urban features such as roads, vegetation, buildings and other types of impervious surfaces<sup>15</sup>. The classification results from RS were compared to previously reported manually digitized airborne images (further referred to as GIS classification data in this work) before being imported to the sewage transport modelling software. This was done to validate the results from the classification and to find additional effects of the RS approach that may influence the urban drainage simulation results. The provided classification layers were used directly by importing them into MIKE URBAN, 2014.

**Comparison of percent imperviousness:** The comparison of the classification and resulting percent imperviousness was

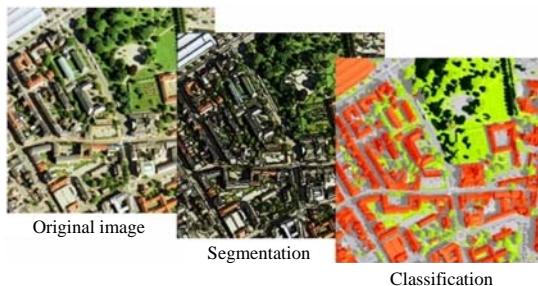


Fig. 1: Workflow for object-based image analysis

done in two steps. The GIS classification data were used as a basis for comparison in this study to first validate the results. This was done by determining the correlation between the GIS impervious data and the impervious data from an existing MIKE URBAN model of the area. The model is a calibrated, well-documented model of the existing sewer system and catchment area.

In step 2, each of the three impervious classes (roads, buildings and other impervious areas) were assessed separately and together. Their comparability was assessed by determining their correlation to the GIS classification data. Their comparability was also tested by using an independent t-test to determine whether the data sets were comparable. Figure 2 gives a visual presentation of the two imperviousness classification data sets.

**Modelling of surface runoff and sewage transport:** The data from the RS classification were imported directly into the storm water model to compare the results of the RS imperviousness classification in terms of water volume and runoff. This is how the shape information of individual sub-catchments in the model was determined. The network plan (area shapes) of the model was combined with a GIS sub-catchment layout. In all respects, it is equivalent to the MOUSE layout but also contains shape information and from now on, this model is called the GIS model. Figure 3 shows the different sub-catchment design used in the study.

Furthermore, to assess the accuracy of the results of the RS imperviousness classification, the original imperviousness information contained in the model was replaced by the GIS classification data previously used for the assessment of the classification accuracy. Using the GIS imperviousness

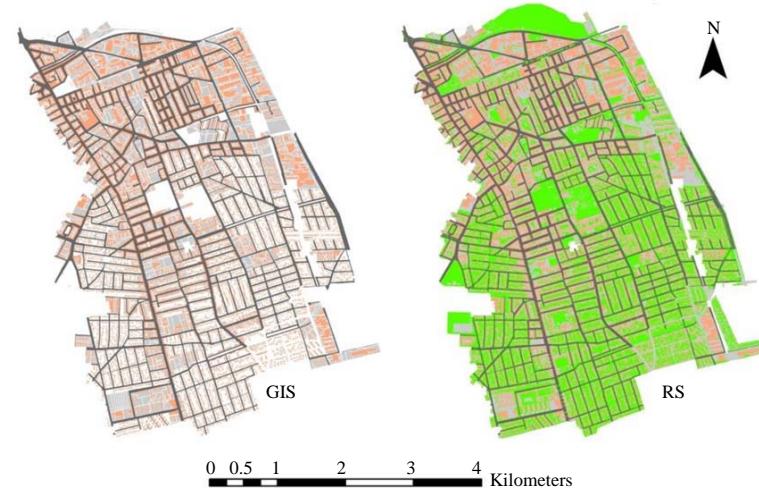


Fig. 2: Visual presentation of the classification data from the remote sensing (RS) and GIS imperviousness classifications

