# Towards a second generation digital elevation model for Denmark

**Jacob Norby Larsen, Thomas Balstrøm & Ole Jacobi**

## Abstract

*In 1985 the first national digital elevation model (DEM) of Denmark was produced, based on 5 m contours from topographical maps with a scale of 1:50,000. Though improved during the last decade, it is obvious that the quality of this model is not sufficient for environmental assessments related to e.g. studies of overland flows. The Danish National Survey and Cadastre, which is responsible for the mapping of the Danish topographical surface is, therefore, presently working on a new DEM derived from a product, named TOP10DK planned for release in the year 2001. This product will feature a second generation elevation model based upon 2.5 m contours and a significant number of measured topographic elements such as streams, lakes, roads and ditches.*

*This paper will describe the current stage of constructing digital elevation models for Denmark. DEMs will then be considered as input to environmental modelling assessments and specifications using a second generation DEM specifically requested by the Danish environmental councils. Demands concerning quality and reliability will also be discussed.*

## Keywords

*Digital elevation model, Denmark.*

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## Background

Scientists and planners have been waiting for years for a digital elevation model (DEM) for Denmark, to be used for environmental assessments. In 1985 the first national DEM was presented. This was originally ordered by the national broadcasting organization to assist in the pointing out of the best locations for a set of transmitters to serve a new mobile telephone system. This DEM has a spatial resolution of 50 metres produced from an interpolation of 5 m contours digitized either by hand or vectorized from scanned map sheets with a scale of 1:50,000 (Frederiksen et al, 1988). A few years later the National Danish Survey and Cadastre formed a new DEM, named D50, to be sold as the first official DEM based on the same data. The DEM is presented in Fig. 1.

Viewed hypsographically, the dominating parts of the Danish landscape are located 0-70 m above sea level and are dominated by glacial deposits from the Saale and Weichsel eras intersected by meltwater sediments. The meltwater plains are flat but the undulating morainic landscapes have numerous local sinks, with or without outlets. Gentle slopes in the morainic landscape generally range between 2-5 % but do not exceed 15%. Thus, many Danish landscape elements may well not be represented in the D50 DEM based on 5 metre contours if they have variations less than 5 metres in height. However, due to the need of a DEM specifically designed for hydrological purposes, the D50 DEM was acquired by several national organizations from 1989-1996. One of the urgent purposes was to estimate the potential leaching of phosphorous from farmlands to streams caused by overland flow (Kristensen

