DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/71

Detection of recent terrain subsidence on Lolland using persistent scatterer interferometry (PSI) processing of satellite radar scanning data

Analysis of the persistent scatterer interferometry data from satellite radar measurements of the area Lolland with focus on the vulnerable south coast of Lolland, a contribution to the EU project SubCoast

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1. SubCoast - Baltic Pilot - Lolland

The EU project SubCoast started in the spring 2010 as a medium scale integration research project under the 7th Framework Programme, Theme 9 – Space. SubCoast is a collaborative project aiming at monitoring subsidence motions for the risk assessment of ground displacement hazard by the application of satellite radar scanning data. The activity is based on the concept developed by Terrafirma project under the Global Monitoring Environment System (GMES) Service Element applying the remote sensing technique of Persistent Scatterer Interferometry (PSI), which is able to map millimetric ground motion phenomena over large areas from space. It is the aim of the service to be distributed throughout Europe via the national geological surveys and institutions (Pedersen et al. 2011).

SubCoast makes full use of Persistant Scatterer-InSAR data to map and monitor subsidence in lowland areas facing the sea. Three pilot areas are selected for the demonstration of downstream service. These pilots are the Rhine-Meuse-Delta, the southern Emilia Romagna and the Baltic Sea area (Fig. 1).

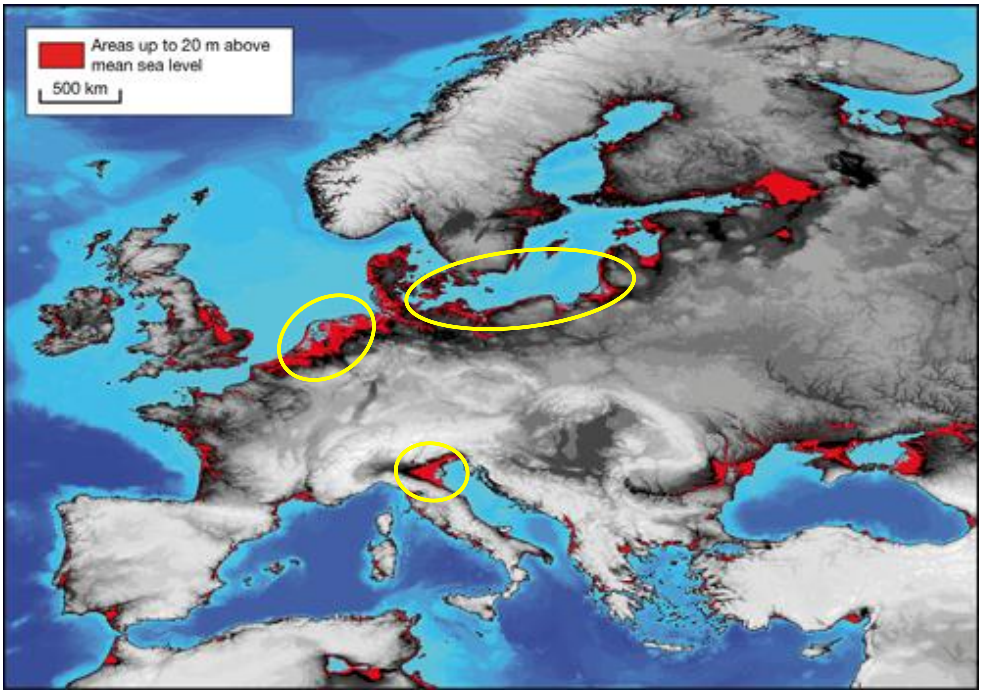

Fig. 1. *Map of Europe displaying the lowland coastal areas. The three pilot areas are encircled by yellow line and comprises farthest to the west Rhine-Meuse-Delta area, to the south the Emilia Romagna area, and to the east the Baltic area with sub-areas in northern Poland, along the Klaipeda Spit in Lithuania, and the south coast of Lolland in Denmark.*

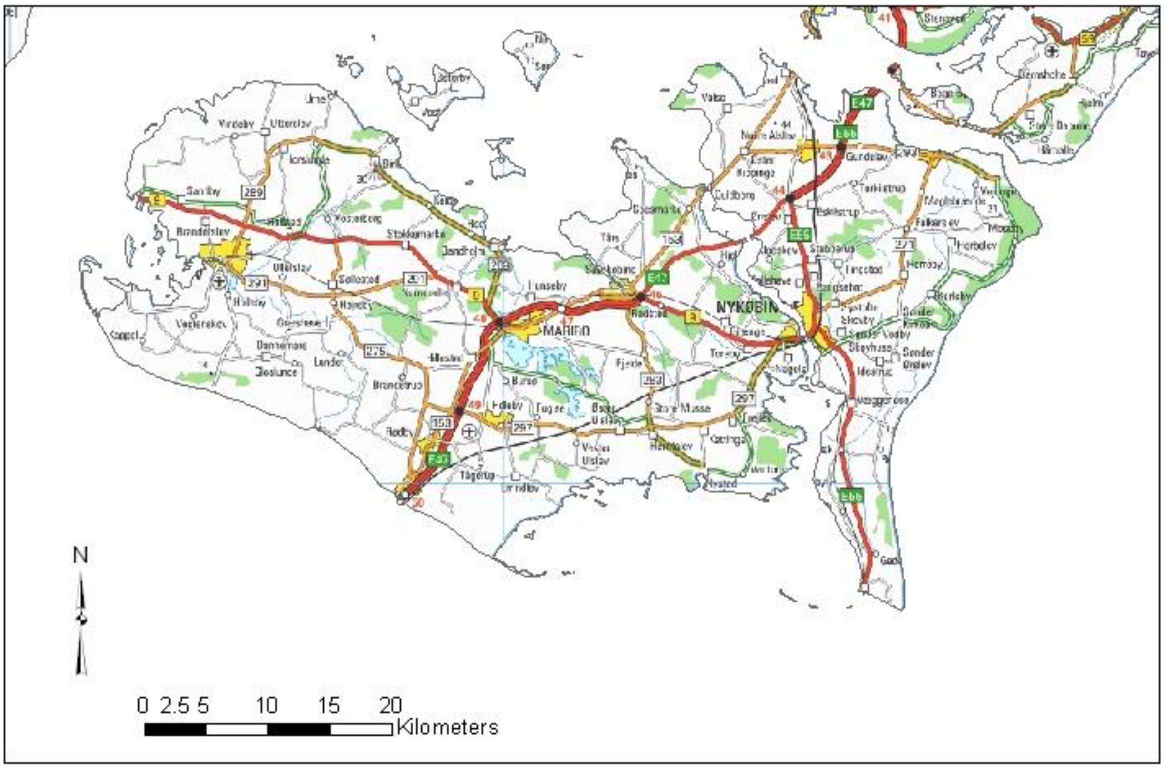

Fig. 2. *Map of the Lolland – Falster area in southern Denmark. The focus for the Danish partner in the Baltic Pilot is the south coast of Lolland, which lowland is protected by a dike.*

1.1 GEUS' participation in the SubCoast project

The island of Lolland and surrounding smaller islands area located in the western part of the Baltic Sea, south-eastern Denmark. The length of the coast lines around the islands is more than 300 km. Most of the coast comprises small cliffs, 3–5 m high, consisting of till deposits with the exception of Møns Klint, which constitutes a 5 km long vertical chalk cliff more than 100 m high at its summit. In contrast nearly 50 km of the coast consists of wetland defended from the sea by dams.

More then 100 000 people lives on the islands and the main town are Nakskov and Nykøbing, and Rødby Harbor is the most important traffic center managing a substantial part of the transport from Scandinavia to northern Europe over the Fehmarn Belt (Femer Bælt). This belt will in the coming decade attract high attention during the construction of a bridge and tunnel connection between Germany and Denmark.

The risk of storm floods affecting the coastal low laying areas is a repeatedly occurrences and courses observant protection of the long dam framing the south coast of Lolland. The last serious storm flood occurred in November 2006, when an unusually meteorological situation resulted in an increase of the sea level by almost 2 m, and points along the dike was damaged. The area is located in a tectonically subsidence area, which has been constantly subsiding due to its position on the slope of the Danish–North Germany Basin. The rate of subsidence can be estimated to be 1 mm per year since the Stone Age preceding the Atlantic transgression. A survey of the Danish triangulation fix-points, established about 100 years ago, was conducted in the year 2000 with precision positioning from satellites resulted in an adjustment of the fix-points levels about 10 cm below the original altitude of their position.

The problems to be addressed and aiming at being resolved in the SubCoast project are:

- Is there a systematic distribution of the subsidence area and can it be mapped.
- Is it possible to located part of the area as faster subsiding, probably caused by the differential movements of salt pillows in the subsurface at about 2 km's depth?
- Will this subsidence be a risk for major constructional projects?
- Which parts of the archipelago is the most vulnerable in relation to sea level rise in the Baltic?
- Is it possible to identify a connection between Neo-tectonic fault systems and morphological surface elements?
- Will the change in meteorological systems result in more frequent flooding event due to the storm pressed water accumulation in the Baltic?

These questions concerning geo-hazards are the targets for the research carried out by the Geological Survey of Denmark and Greenland (GEUS). In the project GEUS contributes to the investigations of sustainable utilization of the GMES Services. Together with the partners in the Baltic Pilot and in corporation with the other partners in the project the evaluation of the satellite monitoring are carried out. The general target for SubCoast is to provide at harmonized concept for the application of GMES Service to be used by the European geological surveys in the assessment of geo-hazard risks.