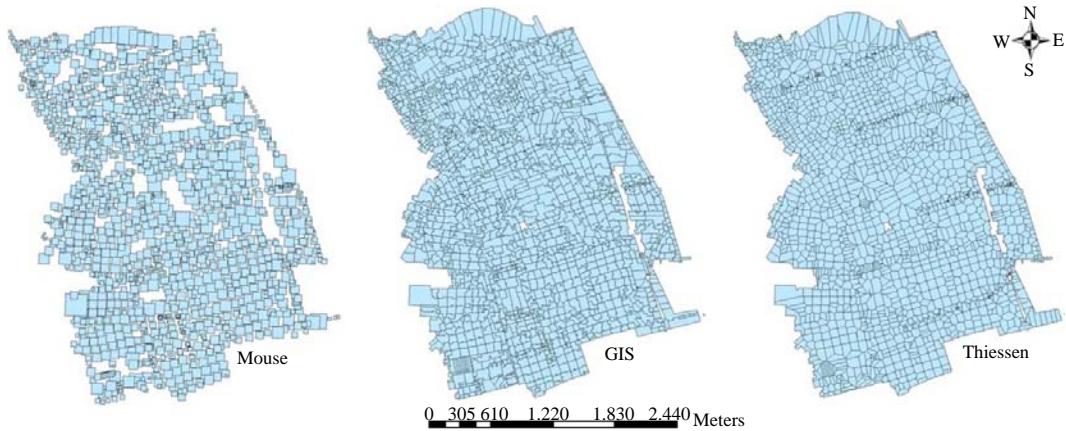


Fig. 3: Catchment layouts used for modelling the sewer system

classification data in the model allows the direct comparison of the sewer simulation results, since neither of the classifications exclude areas that are not connected to the sewer system. The new model (GIS\_RS) based on the RS classification results covers a total contributing catchment area of 662 h with an imperviousness of 67%.

The RS storm water model was used to assess the urban drainage simulation results based on the RS imperviousness classification. The next step was to validate the model performance. This is described in more detail in the section "Comparison of urban drainage simulations".

Additionally, a third approach was tested. The model network was combined with a Thiessen-polygon catchment layout (Fig. 3) generated from the outline shape of the GIS layout and created by the MIKE URBAN catchment delineation wizard. The Thiessen-polygon layout includes 1,948 individual sub-catchments. The model network, containing the Thiessen-polygon catchment layout together with the RS impervious information (Thiessen\_RS), was used to model the sewer system and results in the scenario with the most readily available information on the surface conditions.

**Comparison of urban drainage simulations:** The imperviousness obtained by RS was imported into the sewer models as described previously. This resulted in a total of four models. Two reference models were previously set and validated. One with the MOUSE layout catchment design and one with the GIS catchment design. In both models, the imperviousness is determined using manually assessed GIS data. Two new models were tested against them. One model with the GIS catchment design and one model with the

Thiessen-polygon catchment design. The imperviousness in these two models were generated based on the classification by remote sensing.

Three rain events of increasing intensity (12.9, 24.1 and 73.9 mm rain depths) were used for the computation. The three rain events were chosen to represent different loads on the system in terms of volume and intensity, according to IDA Spildevandskomiteen<sup>18</sup>. The data of the rain events were obtained from local monitoring stations number 5740, placed at Kløvermarksvej and number 5745, placed at Wibrandsvej near the site. The monitoring stations are connected to the SVK-meter network. They consist of tipping bucket rain gauges with a rainfall depth resolution of 0.2 mm/tip and a temporal solution of 5 min.

To establish the validity of the reference models, the runoff and total water volume were computed and compared to the measured water volume at the flow meters in the area. The reference models were also assessed by comparing the total computed pipe flow generated in the area during the three rain events to the total pipe flow measured at the flow meters located in the area.

Once the validity of the reference models was established, the RS models were assessed and compared to the reference models using the same approach. The runoff and total volume were compared as well as the pipe flow.

The simulation using the MIKE URBAN model was performed in two steps: First, the runoff simulation was performed (the time area method was used with a time step of 1 min) and then, the network simulation used the runoff results as the input. The network simulation is based on the dynamic wave approach and used a time step of 1 s (min) to 10 s (max).

**Statistical analysis:** An independent t-test was performed using Microsoft Excel 2010. All t-tests were done with a significance level of 95%. The testing was performed based on the hypothesis that the populations were similar (not different). If the hypothesis is rejected, it is highly likely that the two tested data sets are different.