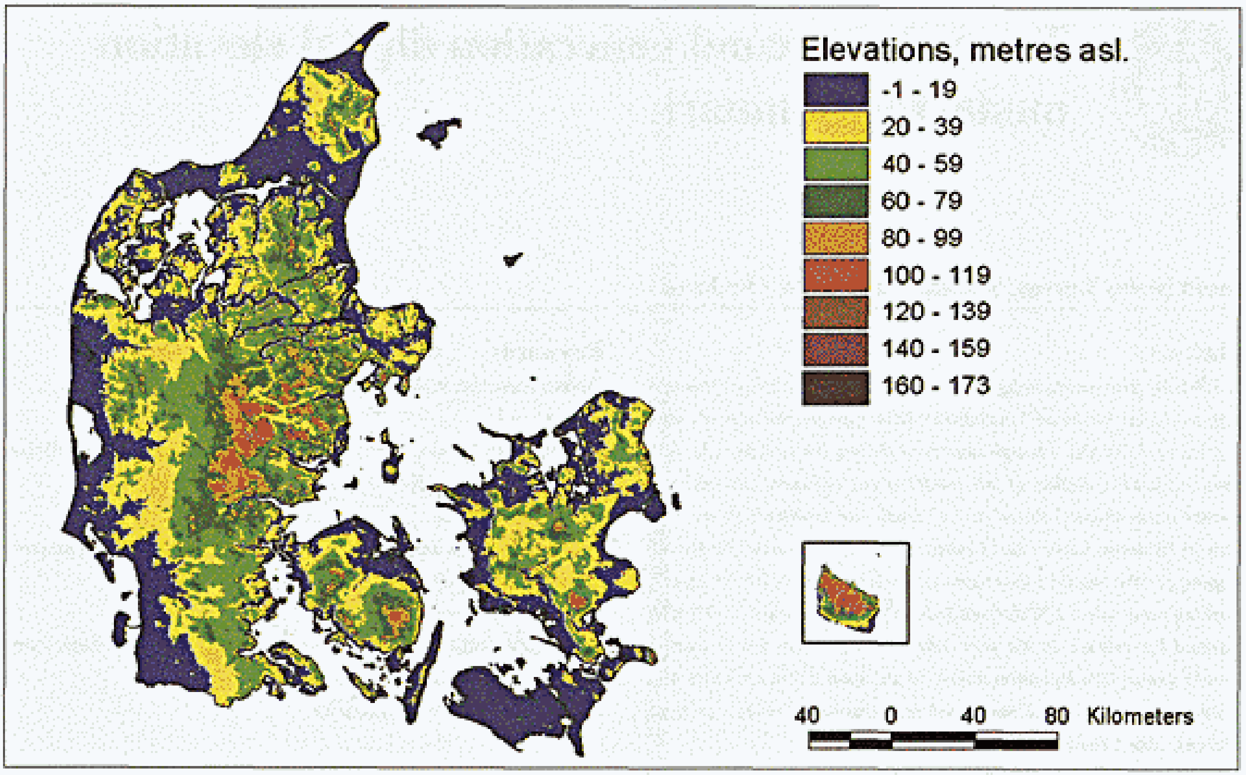

***Figure 1:*** *The D50 DEM for Denmark sliced into 9 intervals. Original data is with courtesy of theDanish National Survey & Cadastre.*

& Olsen, 1996). However, due to several embedded errors of the DEM, only a very rough estimation of loads were published. Other users of the national DEM reported individually that the current model was unusable even in derivations of major watersheds. Studies by the authors of the digital 5 metre elevation contour maps (still as the only input source to the DEM) revealed, that no proper proofreading of the digitized contours had ever been carried out. This might have revealed that several contours had been assigned a wrong elevation level when digitized. Even after the surface interpolation, no quality controls were made. This partly explains why the DEM is not useful for hydrologic modelling purposes.

Besides these error components, Frederiksen et al (1988) describes how the interpolation method used, emphasizes the problem of estimating proper peak and sink elevations in the landscape based only upon contours. Additional spot heights representing the level of peaks and sinks should have been incorporated into the interpolation as well as proper estimations of landscape extremities by extrapolation are very uncertain.

## Method and theory

### *Quality specifications of digital elevation models*

Experiments based on elevation data around Ribe in Southern Jutland and Holbæk in the central part of Zealand demonstrated that a DEM produced from digitized 2.5 metre contours with added spot heights from local peaks and sinks, gave a significantly better result than using the 5 metre contours and spot heights (see Table 1). If the 2.5 metre contours and spot heights were supplied with existing elevation data from the National Survey and Cadastre along streams, roads and ditches, the RMSE (root mean square error) was reduced even further.

The reference DEM mentioned in Table 1 was produced by photogrammetric measurements using aerial photos with a scale of 1:25,000. In such photos, the z-coordinate of well defined points can be measured with a RMSE value (root mean square error) of approximately 0.5 m. Diffuse surfaces (i.e. a field) will have a RMSE of the z-coordinate in the interval of 0.75-1 m. To calculate the accuracy of a generated elevation model, $RMSE(z_1)^2$, the

| *Test area* | *DEM sources* | *RMSE of DEM (m)* |
|---|---|---|
| ***Ribe*** | *Contours 5 m interval* | *1,5* |
| ***Ribe*** | *Contours 5 m interval + roads* | *1,4* |
| ***Ribe*** | *Contours 5 m interval + roads + streams* | *1,2* |
| ***Ribe*** | *Contours 2.5 m interval* | *1,1* |
| ***Holbæk*** | *Contours 5 m interval* | *2,0* |
| ***Holbæk*** | *Contours 5 m interval + roads* | *1,9* |
| ***Holbæk*** | *Contours 5 m interval + roads + streams* | *1,9* |
| ***Holbæk*** | *Contours 2.5 m interval* | *1,5* |