Fig. 3. *The dike along the south coast of Lolland, which has been one of the important elements for the SubCoast projects focus in southern Denmark.*

2. Method and data

***Sub*Coast** are built on the heritage of GMES Service Element ‘Terrafirma’ and use the full capability of PS-InSAR as a technology for large scale subsidence mapping. Necessary R&D will be focused on possible augmentation of datasources (Radarsat, Cosmo-Skymed, TerraSAR-X) and the improvement of retrieval algorithms. Subsequent validation efforts will make full use of the Terrafirma Validation Testsite and possible other current validation initiatives, especially when these are located in coastal lowlands.

For a number of selected areas ***Sub*Coast** bring PSI-derived subsidence estimates together with ground based geodetic measurements, geological data, geotechnical data and sea level measurements into a coherent framework to

- estimate the land movement term of relative sea level rise and to understand the trajectory and regional component of sea level change. Use are made of the sea-level products of the GMES Marine Core Service ‘MyOcean’.
- spatially delineate and derive an estimate of the various components contributing to subsidence in selected coastal lowlands. Use are made of state-of-the-art assimilation techniques to quantify as much as possible these components (natural compaction, fluid extraction, settlement)
- locate risk-zones in coastal and flood defence systems and combine these data with flood hazards maps in order to upgrade risk assessment capability (viz. GMES Emergency Response Core Service)
- develop strategies for a systematic mapping of geotechnical damage of infrastructure in coastal lowlands

A distributed data and information system has been set up, which facilitates the accessibility and operability of EO-data, in-situ data (including geoscientific data) and model results for the selected areas. This system facilitates the integration of tools and services allowing end-users to query, view and access products and data.

2.1 The satellite data

For the project, data are archived from ERS-1,2 (SAR-sensor) and ENVISAT (ASAR-sensor). New data-sources will be exploited in the pilots, using data from TerraSAR-X and RADARSAT-2 in order to make full use of the available SAR-capability after ENVISAT’s ASAR will be turned off, as planned in 2010. The extent of satellite data-exploitation will be stretched to the full archive in order to built up long-term records of subsidence over coastal areas and relate these to decadal trends in climate change.

2.2 The PSI data

Two data sets of image stacks were found to cover the area of Lolland. The first one was ERS descending track 251, which has 74 images, and the second one was ERS ascending track 315, which has only 21 images.

The 21-image stack (ERS ascending track 315) is expected to contain significant amounts of noise and potential for atmospheric bias due to the very small number of scenes, as explained in the report which accompanied the deliverables. Therefore the 74-image stack of ERS descending track 251 was regarded as the most reliable. The examination of these data appeared to show relatively low levels of noise as would be expected from such a large data stack – for example 65% of points are moving less than 0.5 mm/yr, and 97% less than 1.5 mm/yr.

2.3 ArcMAP

The data are analysed using ArcMAP using coordinate system: WGS 1984 UTM Zone 32N
Projection: Transverse_Mercator

The data were statistically analysed using the point to raster and kriging functions in ArcMAP.

2.4 Maps

Danish topographical maps are the basemeaps. These are rasterised maps from the National Survey and Cadastre in the scale 1:25.000, 1:50.000 and 1:100.000. Furthermore rasterised historical maps from 1860 and 1942 have been applied, and even rasterised version of maps from the Society of Science from 1760 have consulted.

2.5 DEM

The digital elevation models used are

- KMS_DTM_Lidar_10m
- KMS_DTM_Lidar_16dm

2.6 Orthophoto

The orthophotos used are from 2005.

2.7 Sea level data

The reference datum for sea level data is DVR90.

2.8 Earthquake data

Earthquake data are provided from the Danish earthquake data base managed by the Geophysic Department at the Geological Survey of Denmark and Greenland. The registration has been systematic and continually since 1930.

3. PSI results

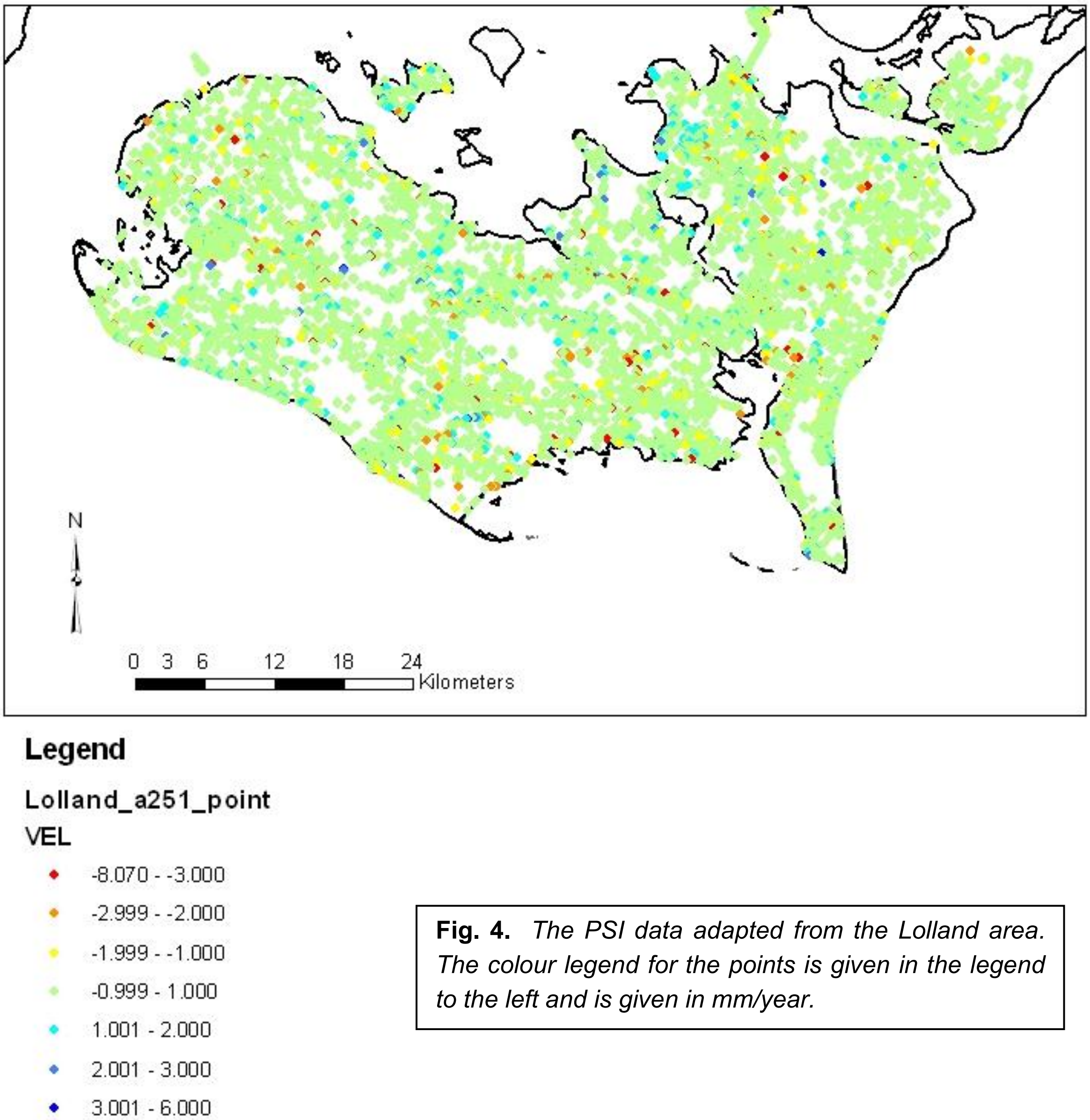

Fig. 4. *The PSI data adapted from the Lolland area. The colour legend for the points is given in the legend to the left and is given in mm/year.*

3.1 Large scale terrain movement

On a large scale the Lolland area is fearly stable as 65% of the points are moving less than 0.5 mm/yr, and 97% less than 1.5 mm/yr.

When the point to raster function in ArcMAP is used, there seems to be small areas with subsidence wich are dispersed distributed. When kriging the data it seems that some of the dipersed areas of subsidence occur in elongated arrays (Fig. 6). The direction of these arrays are parallel to the fault systems seen in the Pre-Quaternary subsurface rocks. Furthermore they occur over graben structures, which also controls the outline of buried Quaternary valleys. It seems therefore that although Lolland generally is stable, minor (local) uccurences of neotectonic subsidence is detected with the PSI data, mainly with subsidence rates of 0.5 to 1 mm/yr.

The dikes along the coasts are generally stable, with a few exeptions, wich are mentioned below.

