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# Digital Terrain Models from Historic Data Sets: The Case of Land Subsidence, Water Management and Sustainable Land Use in the Dutch Lowlands

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**Abstract**
The region surrounding Gouda, in the middle of the Dutch Delta, is one of the lowest-lying areas in the Netherlands. The historic inner city is situated at the current high-water mark (Amsterdam Ordnance Datum, or NAP). In contrast, the surrounding landscape lies between two and six meters below that due to subsidence as a result of draining the land and making it available for urbanization and agriculture. The original factors that caused the land to subside are still at play here, while relative sea level rise adds to the problem by making these areas prone to flooding. In this region, accurate digital terrain models make an invaluable contribution to data-driven governance and decision-making. These models can illuminate how changing conditions affect heritage sites and the cultural landscape. We propose and evaluate a methodology for developing accurate terrain models from historical aerial photographs. The method provides high-density, high-precision data for the past half-century. This data can provide insight into the long-term effects of local interventions on local subsidence, making the method a valuable tool for developing risk inventories for proposed interventions.

**Policy Recommendations**
- Establish detailed risk inventories based on historical digital elevation models to evaluate long-term land subsidence. These inventories will prepare policymakers for potential challenges in spatial planning, water management and heritage management.

KEYWORDS
Data
Land use
Land subsidence
Photogrammetry
Water management

WATER ICONS

CLIMATE
A B C D E
**Cfb:** Moderate sea climate


< Fig.1 Structural damage in a Dutch farmhouse caused by land subsidence (Source: Roeland Emaus, 2024).

## Introduction

The region surrounding Gouda lies within the Rhine-Meuse delta and can be characterized as cultivated clay and peatland. The land is mostly flat, with minimal natural differences in height or slope, and soils that are either loosely packed (unconsolidated) or more compacted (consolidated), containing a high percentage of organic matter (>15 per cent) (fig. 2). The first settlements in the area appeared during the early Middle Ages when the area was colonized and used for arable farming. Currently, the level of the groundwater is artificially kept just below the ground surface. Since the landscape is situated below sea level, the surface water must be pumped continually from the canals between the agricultural fields up into the rivers flowing at a higher level. Consequently, the landscape is peppered with canals, rivers and dikes. The historic fight against the water is deeply embedded in the built environment and the general appearance of the landscape.