***Table 1:*** *Presentation of results achieved from investigations of DEMs based on 5 m contours, 2.5 m contours and additional data for Ribe (southern Jutland) and Holbæk (Zealand) compared to a DEM created from aerial photographs. RMSE = root mean square error. Grid size is 25 metres.*

| *Estimated accuracy of reference DEM,* $RMSE(z_2)^2$ | *Calculated RMSE of the difference between the generated DEM and the reference DEM,* $RMSE(z_1 - z_2)^2$ | *Accuracy of the generated DEM,* $RMSE(z_1)^2$ |
|---|---|---|
| *0.50 m* | *1.0 m* | *0.9 m* |
| *0.75 m* | *1.0 m* | *0.6 m* |
| *1.00 m* | *1.0 m* | *0.0 m* |
| *0.50 m* | *1.5 m* | *1.4 m* |
| *0.75 m* | *1.5 m* | *1.3 m* |
| *1.00 m* | *1.5 m* | *1.1 m* |
| *0.50 m* | *2.0 m* | *1.9 m* |
| *0.75 m* | *2.0 m* | *1.9 m* |
| *1.00 m* | *2.0 m* | *1.7 m* |

***Table 2:*** *Examples of estimated accuracies of a reference DEM contra generated DEM.*

accuracy of the reference model, $RMSE(z_2)^2$, must be estimated. The value on the left of equation 1 is the result of the accuracy test calculated from a summation of the variation of the heights of the reference DEM (estimated) and the variation of the heights of the generated DEM.

$$RMSE(z_1 - z_2)^2 = RMSE(z_1)^2 + RMSE(z_2)^2 \qquad (1)$$

The accuracies derived are presented in Table 2,

### *General aspects of data quality and data consistency*

A DEM based on contours may often have a distribution of levels, with an over-representation of those values which coincide with the contour values. This means that the model may have the appearance of being constructed with segments of large horizontal areas. If the model is to be used for hydrological purposes, these horizontal areas could prove to be most inconvenient, as the water would then have an erroneous flow direction.

When using elevation models for visualization purposes the surface quality of the model can be relevant. A smooth surface gives a better impression than a surface pitted by noise.

It is important that objects in the terrain such as streams are located accurately along the bottom of the valleys in the elevation model. In such cases, the logical connection and consistency between the elevation model and the location of waterways is critical, not only for hydrological assessment, but also for the visual expression. This will cause a highly visible error if the stream does not follow the bottom of the valley. Thus, in many cases, logical consistency between elevation model and connected data takes precedence over absolute accuracy.

Unfortunately, neither in the CEN- nor ISO-standards (CEN/TC287 1996, ISO/TC211 1997) is there made particular reference to the quality assessment of elevation models, but only a series of quality parameters that have been posed which may be applicable to elevation models.

One of the quality parameters is *positional accuracy* which describes the accuracy of elevation in the form of RMSE of height but the accuracy of elevation needs to be described locally as well as globally. When describing the accuracy of surfaces, the covariance can be used as an expression of how accuracy varies as a function of the difference between the points under examination. These methods have been widely used by interpolation procedures such as Krieging and linear prediction. There is no getting around the implication of the covariance or the frequency spectrum when an elevation model quality assessment involves more than a one-dimensional positional accuracy is required.

Another quality parameter is *logical consistency* which can be used to describe the degree of accordance between (for instance) the locations of streams and an elevation model. It is difficult, however, to find the right measure to express the quality one is looking for. A stream constitutes a line and so does the bottom of the valley, but how well do these two elements fit together? If the valley bottom is wide, the course of the stream can be altered without problem, but a small v-shaped valley does not offer much room for variation.

## Quality assessment demands provided from interviews of potential Danish users of DEMs.

As discussed above, quality assessment of DEMs may be a subjective term and an evaluation of the DEM should always be considered in combination with its expected use. Therefore, in spring 1997 approximately 20 Danish users of DEMs were interviewed in order to specify the present and expected uses of DEMs and to get an impression of the quality demands. In the following section the results from the interviews are summarised including the relevant parameters describing the quality of a DEM. The most common use of DEMs will also be described.