## RESULTS AND DISCUSSION

### Imperviousness classification based on airborne images:

The two steps for assessing the imperviousness classification involved first finding a correlation between the remote sensing data (e.g., ha of road in a specific area) and the already existing GIS data. Second, the compatibility is tested using a t-test.

**Roads:** The road classifications obtained by the 2 different approaches (GIS and RS) are highly correlated,  $R^2 = 0.94$  (Fig. 4). Figure 4 also shows that the RS classification seems to overall under estimate the share of road surfaces in the sub-catchments compared to the GIS classification data. This can be seen by the fact that the slope of the best fit is below one. A significant difference was found between the two classification approaches by using an independent t-test to compare the amount of road hectares determined. The t-test indicates a likely significant difference with a significance level of 95% between the GIS classification data with a mean (M) and standard deviation (SD) of ( $M = 0.085$ ,  $SD = 0.003$ ) and the RS classification data ( $M = 0.076$ ,  $SD = 0.0025$ ),  $t(3225.45) = 4.73$ ,  $p = 2.322e-06$ .

To determine the cause of the discrepancy, the areas with high percentages of absolute discrepancy (areas with a difference of 40-80%) and the areas with low percentages of

discrepancy (areas with a difference of 10-40%) were inspected. It can be seen in Fig. 5 that all the areas show the same pattern of discrepancy. There are two main reasons for this discrepancy (Fig. 6), (a) The road edges of these areas are jagged because of the influence of the surrounding vegetation, i.e., the impervious surface road is permeable because of the proximity of the vegetation to the road. This is also the reason for the general under estimation of the RS classification and (b) The manual GIS classification data does not consider the vegetation around the road areas. The RS classification distinguishes these surfaces as vegetation, leading to a lower road cover in the RS classification.

**Buildings:** The building classifications obtained through the two different approaches (GIS and RS) are highly correlated ( $R^2 = 0.97$ , Fig. 7). The line obtained by linear regression, with a slope of 1, shows that the two methods predict the same share of buildings in both classifications. There are a few sub-catchments where the share of buildings is randomly over estimated or underestimated compared to the GIS classification data. This is mainly due to changes in land use between the periods at which the two classifications were performed (the manual GIS classification data are older than the RS classification data). Moreover, for two areas, there is a discrepancy in the two classifications above 10%. This is found by plotting the difference in the share of buildings in the individual sub-catchments between the two classifications as shown in Fig. 8. The area with a discrepancy between 40 and 60% fails to detect a building and instead classifies the building in the "other impervious areas" category because the roof top of the building appears to be white and therefore, the spectral response is closer to that presented in parking lots. The area with a discrepancy between 10 and 20% detected all

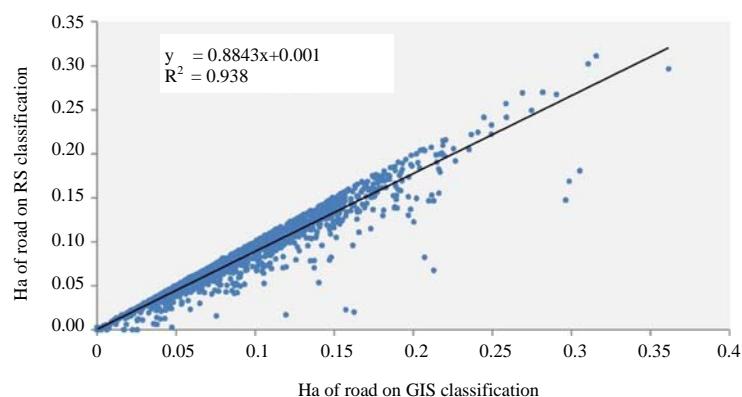


Fig. 4: Comparison between the GIS and RS classifications regarding the road surface (ha) in each sub-catchment