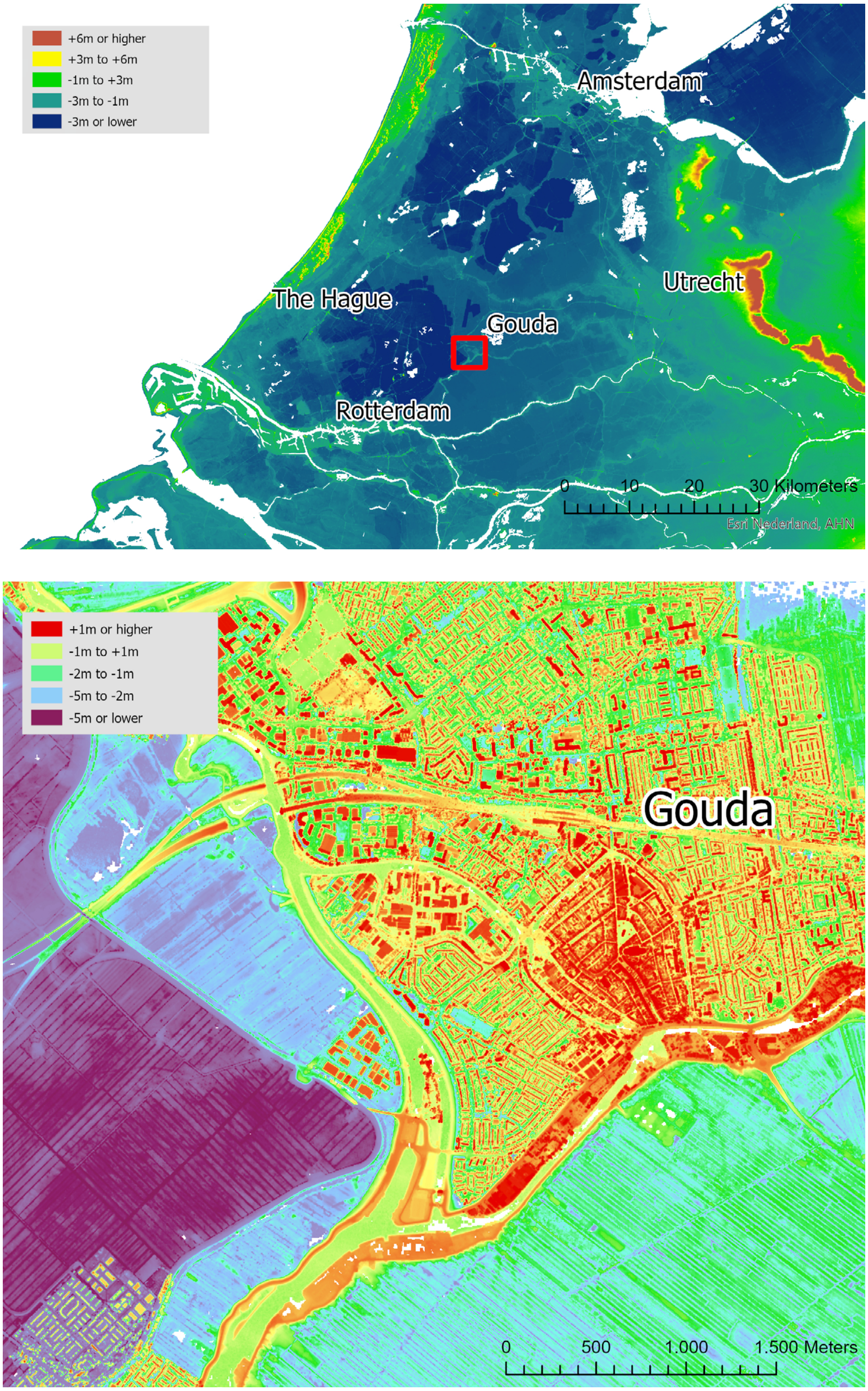
Dairy farming currently dominates land use in the region, as the high groundwater level makes arable farming impractical. The soil, primarily composed of organic matter, faces inevitable subsidence wherever it is not waterlogged. Subsidence occurs due to both consolidation and, more significantly, the oxidation (or decomposition) of the organic matter. Even pasture-based agriculture requires relatively dry soil, which depends on maintaining a relatively low groundwater level. However, the drying process accelerates the loss of the soil's top layer. To sustain healthy pastures, further lowering of the water level becomes necessary, creating a "land use trap."

This trap is rooted in historic land use decisions, which continue to shape contemporary challenges by deeply influencing current agricultural practices and the local economy. It is important to recognize the historical and social complexity of the situation, in which any technical intervention is inherently a socio-political act, as it directly affects peoples' daily lives. In this context, high-accuracy elevation data from the past half-century are crucial for revealing the effects of past interventions and for developing effective governance strategies. Without this data, detecting local and sometimes delayed responses to certain changes – such as those reported by Locher and De Bakker (1990), who observed effects taking place up to 30 years after 1960 – would be nearly impossible.

## Socioeconomic Context

Land subsidence began occurring as soon as farmers colonized the region and began draining the land, during the ninth and tenth centuries. Although conditions were relatively wet, once drained, the soil was also relatively fertile. Ditches were easily dug in the soft peat, and arable farming was possible. Over time, the drained soils began to oxidize and subsided. However, in locations on top of the bog, well above groundwater levels, this problem was quickly addressed by digging deeper ditches and moving further into the bog, where the surface level was still unaltered.

This process has continued into the current era. All the land has been exploited and it has subsided to a level lower than the original water table. Ditches cannot be dug any deeper unless the water table is artificially lowered. In its basic form, the process of land subsidence due to agricultural practices is already some eleven centuries old. The current agricultural practice resulting from this centuries-old process is uniquely tied to the land and part of the local




^ Fig. 2 The research area in relation to regional elevation (Source: Roeland Emaus and Sylvia Leenaers, based on AHN-data, 2024).

way of life. The problem is, therefore, a technical one with a significant socioeconomic component. This context highlights the importance of governance based on empirical data, rather than conjecture or economic interests. Well informed, long-term and data-driven technology governance is essential to signal the need for local interventions in water management, land use planning (Stouthamer et al. 2020). Data provides a valuable empirical foundation, however, it must be interpreted and contextualized to ensure that policies are comprehensive and address the complexities of real-world issues.