## Relevant parameters describing the quality of a DEM - derived from interviews

*Accuracy of heights in the model (absolute accuracy)*
The classic method of describing quality, is to estimate the accuracy of the heights in the DEM. Surveyors and mapping companies are used to evaluate accuracy using statistics describing accuracy (Shearer, 1990). The accuracy of a DEM can be estimated by comparing the DEM with an independent DEM of high accuracy.

According to Shearer (1990) errors concerning heights in a model can be divided into two groups:

- Random errors
- Systematic errors

*Random errors*
The characteristic of random errors is that the deviation from a true value is located around zero. Random errors will appear as both positive and negative deviations from a true value. Random errors may e.g. be based on erroneous labelling of contours or manual errors produced during the photogrammetric extraction of contour heights.

*Systematic errors*
Systematic errors will appear as deviations from the true values that are located around a mean value different from zero. Such errors may e.g. occur from an erroneous local setting of the level of the height measurements or from differences in used datums of combined data sets.

As the systematic error component is described above it seems to be very easy to eliminate this error by simply adding a fixed value to all z-coordinates of the generated DEM but this is not the case. Regarding errors in a generated DEM as waves, may illustrate the situation in a better way. Systematic errors can then be regarded as waves of low frequency and the random errors can be regarded as waves of high frequency. When analysing a DEM these two different types of errors clearly affect the results in different ways. The accuracy of calculated slopes and aspects in a DEM is a function of the wave length of the errors in the DEM. The maximum error-effect on the results is found when working on areas covering half the wave length of the error. Calculated volumes of small areas are very much affected by high frequency errors (random errors) - low frequency errors have no effect on these calculations. The same calculations on large areas will be largely affected by low frequency errors, where as high frequency errors will add up to zero.

Moreover, a further set of components derived from a DEM describing accuracy are:

- Derived terrain slopes and aspects
- Visual presentations
- Cartographic presentations (contour lines)
- Integrability

*Slope and aspect (relative accuracy)*
Users working with different types of environmental research including watershed modelling are very interested in the slopes and aspects of the landscape. These components actually reveal the relative accuracy of the model. An estimation of the relative accuracy may be expressed from comparisons of the differentiation of the covariance function twice for the actual respectively the estimated DEMs. Such tests, however, have not yet been carried out.

*Visual presentation*
What does the model look like? An easy way of quality assessment is to present a perspective view of the model on the computer display or paper and have a look. If the model has artificial structures like large horizontal areas, large pits or peaks one will notice these at once. This is a very subjective way of judging the quality of a model but it is an efficient method (fast and easy) and very common.

*Cartographic presentation (contour lines)*
On paper maps contour lines are the most common way of illustrating elevations. In many cases contour lines are still

very useful so another demand to an elevation model is, therefore, that it should be possible to generate contour lines with a good cartographic representation from the DEM. This requires that the model is based on both accurate data and that the structure and the mathematical part of the model is flexible.

*Integrability*

None of the interviewed users work with DEMs as their sole data set. Different data sets are always used in combination with the DEM and it is unsatisfying if these combined data sets do not fit together. It must, therefore, be considered how the elevation information from the DEM can be related to information from the most frequently used map data so that the combined information does not conflict.

## Groups of users

During the interviews it was found that the users could be divided into three groups according to their professional use of elevation models.

- *Environmental planning*
- *Engineering and physical planning*
- *Radio transmission planning*

*Environmental planning*

Several different users are working within environmental planning. One of their main applications concerning elevation models, is the use of the model to analyse the movement of surface soils and sediments caused by overland flow. This increases the accuracy requirements to the DEM in order to calculate the water flow to streams, lakes and coastal areas precisely. This group of users also uses elevation models for the presentation and visualization of the terrain.

In some cases it can be relevant to use elevation models to optimize calculations on areas measured in areal photos or other remotely sensed data. If the slopes of the landscape are well described the accuracy of area and volume calculations will increase.

*Engineering and physical planning*

The common applications of elevation models by this group of users is the planning of corridors for different pipelines, newly built-up areas, roads and railroads. In the last part of the planning process the accuracy requirements of the model are very high. As an example of this, the final calculations on a new road are based typically on an elevation model in a 10 m grid with an accuracy of 10 cm on the z-coordinate. However, a less accurate elevation model can be used in the drafting of the planning process.