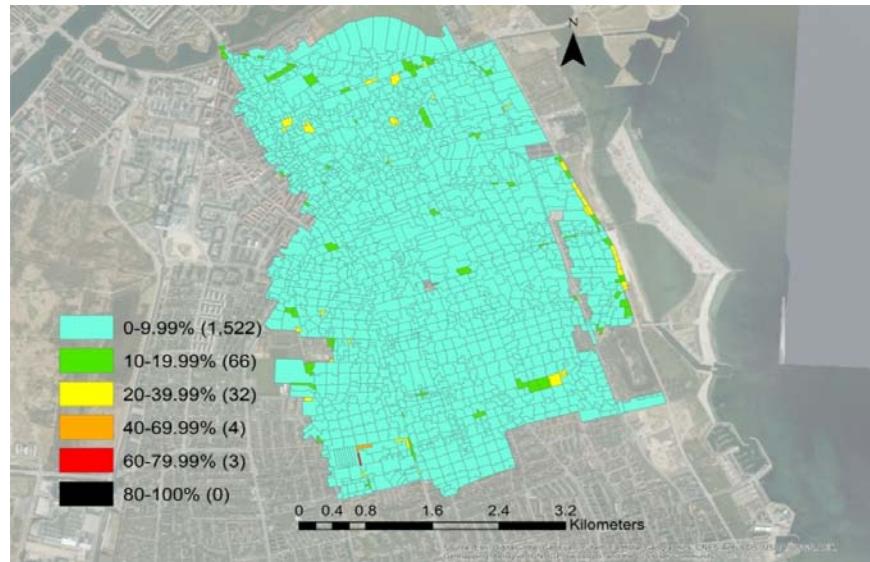


Fig. 5: Absolute difference between the GIS and RS classifications regarding road cover in each sub-catchment  
Background image source, ArcMap®

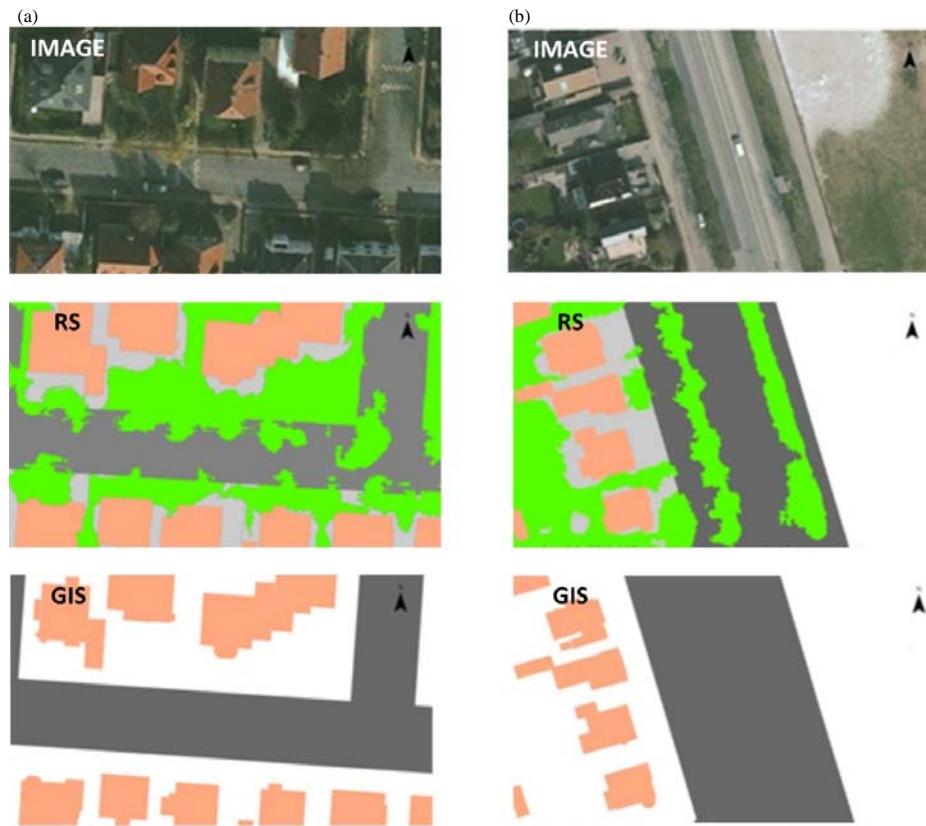


Fig. 6(a-b): (a) Jagged edges are the main reason for underestimating road cover in the RS classification and (b) Ignoring the vegetation cover on road surfaces in the GIS model is the second reason for the discrepancy between the two types of classifications

Grey: Roads, Light grey: Other impervious areas, Green: Vegetation and Salmon: Buildings