## Current Practices

To allow for the precise modeling of areas prone to flooding, the Dutch water authority has commissioned an integral laser-altimetric-derived digital terrain model for the entire Netherlands, the AHN (www.ahn.nl). Since the production of the first AHN in the 1990s, the data set has been renewed with increasing resolution over the years, leading to the current preparation of the fifth updated version, the AHN5. For the last 25 years, we have been able to monitor landscape change at increasing levels of precision. Not only are anthropogenic changes such as urban sprawl and infrastructural developments visible, but the more natural processes of fluvial dynamics and dune formation can also be quantified. In many cases, changes in surface elevation can be followed precisely.

Over the last 25 years, Dutch agriculture has become increasingly industrialized, leaving its mark on the landscape. While remnants of the cultural landscape formed over the past eleven centuries were still visible in the relief of a quarter-century ago, many of these elements have since eroded or vanished. The loss of heritage sites and historic landscape features from this period can now be studied using historic digital terrain models.

The rate at which land subsidence occurs can be estimated in millimeters per year. Since accurate monitoring has become available, the total amount of land subsidence that has taken place is therefore low and difficult to measure in a high-density grid. Therefore, land subsidence changes cannot be substantiated yet for a continuous surface over a more extended period, although short-term monitoring is taking place (van Asselen et al. 2018; van Asselen, Erkens and De Graaf 2020). Long-term processes are, therefore, only modeled and not measured (e.g., Koomen and Exaltus 2003; Van der Meulen et al. 2020). Local and historical changes in the built environment and the landscape have, until now, only been modeled rather than directly measured. As a result, governance and decision-making have relied on generalized data, potentially overlooking or misapprehending local and long-term phenomena. Using the new methodology, we can check the models on which governance is based.

## New Methodology

Recent developments in computer science have led to the wide scale availability of powerful computers that can handle large data sets and perform complex tasks. At the same time, software developers have integrated the classical principles of aerial photograph triangulation into modern end-user software packages, specifically designed for drone-based surveying and remote-sensing practices.

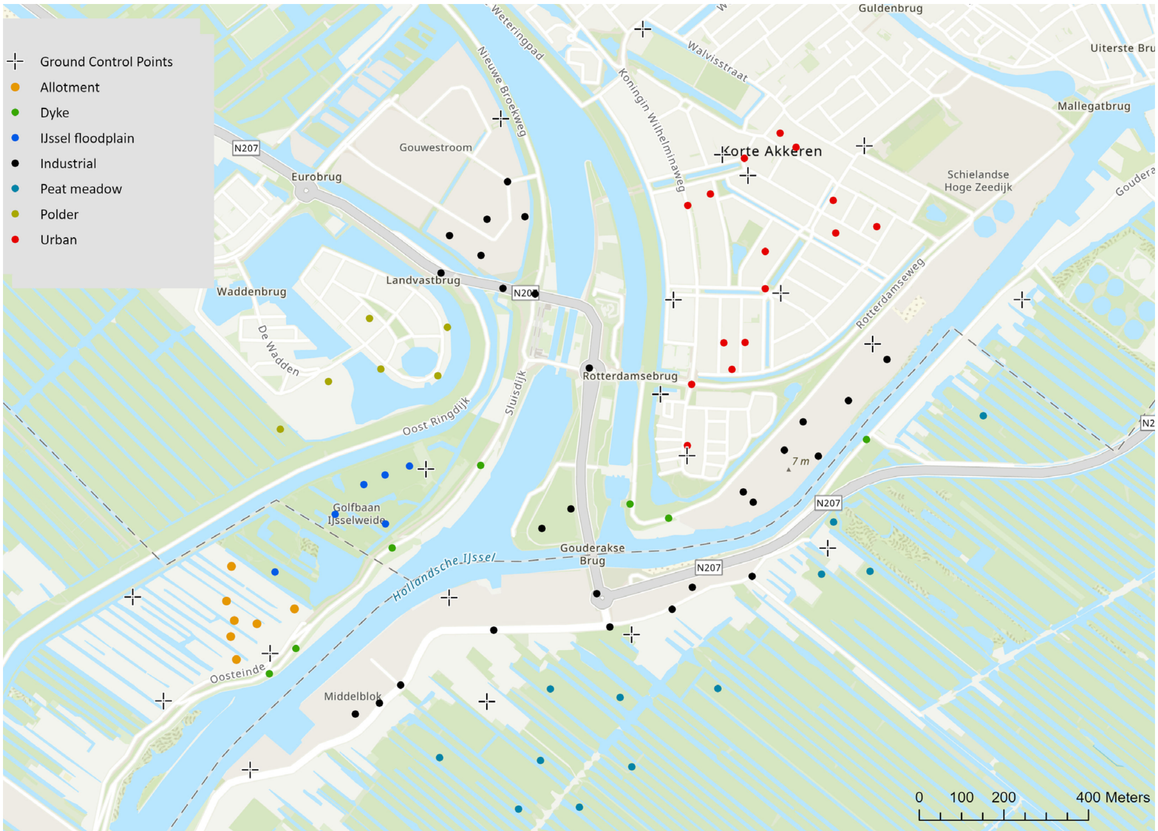
The principle of photogrammetry involves extracting 3D information from a series of overlapping aerial photographs (Avery 1968).