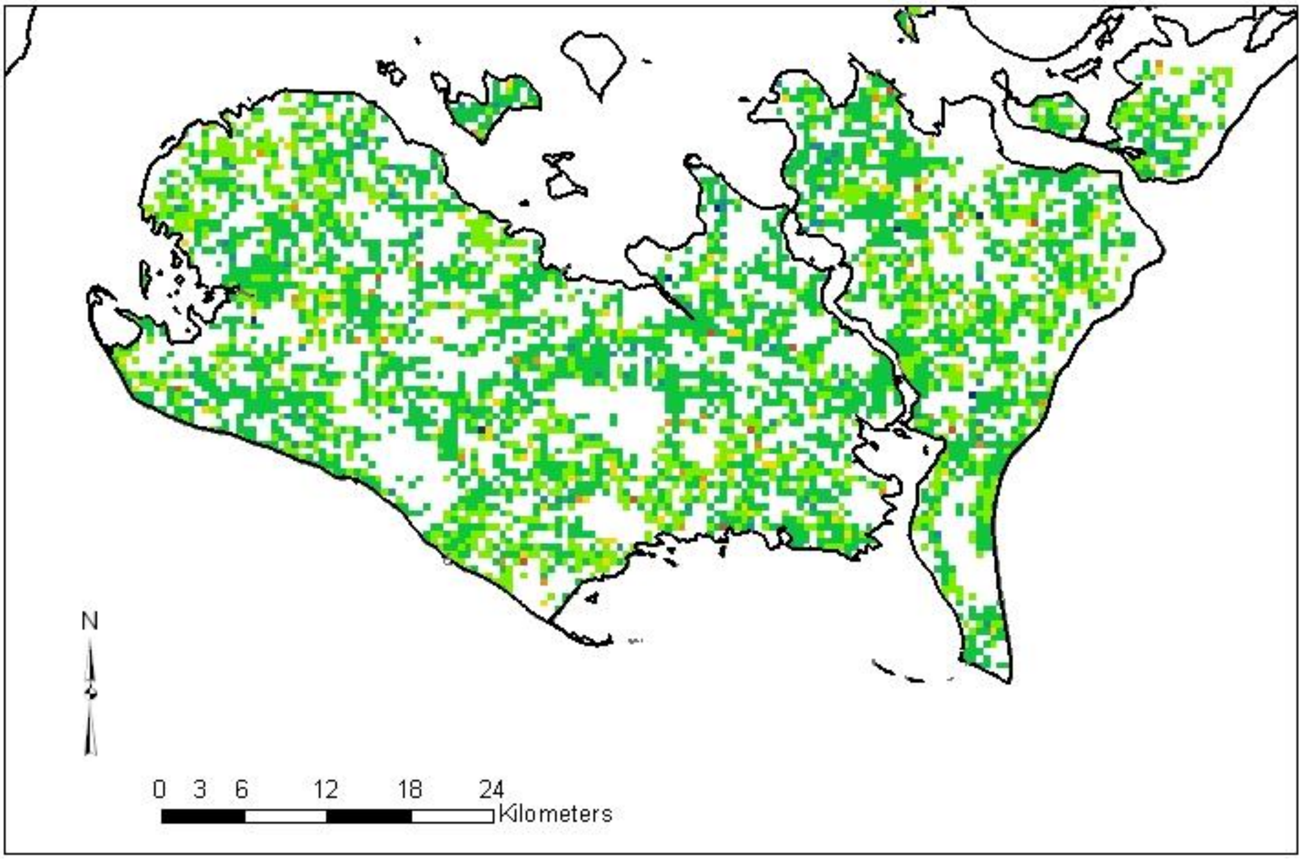

Fig. 5. *Mean velocity of PSI data in a raster grid with 500 m cell size. The values for the pixels are the same as in Fig. 4.*

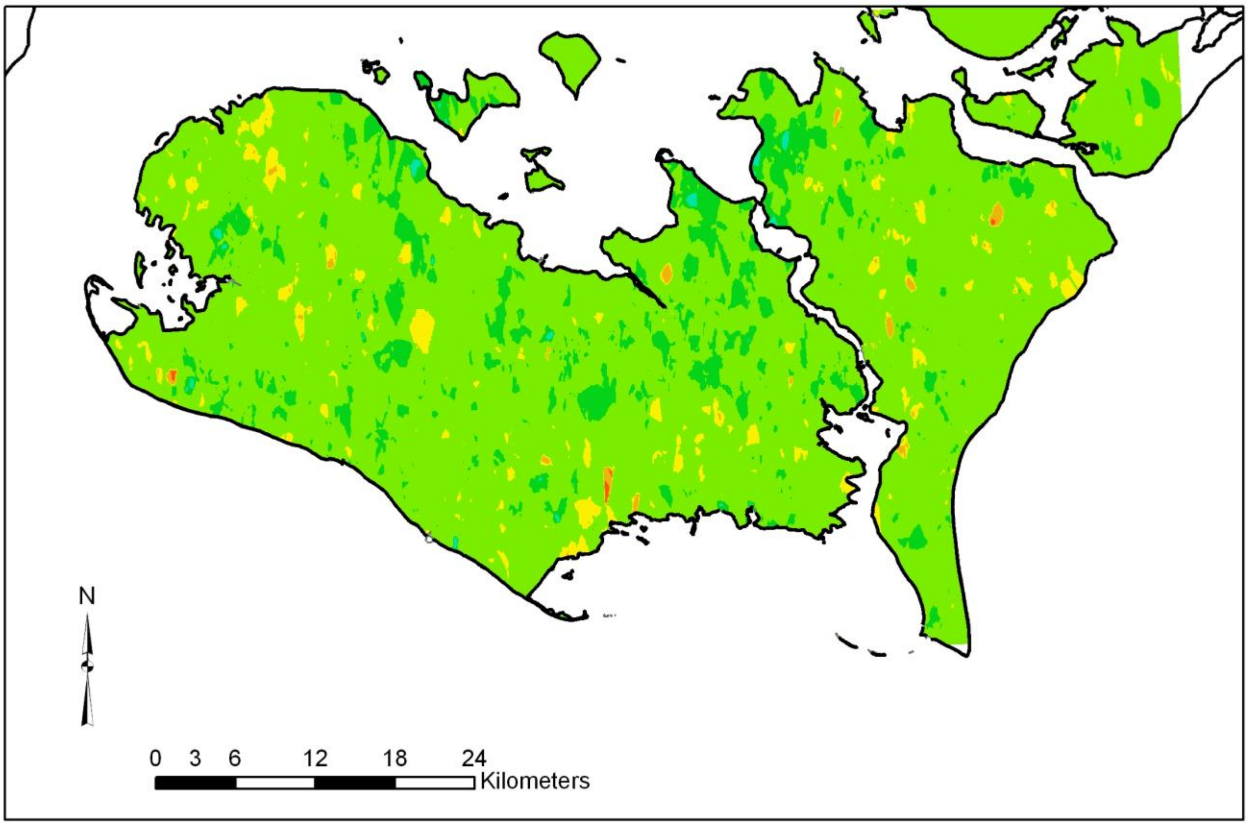

Fig. 6. *Kriging of PSI data. The values for the colours are vertical distance in mm/year.*

3.2 Local terrain movements

On a local scale subsidence is seen within minor area, which generally can be ascribed to settling of soft sediments. In Fig. 7 and 8 two examples are shown, which document subsidence at local sites. The first case is from the western part of the town Maribo, where a point is identified in the road site. The road was built on the fill of an old lake, which formed the bog-dominated southern tip of one of the Maribo lakes. The subsidence, which is detailed documented on the graph in Fig. 7, is evidently caused by compaction of the fill and compression of the peat below the fill.

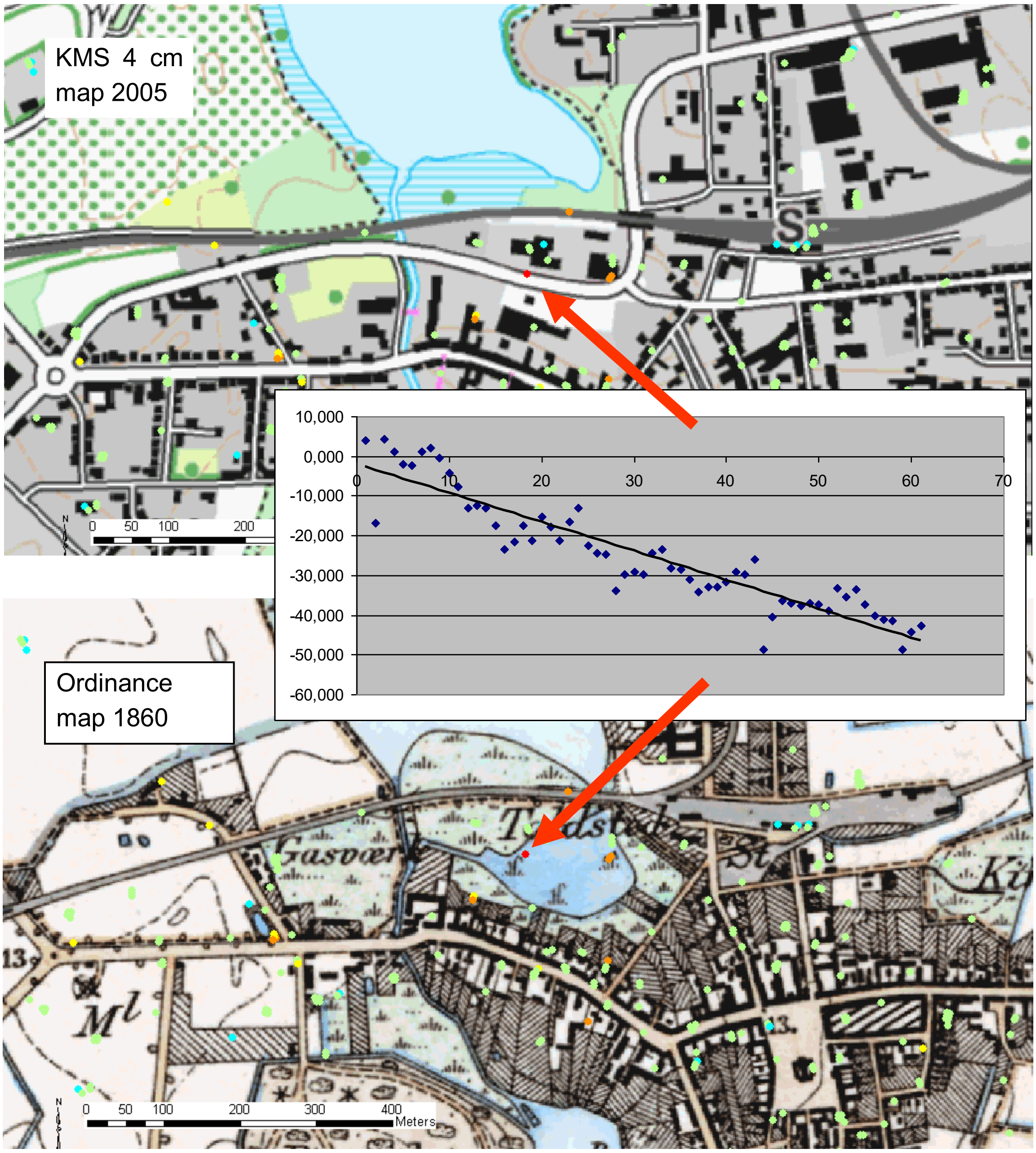

Fig. 7. *A point of subsidence identified in the Maribo town. The point is today located in the site of a road, which have been constructed over fill covering a small lake. The lake is documented on the old maps (in scale 1:20.000) from the Geodetic Institute in 1860. The red arrows indicate the position of the point on the recent map and the old map. The graph demonstrate the measured distances in vertical subsidence on the y-axis in mm. The x-axis indicates the number of satellite passages over the area.*