Another use of a rough elevation model is in project visualization. The model can be used as background for e.g. 3D drawings of new roads or buildings, so that politicians or the public can see the visual impact on the landscape of newly planned land uses.

*Radio transmission planning*

This group of users, uses elevation models to model the influence of the terrain on broadcasting of signals from radio transmitters or mobile telephones. The special demand from this group is that objects on the surface must be described, as well as the terrain itself. Thus, buildings and forests are as important features as the elevation surface itself, so that the resulting analysis must therefore be described in 3D.

## Finding the optimal basis of the model

After the interview sessions, different data sets were tested during 1997 to find the optimal basis for a new DEM. The tests concentrated on 1) making a DEM suitable for visualization and presentation of the landscape and 2) to investigate whether it is possible to make a DEM that can form the basis for watershed modelling.

According to various tests described earlier, 2.5 metre contour lines from maps with a scale of 1:25,000 were found to be the most accurate of all the existing elevation data. The accuracy of these maps was tested in four different parts of the country. The test sites were selected to represent major landscape units in Denmark. According to Table 1 the tests showed that the height accuracy was within the interval 1.0-1.5 m (RMSE) with a few exceptions up to 2.3 m, when data was interpolated into a grid, with a cell size of 25 metres. Roads up to a width of 6 metres were added to the contour lines to increase the accuracy and the level of detail in the model.

To create a DEM that fits the demands of users working with watershed modelling, additional data was selected from the hydrological part of the future digital map

(TOP10DK) such as ditches, streams, lakes and coastlines and then added to the model. These objects are, however, not always hydrologically correct. As an example, the z-coordinate assigned to a lake can vary by 2-3 metres from one side of the lake to the other, as lakes are measured either at the water surface or at their banks. A similar situation can be found regarding ditches and streams. In order to ensure that the additional data is correct, a preprocessing of this data is carried out. Lakes are corrected to a horizontal level and ditches and streams edited so that they have an unambiguous slope. The objects are then reconnected so that they once again form a 3D topological network. In this type of water network, the relative accuracy tends to be very high, as the slope of each object in the network of streams has been verified.

## Project implementation

Based on the results of the experiences summarised in Table 2, it was decided later in 1997 by the National Danish Survey and Cadastre to develop a second generation DEM for Denmark. The DEM combined digitized 2.5 m contours gathered from vectorizations of scanned map sheets with a scale of 1:25,000 and additional topographical elements achieved from aerial photographs. This product will be presented in the year 2001 together with the release of the new digital topographical map for Denmark (TOP10DK). Although other DEMs for Denmark elaborated by non-governmental companies may be available before this release there is no doubt that this new DEM will provide a long awaited high quality base for many potential users.

## Results

### *Screening the accuracy of the model*

The data sets involved in the future DEM are from two different sources. The contour lines from the maps with a scale of 1:25,000 may be up to 100 years old and have only been partly updated. The objects from the digital TOP10DK map are all newly measured using photogrammetry.

TOP10DK-objects are up to 6 years old but will normally be updated in a 5 year cycle. This means that the two data sets are totally independent with respect to origin. Fig. 2 presents the contours from analog maps with a scale of 1:25,000 from Northern Zealand. Fig. 3 presents the generated contours from the DEM from the same area produced from the contours and features from TOP10DK. From the available data sets it is possible to calculate the accuracy of the heights in the DEM and to calculate the accuracy in the (x,y)-plane. Therefore, it has been decided to work on the accuracy of the heights, as there are no investigations on the general planar accuracy of input contours.

The accuracy requirements of the objects in TOP10DK is such that the precission of the z-coordinate must be greater than 1 m (absolute accuracy). The accuracy of the contour lines has not (until now) been tested systematically. However, to get an estimate of the accuracy of the contour line, objects from TOP10DK can be used as control points. This means that before the objects from TOP10DK are included in the DEM, they are used to verify, that the two data sets fit together. Until now, the tests have shown (as mentioned earlier) that the DEM has a general accuracy within the interval of 1.0-1.5 metres (RMSE). A few exceptions up to 2.3 metres (RMSE) have been found in the most hilly parts of the country.