As the software described above is a further development of manual aerial triangulation techniques, it can generate digital terrain models not only from modern drone imagery but also from any set of overlapping aerial photographs. In this project we will use this technology to analyze historical images.

Since the Second World War, practically every national topographical service worldwide has produced its topographic cartography through manual aerial photogrammetry (Cosgrove and Fox 2010). The historical aerial imagery that formed the basis of this cartographic production is often still available as hard copies in national archives. However, in some countries, it is still regarded as military intelligence even though the imagery is over 50 years old.

Our research was based on the premise that these legacy data sets, produced for manual processing, can now be digitally processed to the same standards we produce terrain models today. Legacy data coupled with new technologies have more potential than was conceived at the time of its original production.

To test our premise, we acquired a set of overlapping aerial photographs from the region of Gouda made in 1999. Older imagery is available in this region. However, as we are dealing with a dynamic landscape, we would have no way of estimating the accuracy and precision of the digital terrain model produced with our new methodology. If we want to determine the quality of a data set, we need to compare it to another data set from the same period with




^ Fig. 3 Ground control points (GCPs) used in the photogrammetric production process, and sample locations for the statistical accuracy analysis of the historic elevation models comparison with the AHN1 (Source: Roeland Emaus and Sylvia Leenaers, readapted from the map by ESRI, 2024).

known accuracy. The oldest appropriate available data set is the first national digital terrain model from the late 1990s, the AHN1, which has an accuracy of 0.2 meters. This way, a direct comparison can be made between the terrain model produced with legacy data and a contemporary LiDAR data set.

We selected 20 distinctive landmarks in the area. Through cadastral databases and historical data, we were sure these landmarks had remained unaltered by land subsidence in the last decades, or at least to a negligible degree. We determined the coordinates of these landmarks through a topographic survey with GPS and Total Station which we could use as ground control points for the photogrammetric restitution (the plus signs in fig. 2). Since this is a novel application, we chose three software packages to process the historical photographs and compare their performance: Pix4D, Agisoft Metashape and ERDAS Imagine. Within these packages, we ran multiple models with varying settings regarding triangulation, automatic (tie) point extraction, point cloud production and filtering. This resulted in a total of 16 digital terrain models. These digital terrain models were then compared with the AHN1. To analyze the results, we divided the region into seven distinct areas based on their land use types and morphology. Within these seven groups, we located control points that are the most meaningful for this kind of landscape. For instance, we only used rooftops and street level locations for comparison in the "urban" category since facades of houses are always challenging to model with conventional aerial photogrammetry. In the same fashion, we excluded waterbodies and high-rise vegetation. In the final analysis, we calculated the performance of each terrain model for different terrains at a total of 80 locations (the dots in fig. 3).

| Software | Pix4D | Agisoft | ERDAS |
|---|---|---|---|
| Model no. | 18 | 232 | 3-0047 (7) |
| Overall | 1.54 | 0.62 | 2.81 |
| Allotment | 1.81 | 1.47 | 1.06 |
| Dike | 0.4 | 0.41 | 0.76 |
| IJsselweide | 1.36 | 0.4 | 1.61 |
| Industrial | 0.84 | 0.23 | 0.94 |
| Polder | 1.8 | 0.27 | 2.74 |
| Urban | 1.42 | 0.9 | 4.85 |
| Veenweide | 2.52 | 0.39 | 1.38 |

^ Table 1 Comparison between the results with the lowest RMSE of each software package in this study. The values are the calculated error (RMSE) of the photogrammetric models compared to the contemporaneous LiDAR elevation model (AHN1).