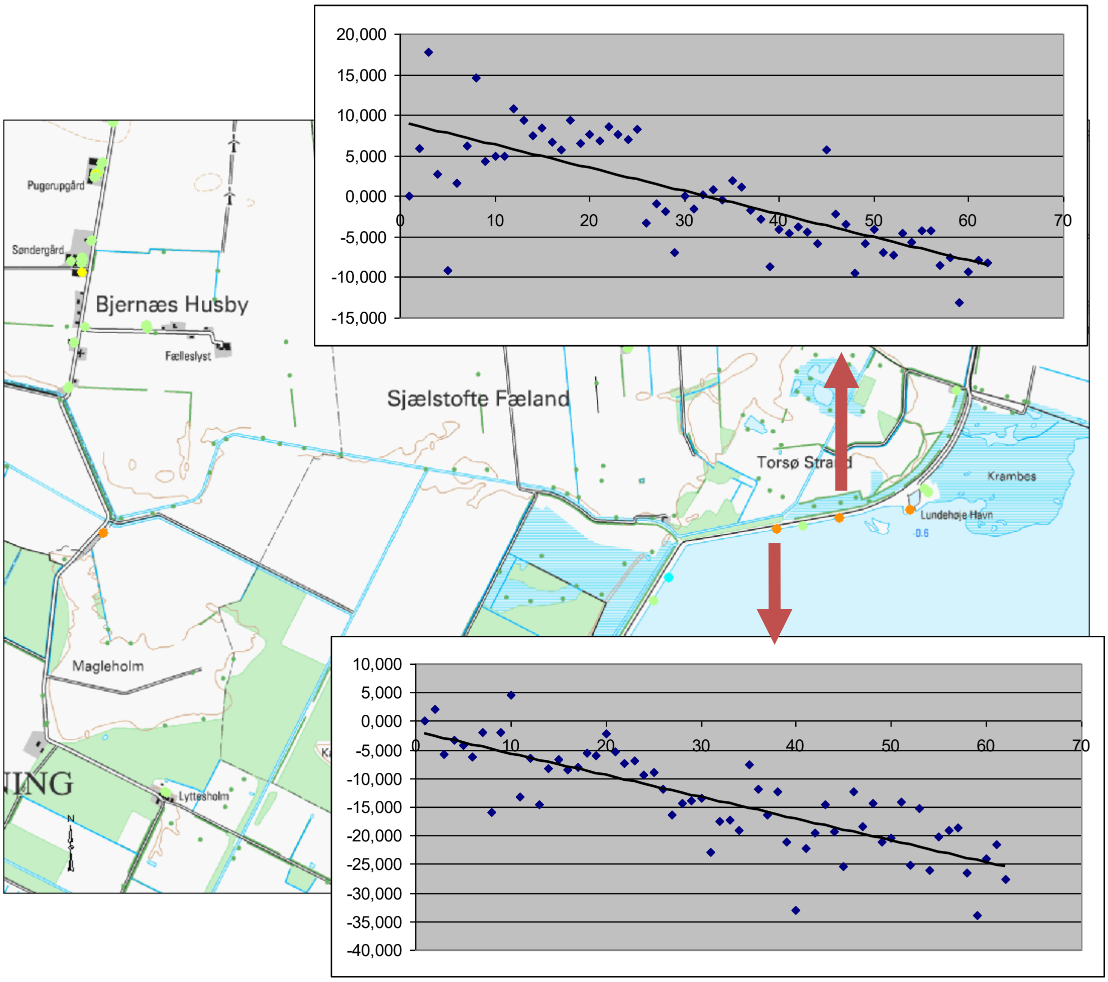

Fig. 8. *Two point identified along the dike east of Rødby Havn.*

4. Risk assessment

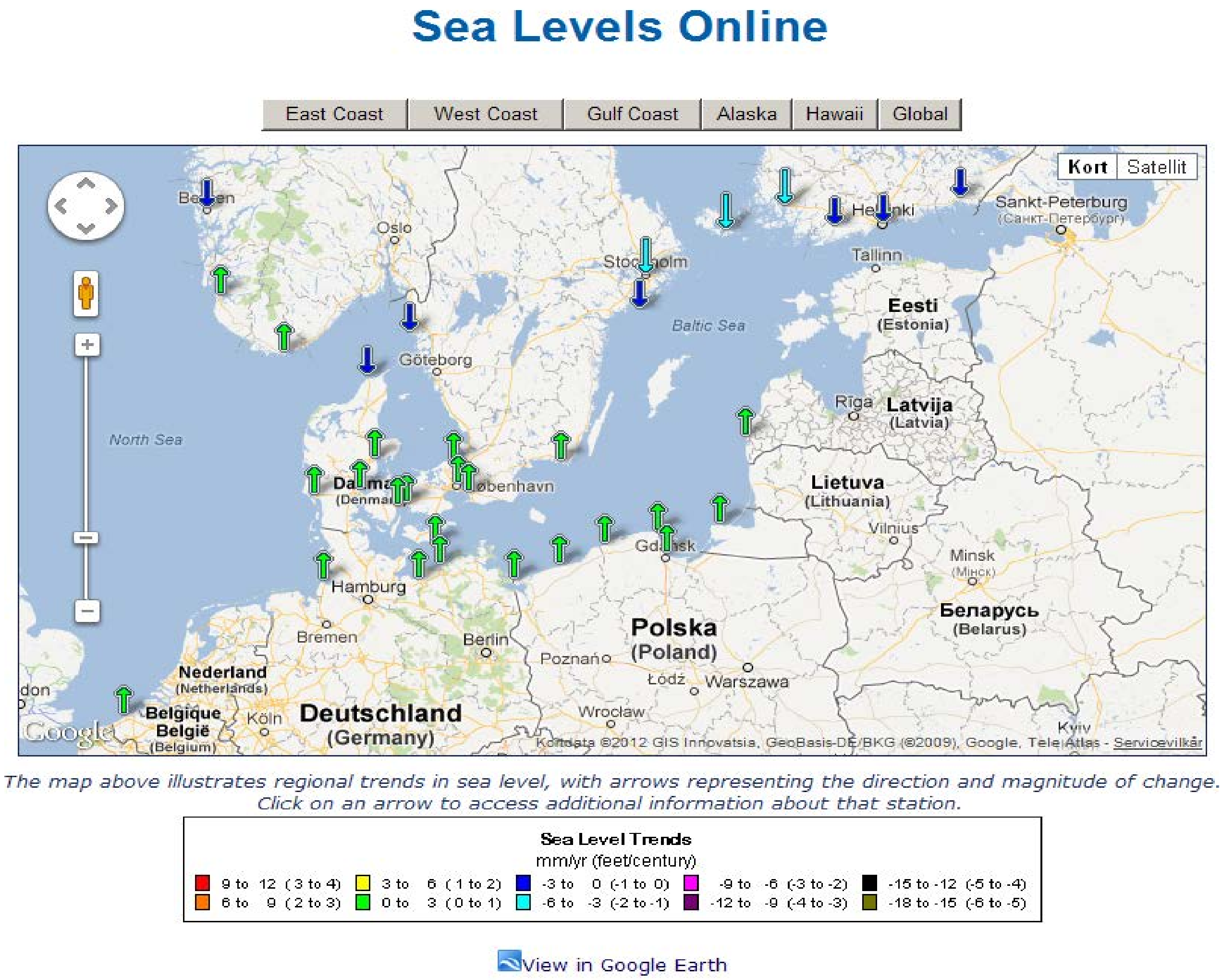

Fig 9. *Map of the Baltic area with sea level trends. Due to glacioisostatic elevation the relative sea level is decreasing in northern Denmark, as well as north of a line from Göteborg over Stockholm to Helsinki.*

The sea level in the southern part of the Baltic Sea has in the last 100 years raised about 10 cm. The nearest station to Lolland for measurements of the relative sea level, i.e. the height of the water surface in relation to fixed points on the land, is the station at Gedser. Here the sea level rise has been measured to 1 mm/year (Fig. 10). The general eustatic sea level elevation in the sea surrounding Denmark is estimated to be about 0.5 mm/year determined from measurements carried out during the last 100 years (GEUS & DMI 2012). In the northern part of Denmark the land is still influenced by the glacio-isostatic rebound due to the melting away of the Scandinavian Ice Sheet. Here at station Hirtshals the relative sea level has fallen by 2 cm over 100 years (Fig. 10). A similar relative sea level fall occurs in the northern part of the Baltic Sea (Fig. 9), with an increasing tendency up towards the Bay of Botnia. At Lolland the sea level is raising about 10 cm during the 100 years period, which is interpreted as a combination of the general eustatic sea level rise and the tectonic subsidence of the land areas (islands) along the northern slope of the Femern Belt depression. The relative sea level data for the Lolland island adapted from the harbour at Rødby Havn (Fig. 11) are consistent with the data from Gedser and show the same magnitude and tendency of sea level rise.