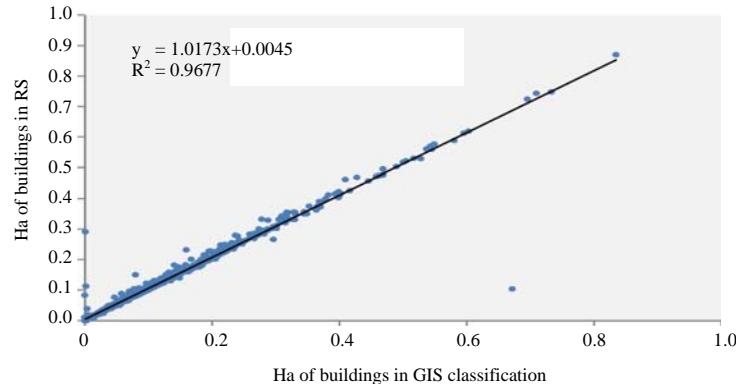


Fig.7:Comparison between the GIS and RS classifications regarding the amount of building coverage (ha) in each sub-catchment

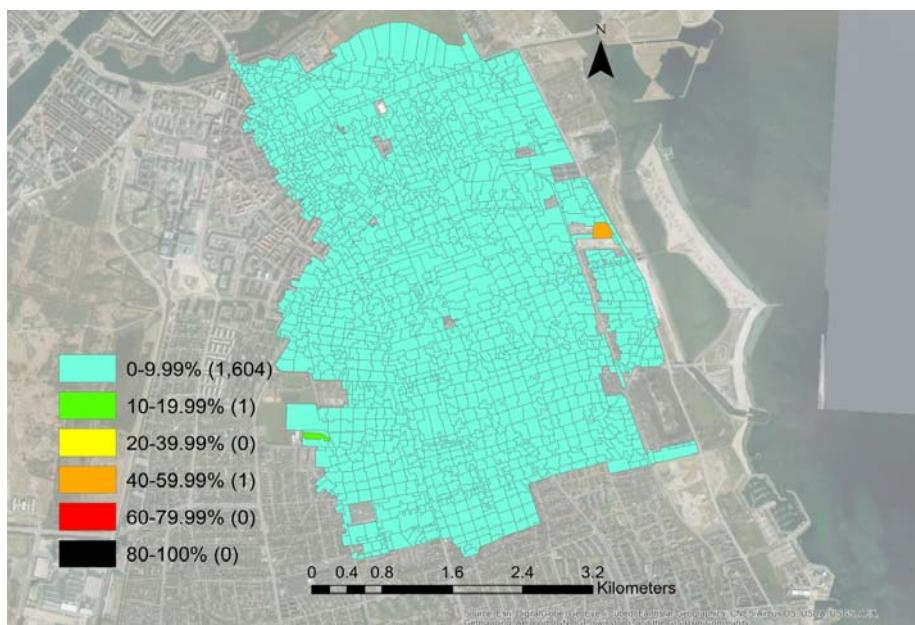


Fig.8: Absolute difference between the GIS and RS classifications regarding building coverage in each sub-catchment

Background image source, ArcMap®

the buildings in the area but in the RS classification, one of the buildings is estimated to be wider. The RS classification presents the areas of the buildings accurately and no systematic mistakes are observed. An independent t-test comparing the share of hectares of buildings determined indicates that there is no significant difference between the GIS classification data ( $M = 0.089$ ,  $SD = 0.0092$ ) and the RS classification data ( $M = 0.095$ ,  $SD = 0.0098$ , conditions,  $t(3206) = 1.75$ ,  $p = 0.0799$ ).

**Other impervious areas:** The final classification group, "other impervious areas", includes all the paved areas that are not part of the road, e.g., parking lots, pedestrian streets, squares

and impervious surfaces inside properties. The RS technique classifies every visual feature in the airborne images and therefore, this technique makes it possible to classify every impervious surface present in private properties and urban areas. The RS technique assesses 148 h of impervious features belonging to the class "other impervious areas".