### *Data integration*

When the accuracy of the contour lines was verified, the different data sets were integrated. The contour lines were

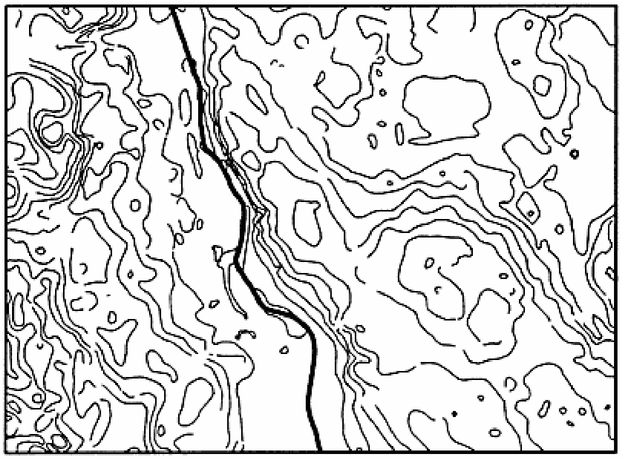

*Figure 2: Part of streams and lakes from the TOP10DK map with 2.5 m equidistant contours from analog maps with a scale of 1: 25,000. Filled polygons are lakes and the bold line running North/ South is a stream. The location is Dronningmølle/Esrum Å (in the northern part of Zealand). Extension of area: 2.6 x 1.5 km. Original data is with courtesy of the Danish National Survey & Cadastre.*

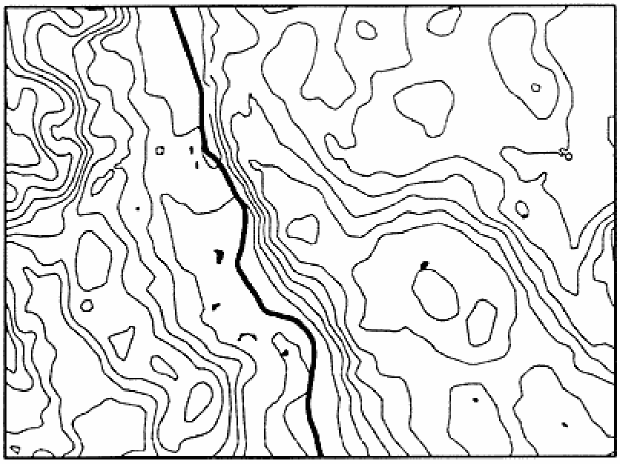

*Figure 3: The same location as in Figure 2 including the same topographic features but streams and lakes are compiled from TOP10DK and presented together with contours generated from the new DEM with grid cell size 25 m. Original data is with courtesy of the Danish National Survey & Cadastre.*

then used as the basis of the resulting model and roads, ditches, streams, lakes and the coastlines from TOP10DK were included as breaklines in the model.

The generated contours, Fig. 3, may look more edged than the contours in the analog map, Fig. 2. This is due to the contour generation method that ideally should optimize 2 parameters: 1) the contours should be smoothed to a nice cartographic presentation and 2) contours should not intersect. Both parameters can not be optimized at the same time and, therefore, some compromises must be made.

*The production to date*

The DEM has been in production for the last 1½ years and the screening of the accuracy of the model gives the following results (see also Fig 4):

- In 3% of the produced area the accuracy of the model is between 2 and 2.5 m.
- In 16% of the produced area the accuracy of the model is between 1.5 and 2 m.
- In 60% of the produced area the accuracy of the model is between 1 and 1.5 m.
- In 20% of the produced area the accuracy of the model is between 0 and 1 m.
- In 1% of the produced area there is not sufficient data for reliable statistical calculation.

In general the accuracy of the produced model is better than 2 metres (RMSE). For the major part of the model the accuracy is within the interval of 1 to 1.5 metres (RMSE).