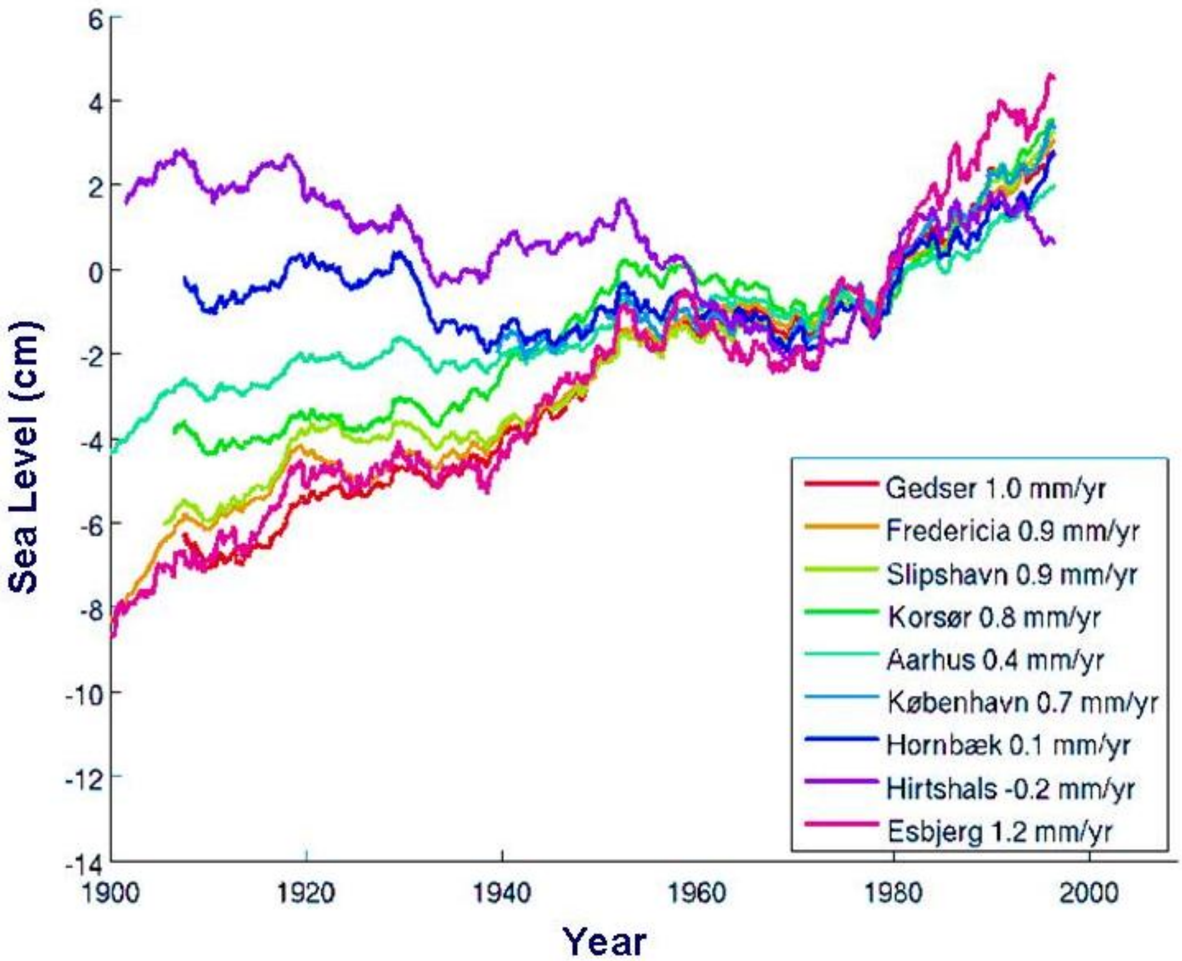

Fig. 10. *Sea level changes measured at 9 stations at Danish harbours. The lower red curves show the general sea level elevation in southern Denmark, where the station Gedser is the nearest to Lolland. The middle green curves are from stations in central part of Denmark, where a general sea level rise of about 5 cm/100 years is regarded to represent the eustatic increase. The upper curve (violet) is from the northernmost station in Denmark, where the relative sea level is depending on glacio- isostatic rebound still on-going in Scandinavia. The diagram is modified after GEUS & DMI (2012).*

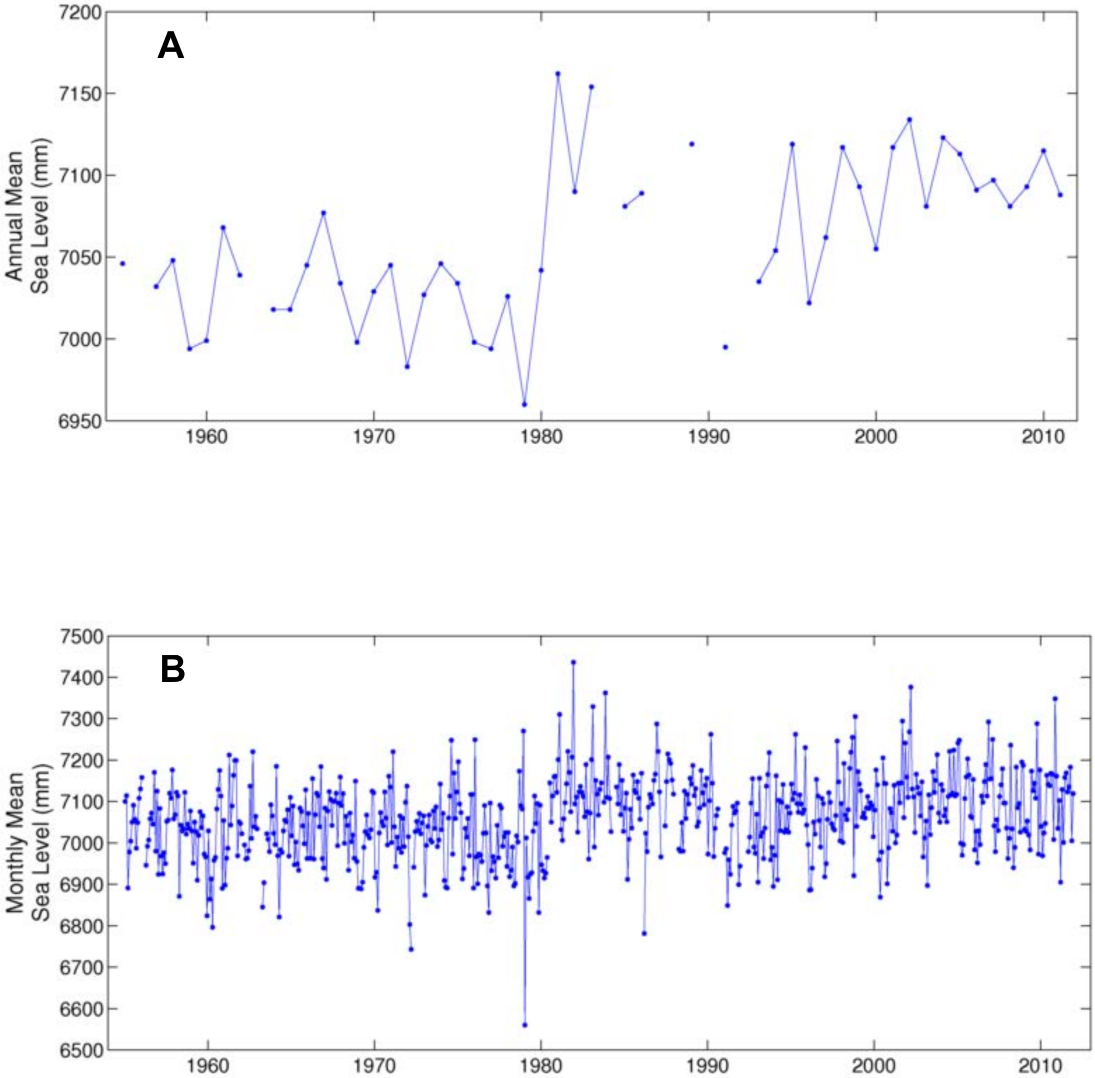

Fig 11. *Measurements of the mean sea level at Rødby Havn on the south coast of Lolland. Diagram A shows the yearly variation over the period from 1900 to 2012. Diagram B shows the average monthly variation in the same more than hundred years' period. Note that a subsidence of 10 cm during this period supports the data in Fig. 10. Data from the International Database of Sea Level Registration.*