When performing the GIS classification, airborne images are manually interpreted, hence, it is too demanding to classify all the impervious surfaces of the area. Instead, the areas are classified according to their land use (e.g., construction areas, paved areas around buildings, streets and industrial areas) and different imperviousness values are given to these areas. A detailed classification of all housing areas is not made by the



Fig. 9: Imperviousness classification of the category "other impervious areas": (a) RS and (b) GIS

GIS classification (e.g., the big empty spaces at the bottom right of the GIS classification image in Fig. 9). The GIS classification assesses 110 ha belonging to the class "other impervious areas". The different approach used to identify the surface type for the class "other impervious areas" will lead to different results. Additionally, some misclassifications were observed when studying the impervious class resulting from RS. Permeable surfaces were assessed as impervious, which occurs mainly because some sand areas are incorrectly assessed to be paved areas because of their similar spectral reflectance.

#### Discussion of the RS classification data assessment:

Previous studies<sup>1,15,16</sup> have found classifying areas with

sufficient accuracy to be challenging. The previous studies Jacobson<sup>1</sup> and German<sup>16</sup>, however, also used images with resolutions larger than 0.6 m. The findings by Yifan<sup>15</sup> indicated that the classification accuracy was highly dependent on the resolution. This study shows that using images with a resolution of 20 cm provides sufficient accuracy for buildings as the two data sets were statistically proven (on 95% significance level) to not be different.

Comparison of the results of the classification approach reveals challenges related to classifying roads and other impervious surfaces. The classification showed inaccuracies when the roads were placed close to vegetation. In the orthophotos, trees overlap the road surface, which makes it impossible to detect the road beneath. The RS technique

Table 1: Total measured and modelled volume ( $m^3$ ) obtained during rain events, when modelling either using the MOUSE or GIS catchment layout

	Measured ( $m^3$ )	Computed ( $m^3$ )	Difference (%)
<b>18/05/2014 12.99 mm</b>			
MOUSE	38.721	36.297	6.7
GIS		38.043	1.8
<b>12/08/2010 24.1 mm</b>			
MOUSE	38.721	72.920	-0.1
GIS		72.312	0.8
<b>14/08/2010 73.8 mm</b>			
MOUSE	215.201	224.904	-4.3
GIS		224.669	-4.2

Table 2: Total accumulated runoff ( $m^3$ ) in the area of the models during the studied rain events

Runoff (mm)	MOUSE	GIS_GIS	GIS_RS	Thiessen_RS
12.99	35.092	35.098	35.151	35.001
24.1	68.208	68.219	68.323	68.032
73.9	216.919	216.956	217.287	216.360

erroneously classifies the top most feature in the orthophotos as the surface type. Moreover, the contour of the vegetation in RS is taken in its full extension, though it is unlikely that the full size of the vegetation next to an impervious surface contributes to retaining rainwater. This is consistent with the conclusions presented in<sup>15</sup>.

Furthermore, the systematic misclassification of sand areas (a permeable surface) was observed. These areas were classified as "other impervious areas". This issue requires further development of the classification method to be overcome.

### Modelling of surface runoff and water transport

#### Validation of the basic MIKE URBAN model used for comparison:

The MIKE URBAN drainage model using the GIS-based classifications as the basic input data for the sub-catchment area and percent imperviousness are compared to the MIKE URBAN, MOUSE layout. The comparison shows agreement between the data and models as expected. The results are shown in Table 1. The correlation is high ( $R^2 = 0.9$ ), though some differences between the previous calibrated model and the GIS classifications are noted. The differences are assessed to be due to the nature of the classifications. The imperviousness data contained in the previous urban sewer model were only set for areas contributing to sewer flow. Consequently, areas not connected to the sewer system were not included in the impervious data in the previous model, while the GIS model includes all impervious areas.