### Results

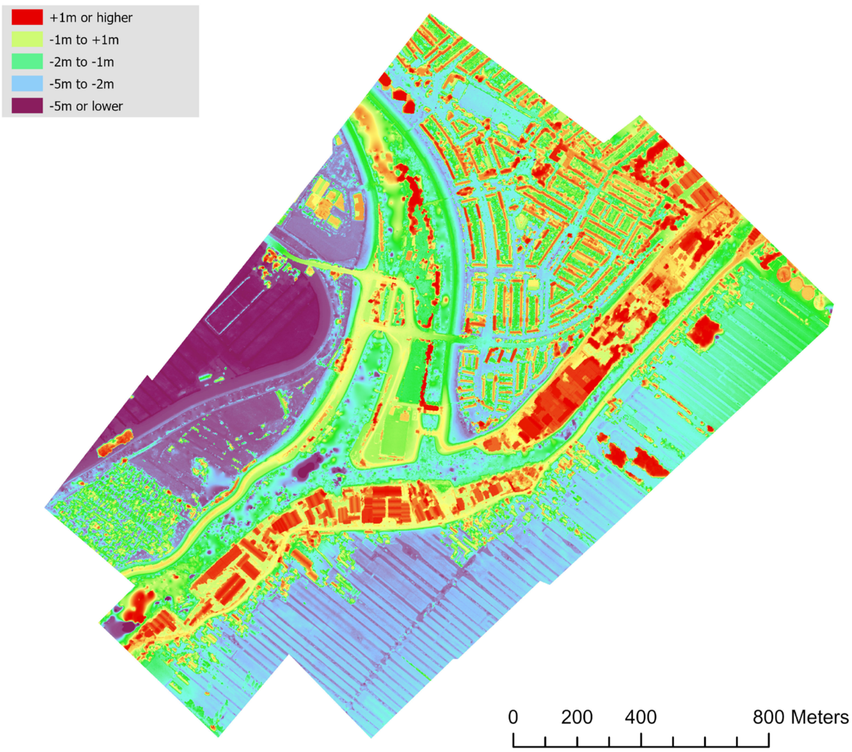
Since all measurements can contain errors, we first filtered the sample points for outliers. We used a statistical measure to reject measurements from the comparison that seemed stable in our legacy data sets, having a high RMSE compared to a relatively low standard deviation, but that did not correspond well to the AHN1. The assumption is that our legacy measurement at some locations might be more accurate than the AHN1.

All software packages performed well in industrial and rural terrains, but relatively poor results were obtained in residential areas (table 1). Overall, the Agisoft Metashape package performed well on most terrains with a consistent error (RMSE) of 0.6 meters in general but between 0.4 and 0.2 meters in agricultural and industrial areas. The ERDAS package performed relatively well in one type of terrain but poorly in others. The Pix4D package performed poorly on all terrains, with an overall RMSE of 1.5 meters. This means that the landscape and (historic) buildings can be measured and monitored retrospectively, with an accuracy between 0.2 and 0.4 meters or larger and the effects of local (construction) interventions and even general impacts of climate change can be detected and monitored.

## Conclusion

Combining advanced computer technology with historical imagery makes it possible to produce historic digital terrain models with an accuracy of 0.2 to 0.4 meters for most types of terrain (fig. 4), comparable to the accuracy of AHN1. This approach allows for the creation of digital terrain models from the 1950s on, providing an accurate model of the terrain before extensive urbanization, land consolidation and industrial agriculture changed the landscape beyond recognition and impacted local hydrology and land subsidence. This way, the original cultural landscape, with all its (historical) buildings, waterworks and hydrological installations, can be studied as it was in the 1950s and more recently.

Furthermore, the methodology will allow us to monitor changes through time accurately since a terrain model can be produced for every decade or even every year from the 1950s to the present. Landscape changes can be linked to hydrological interventions, urban planning and land use practices. We can now offer accurate historical context and show trends in how the landscape has changed. This is potentially valuable input for decision-making, as we can understand how original hydrological processes functioned before large-scale industrial interventions changed the landscape. However, it also enables us to learn from the often-invisible long-term effects of local interventions and the gradual impacts of global climate change.




^ Fig. 4 Result of the photogrammetric production of a historic elevation model from 1999, model no. 232 (Source: Roeland Emaus and Sylvia Leenaers, 2024).

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