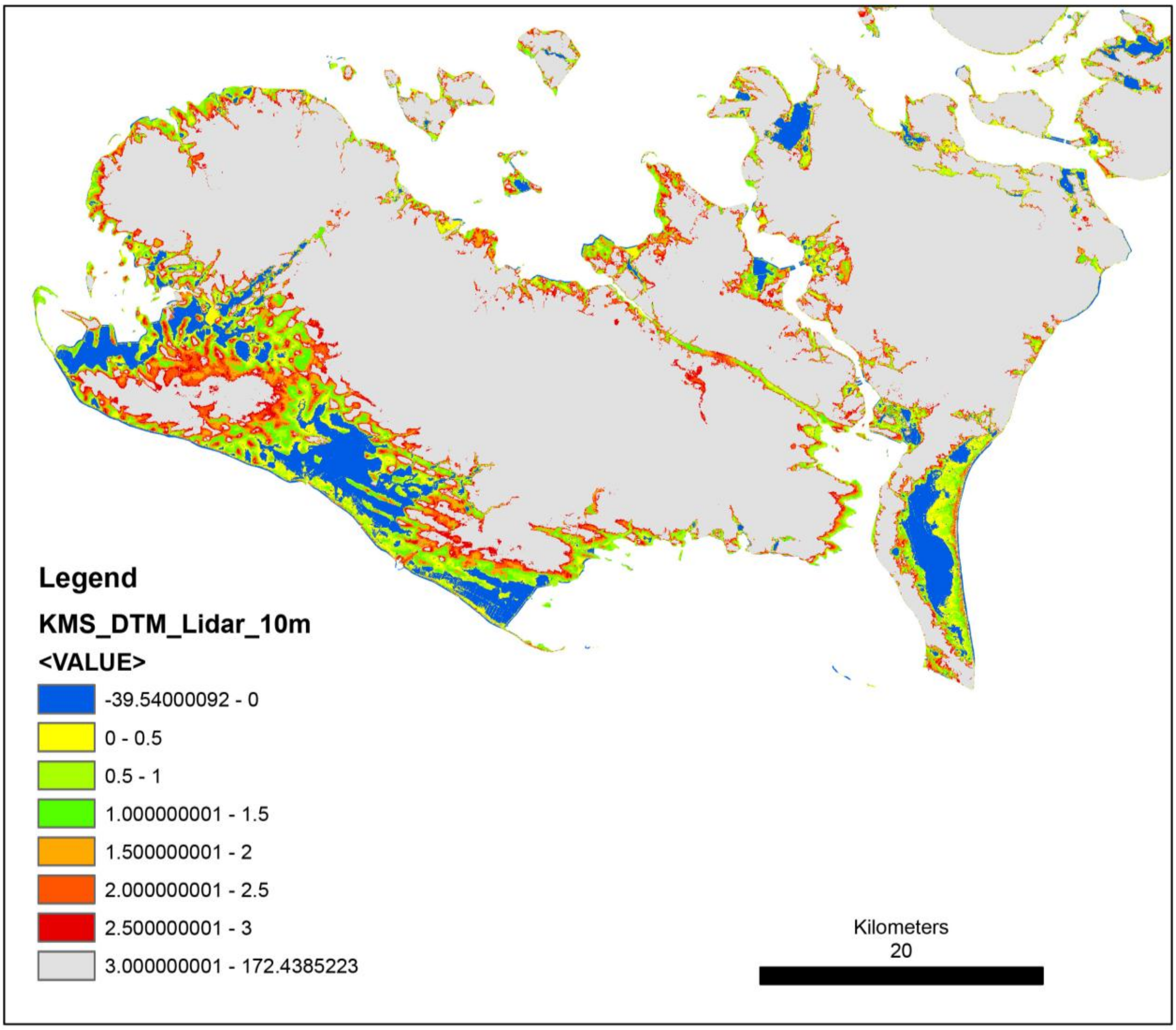

Fig. 12. *Elevation map of the low lying coastal areas. The map is based on Lidar measurements in 10 m grid. The scale for the colour units is in meter.*

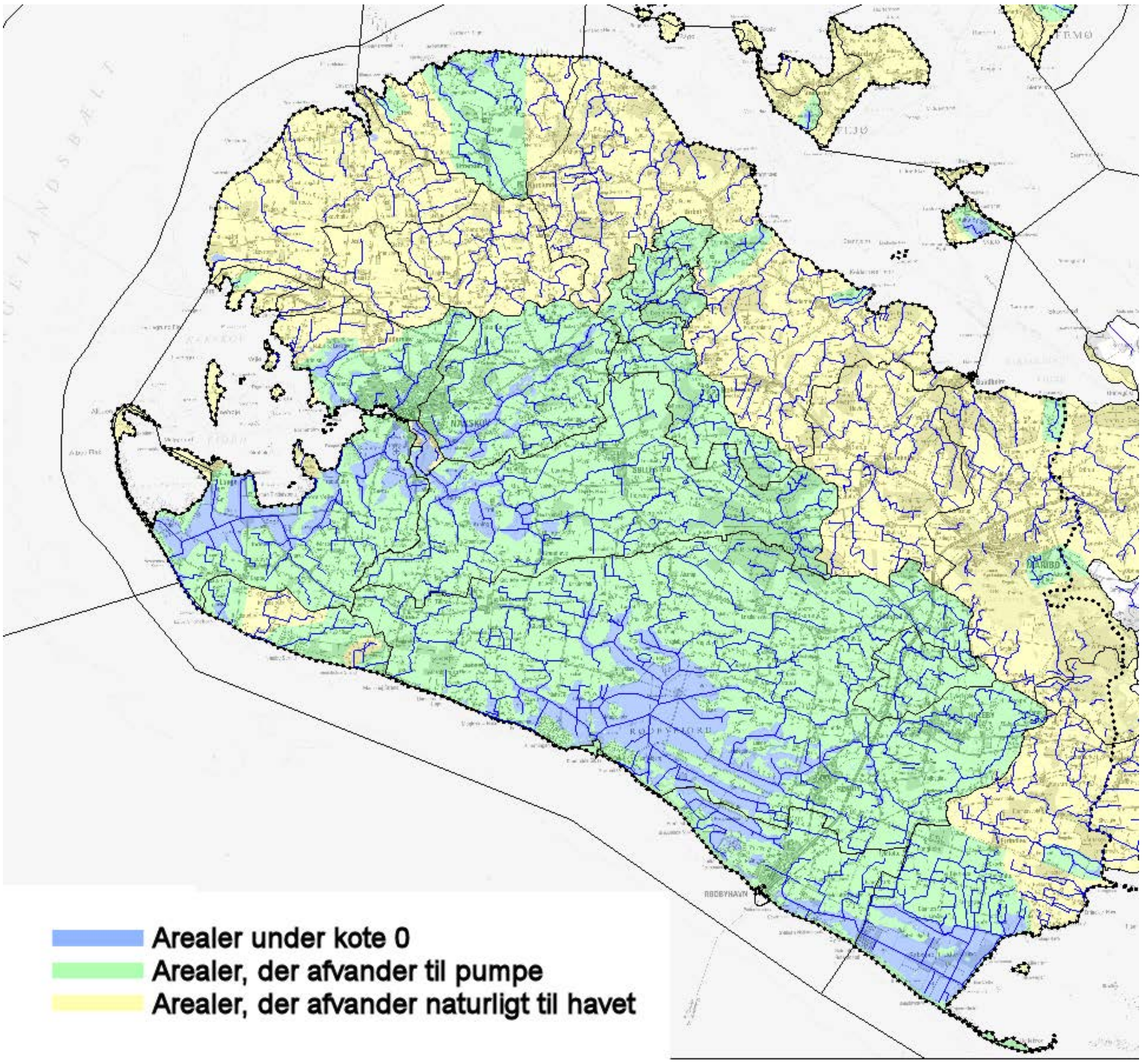

Fig 13. *Map of the drainage condition of the main part of Lolland. The blue colour indicate areas below sea level. The green colour indicates areas drained by artificial pumping. The yellow colour indicates areas, which are drained naturally. The map is copied from the report prepared for LollandKommune by NIRAS 2012.*

In Figs. 12 and 13 the low lying areas of Lolland are indicated. These areas will be the most vulnerable due to the relative sea level rise. Most of the areas comprise farm land and summer cabin areas. Due to the low population and the value of the land (Fig. 14) these areas are not regarded as the most risk assessed sites compared to other subsidence areas. There has not been identified any distinct domains of subsidence that would increase the general risk of flooding. Due to special meteorological conditions in the Baltic Sea local increase of sea level by 2 meters may occur. This was the case in 2006, which harmed a lot of buildings and constructions.