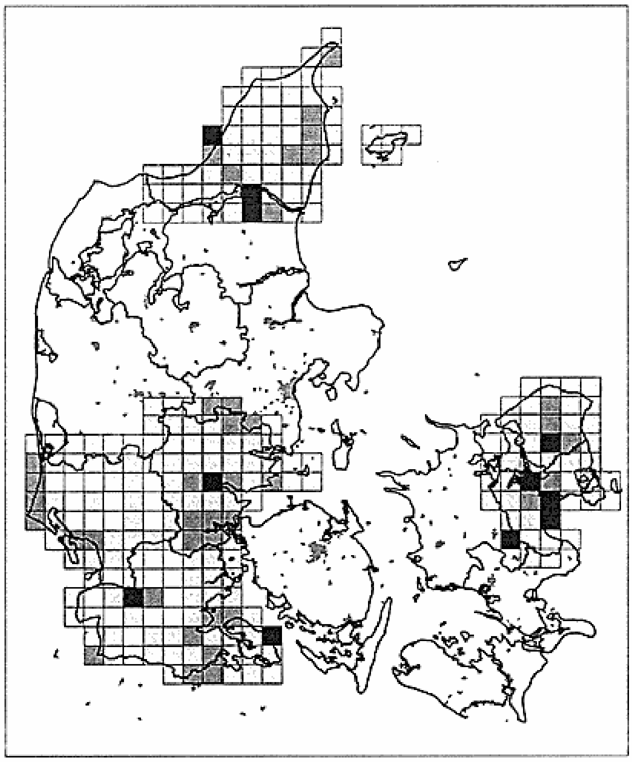

*Figure 4: The accuracy of the generated DEM. White squares indicates accuracy better than 1 m. Litegray squares indicates accuracy between 1 and 1.5 metres. Darkgray squares indicates accuracy between 1.5 and 2 metres. Black squares indicates accuracy worse than 2 metres or insufficient statistical basis for the accuracy test. Data is with courtesy of The Danish National Survey & Cadastre.*

*User response*

To date, only, a part of the model has been applied in a few projects. For the Bjerringbro municipality and Hvorslev municipality, the Danish Institute of Plant and Soil Science has used the model for visualization and draping of orthophotos. Their spontaneous reaction is that the visual impression of the new model is good. However, the model has not yet been tested for watershed modelling purposes.

*Updating*

The different data sets (contour lines and objects from TOP10DK) used in the model are stored separately. Every generated DEM has been regarded as a derived product, and has, therefore, not been stored digitally. Updating of the DEM is therefore a change in the data sets forming the basis of the model. An updated DEM can then be generated from the updated basis data when needed.

## Further perspectives

*Maintenance of the DEM*

When the new DEM is produced,the accuracy of the model is tested in grids of 10 by 10 kilometres. These accuracy tests will be used to point out areas where improvements of the DEM are required. The improvement procedure has not yet been decided on, and no scientific literature or references are available on this topic. However, on going research indicates some interesting possibilities in automated improvements of grid based DEMs. It has been suggested that an existing grid model based on contour lines can be compared to an automatically generated grid created from stereo pairs of aerial photographs. It may then be possible to define a set of rules defining when to keep a cell from an existing model and when to use a cell from an automatically generated model based on newer data. Manual work is still needed if a set of decision rules is to be optimized so that a regular revision of a nationwide DEM can become more manageable. Meanwhile, the rules must handle the situation so that DEMs generated automatically from digital photogrammetry or radar data should describe the topographic surface (treetops and buildings) instead of the terrain surface (Henderson 1998, Treuhaft et al. 1996, Zebker et al. 1994). The rules of comparison should then be used to detect whether a cell in the automatically generated DEM describes the height of a feature above the terrain. If polygons from a vector map such as forests or built up areas are included in the comparison, it might very well be possible to reach a higher level of automization and an improvement of the DEM.

*Perspective viewing*

There are interesting possibilities in perspective map viewing. Raster maps or aerial photos draped upon a DEM give a very good impression of a landscape's morphology and land use. A realistic impression of the landscape can be further improved if symbols or objects, with a vertical extent (buildings, forests, windmills etc.) are added to the perspective view.

*3D topographic model*

If objects in the topographical map are available with a reliable height, it is possible to establish a 3D topographical model of the landscape including 3D objects. Mapping in 3D is, however, not a simple task and neither is the production of software for visualisation of large 3D data sets. Although such a product is eagerly awaited by planning authorities etc. it will probably not be available before year 2002.

## Acknowledgements

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basis of the model. An updated DEM can then be generated from the updated basis data when needed.

## Further perspectives

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