**Comparison of modelled runoff:** The amounts of runoff generated by each model for the three examined rain events are shown in Table 2. An independent t-test was performed to compare the runoff generated using the reference model based on GIS\_GIS ( $M = 130.46$ ,  $SD = 16195.6$ ) and from the GIS

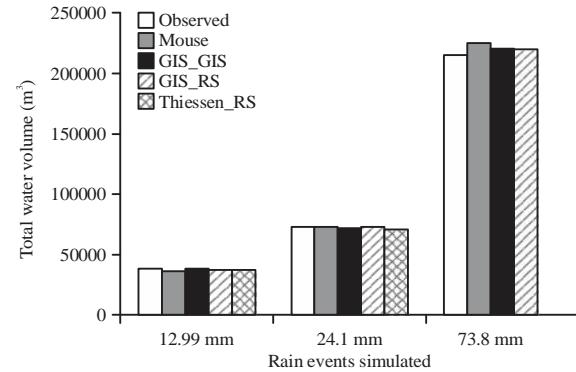


Fig. 10: Computed and measured pipe flow for the different models during the three examined rain events

model using RS classification ( $M = 130.65$ ,  $SD = 11327.1$ ), conditions:  $t(3223) = 0.048$ ,  $p = 0.96$ ,  $\alpha = 0.05$ .

The results indicate that there is no significant difference among the three rain events examined in this study.

The same comparison was made between the reference model based on GIS\_GIS ( $M = 130.46$ ,  $SD = 16195.6$ ) and Thiessen\_RS ( $M = 111.06$ ,  $SD = 6654.83$ ), conditions:  $t(2744) = 5.34$ ,  $p = 9.68e-8$ ,  $\alpha = 0.05$ .

The runoff volume differs significantly for the Thiessen\_RS model due to the structural differences between the models resulting from the different approaches for determining the sub-catchment areas. To make the two models comparable, the number of nodes in the Thiessen model should be reduced.

### Comparison of the total water volume and flow in the sewer system:

Figure 10 shows the total computed pipe flow generated during the three rain events by the different models. The figure also shows the total measured pipe flow in the system. There does not seem to be any difference

between the reference models (original MOUSE model and GIS\_GIS) and the tested models (GIS\_RS and Thiessen\_RS). Neither does there seem to be any difference between the tested models and the observed data during the 2-3 studied rain events of various sizes. The water volumes generated by all models are in the same range.

It was not possible to successfully simulate the largest rain event using the Thiessen\_RS model. When attempting to simulate the rain event, a major quantity of water was generated in the empty parts of the system. This water was generated to counteract the instability created by the high running velocity in some links. More links with the problem of high running velocity are found in the Thiessen model compared to the other models.

**Discussion of the assessed models:** Comparing the runoff and water volume generated in the system shows no significant difference between the models using the RS percent imperviousness data and the models using manually assessed percent imperviousness data. This result proves that the automatically generated models using the RS-generated impervious surface information can be used without distorting the results.

The Thiessen sub-catchment layout provides results. The Thiessen sub-catchment layout is generated automatically and results in smaller size catchments than the GIS catchment layout as the size of the sub-catchment areas was not reduced to the point at which the time-area response would be more like that of the GIS catchments. This result underlines that using the Thiessen sub-catchment layout for the automatic generation of catchment areas is not necessarily a time-saving approach. This method was not further investigated in this study.

## CONCLUSION

The use of remote sensing for the areal classification and quick estimation of percent imperviousness as the basis for urban sewage modelling was assessed in this study. Percent imperviousness and catchment delineation can be obtained by an object-oriented remote sensing technique with a resolution of 20 cm.

However, there are uncertainties and errors in the determination of percent imperviousness that must be improved. The errors were found to be related to neighbouring trees covering road surfaces, causing an underestimation of the road surface area. Errors related to the classification of sandy soils as an impervious surface were also found.

In general, to use RS to determine the percent imperviousness, adjustments need to be made to refine the classification. This can be done by going back to the object-oriented classification methodology and establishing additional criteria to ensure that the surface types are properly distinguished.

It can be concluded that the imperviousness data obtained by RS can be used to accurately model large heterogeneous urban areas, such as Amager Øst, Copenhagen, Denmark. In this specific case, the inaccuracies found in the classification of "roads" and "other impervious areas" counteract each other and do not affect the urban drainage simulation results.

## SIGNIFICANCE STATEMENT

This study determines the percent imperviousness using an object-oriented approach to potentially increase the speed of urban drainage models using automated techniques. This approach can be beneficial in regions of the world with low digitization of land coverage as this approach is a faster, potentially easier and thereby cheaper method. This study will help researchers to uncover critical parameters to be aware of when using this technique.

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