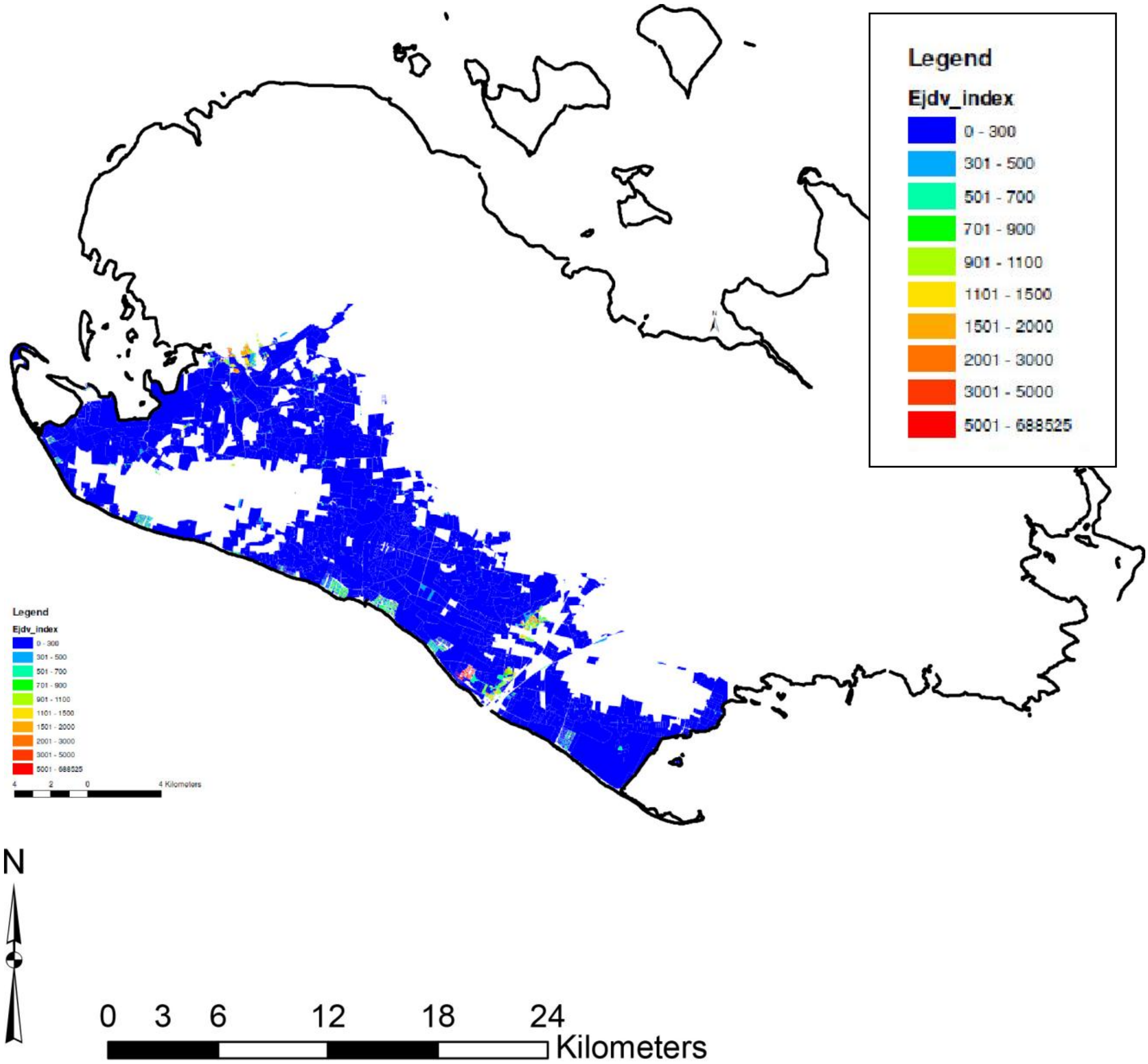

Fig 14. *Map of the cost of areas per m^2 within the geohazard -vulnerable field threatened by flooding on Lolland. The main part of the field constitute farmland, along the coast a number of summerhouse resorts with higher ground prices occur, and in the towns Rødby and Nakskov the price of domestic properties peaks. The map is copied from the report prepared for LollandKommune by NIRAS 2012.*

5. Coastal difference maps

The VHR optical and the TerraSAR-X data were to be acquired for each of the Baltic Pilot areas. TSX data processing included obtaining intensity and coherence images. All these data types should allow the identification of the coastline changes occurring in the pilot areas.

Additionally, coherence images should be used to test their utility for change detection of natural flood barrier protection.

Unfortunately, acquisition of data and their processing met with various problems. VHR data in general have not been obtained. TSX data were possible to obtain only for a period of less than one year (from April to November 2011). Due to the short acquisition time, a sets of data were very difficult to be processed and the results are not satisfactory.

TSX intensity images acquired in less than one year does not allow to gain information of the coastal erosion. However, in some cases it was possible to obtain coastal differences maps using other optical data: archival aerial photographs, archival topographic maps and contemporary orthophotos. Comparison of archival and contemporary optical images together with geological analysis made it possible to obtain information about the changes in pilot coastline areas.

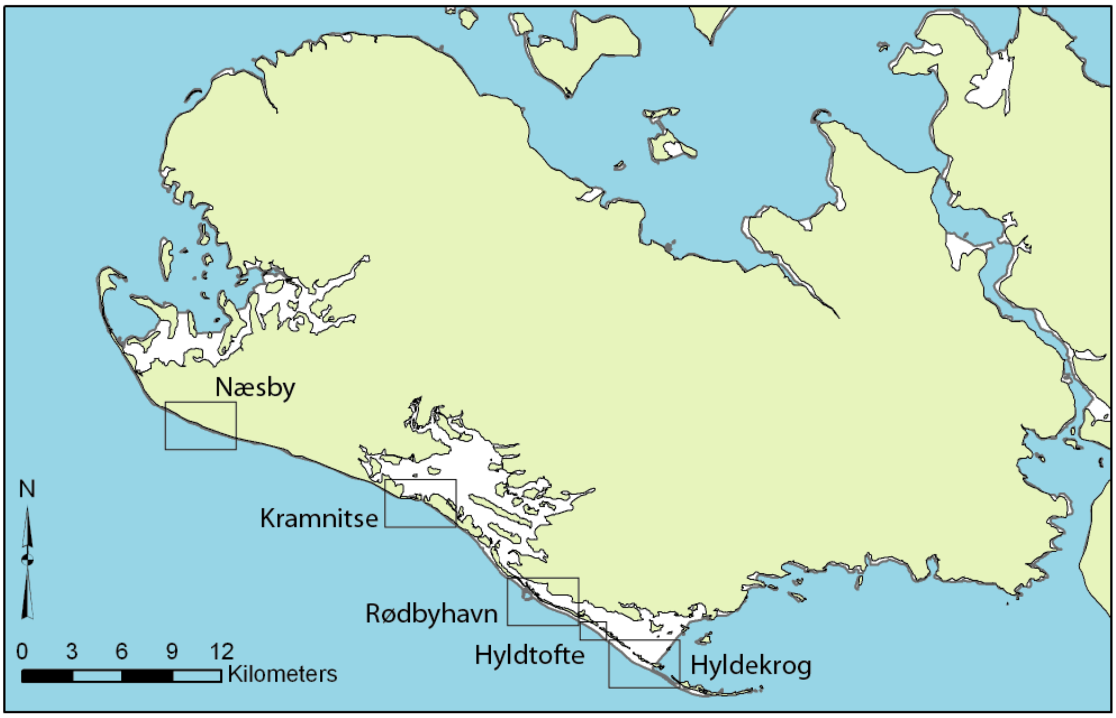

Fig 15. *Map of Lolland showing the outline of the island (green area) before the construction of the dike along the Baltic coast. The white areas are reclaimed land, situated below sea level. Examples of coastal changes from 1942 to present is shown in selected areas indicated by rectangles on the map.*

The coastal difference map is made using topographic maps from 1942, and orthophotos from 2005. A topographic map from 1760 is used to show the general outline of the coasts of Lolland, before the construction of the coastal dike protecting Lolland towards the Baltic Sea.

The most comprehensive change of coastline on the island of Lolland is due to the construction of the dike, protecting the entire SW facing coast line. The dike was build after a storm surge in 1872. The work meant that a series of islands and lagoons on the south coast of Lolland were transformed into a long, straight, reinforced section of coast. The original coastline is outlined on the map in Fig. 14, and it is based on ' Videnskabernes Selskabs kort' (Maps of the Society of Science) from 1760. The accuracy is not good enough to use it to make the coastal difference map, but is outlines very well the areas which were reclaimed after construction of the dike (white areas on Fig. 15).

The coastal difference map is based on Topographic map of Denmark 1:20.000 from 1942 and orthophotos from 2005. Examples of erosion and accumulation of sediments causing changes of the coast line of Lolland are shown in Figs. 16 to 20, where the old coast line, digitized from the topographic map from 1942, is shown with a green line and the present coast line is outlined on the orthophoto from 2005.

The general picture is that erosion occurs along most of the Baltic coast line of Lolland. Sediment transport is from west to east and accumulation occurs along the spit called Hyldekrog (Fig. 15), and sediment is also accumulated on submarine banks in continuation of the Hyldekrog spit. Along most of the coastline erosion is stopped at the foot of the dike, which along long stretches has been reinforced with concrete and stones (Fig. 16). The retreat of the coastline, caused by erosion, is generally between 20 and 40 m in the period from 1942 to present. Locally accumulation occurs along the coast, caused by artificial structures such as harbors.

Fig 16. *Along the Baltic coast the foot of the dike is reinforced along long stretches.*

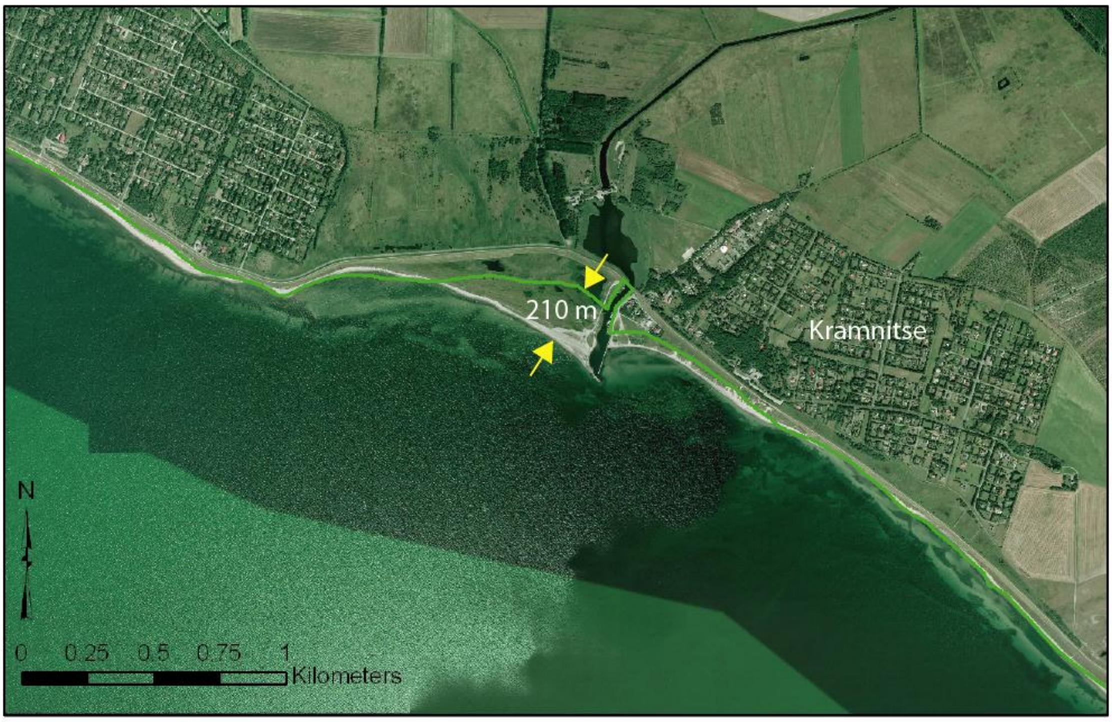

Fig. 17. *The coast line at Kramitse. Accumulation of sediments occur west of the harbour has moved the coast line up to 210 m. (Green line: Digitized coast line from 1942)*

Accumulation is seen, for example, on the west side of Kramnitse harbor (Fig. 17) and on the west side of Rødbyhavn (Fig. 19), where sediment is accumulated because the harbour blocks littoral drift. East of Rødbyhavn the coast line is eroded 30 to 37 m inland and it is stopped by reinforcement of the dike (Fig. 16, 18, 19).

In a few places coastal defences has been build, to protect the coast from erosion. At Næsby erosion has generally occurred along the coast (Fig. 18). In front of the summer cottage village Næsby breakwater construction has been build to protect this stretch of coast from erosion. Furthermore, beach nourishment is carried out at this stretch. The same coastal defence strategy is used at Hyldtofte (Fig. 20).

Accumulation occurs at the Hyldekrog Spit, which used to be a series of barrier islands. Now it has been transformed into a spit growing out from the south-eastern part of Lolland towards east (Fig. 21) (Green line: Digitized coast line from 1942).

Fig 18. *The coast line at Næsby. In front of the summer cottage village Næsby coastal defence structures and beach nourishment protects the coast line from erosion (Green line: Digitized coast line from 1942).*

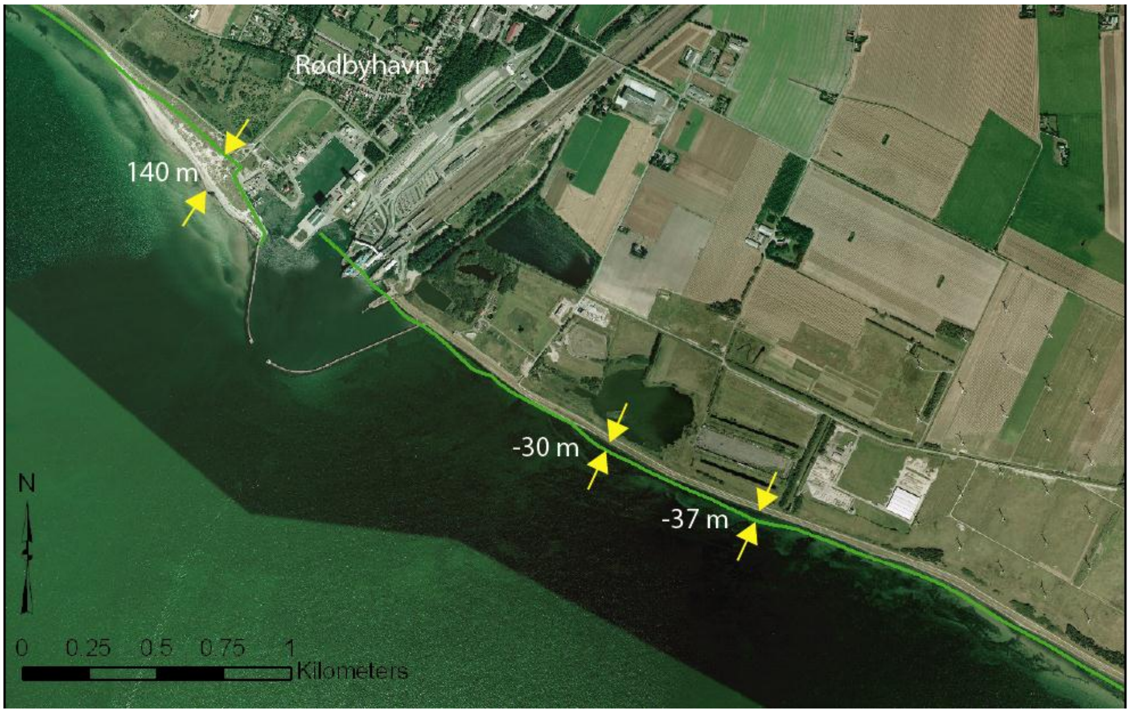

Fig. 19. *At Rødbyhavn Accumulation of sediments has moved the coast line 140 outwards just west of the harbor. East of the harbor the coast line has retreated 30 to 37 m due to erosion. The erosion is stopped by reinforcement of the dike (Fig. 14) (Green line: Digitized coast line from 1942)*

Fig. 20. *At the coast line at Hyldtofte there is also coastal defence structures and beach nourishment is carried out to protect the coast line from erosion in front of the summer cottage village.*

Fig 21. *The Hyldekrog Spit used to be a series of barrier islands. Sediment accumulation has transformed the barrier islands into a spit, stretching out from the south-eastern part of Lolland (Green line: Digitized coast line from 1942).*

6. Earthquake risk

In general the earthquake risk is rather small in Denmark. The main magnitude of earthquakes is smaller than 3 on the Richter scale. The strongest earthquake was recorded in 1841 with a magnitude of about 6, located in northern Jutland. The epicentres are located along the fault trends following the Törnquist—Sorgenfrei Wrench Fault Zone (Fig. 22). Earthquakes are more frequent in Scania and south of here in the Baltic Sea, in the southern part of Kattegat and in the Skagerrak between Denmark and Norway. Lolland may be regarded as an earthquake-quiet area (Fig. 22), since no earthquakes have been recorded in the period from 1930, when the systematic registration of earthquakes in Denmark was initiated.

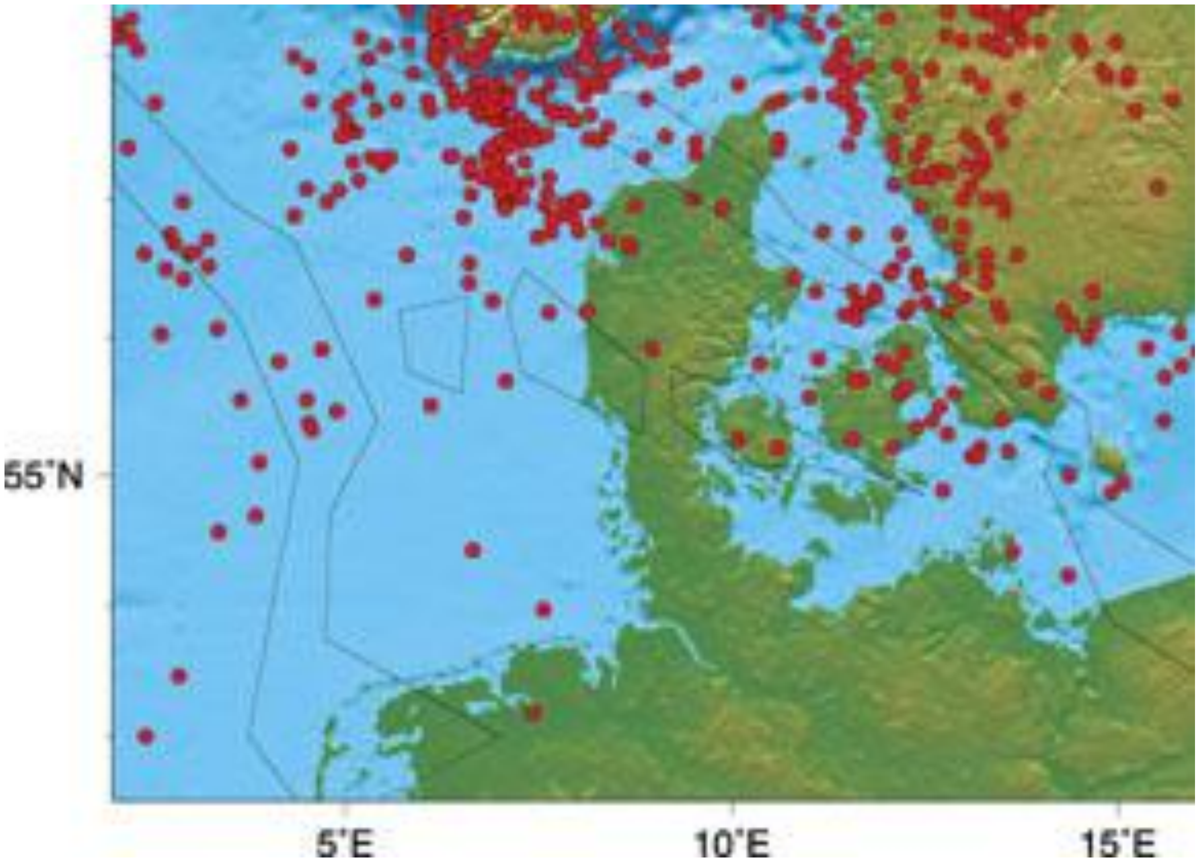

Fig. 22. *Distribution of earthquake epicentres in Denmark. The data have been collected systematically since 1930, and the strongest earthquake recorded was about magnitude 6 appearing in 1841. The epicentres are mainly located along the fault systems related to the Törnquist-Sorgenfrei Wrench Fault Zone. However, the risk of earthquakes at Lolland is very small as seen from the map where no earthquakes have been recorded from the area.*

7. Neotectonics at Lolland

The bedrock in the subsurface of Lolland was strongly affected by fault deformation from the Triassic until the middle Cretaceous (Pedersen et al. in press) (Fig. 23). During the Late Cretaceous the Chalk Group was deposited discordantly above the fault structures, and in the Tertiary time only weaker displacements affected the Cretaceous chalk and overlying Danian limestone and older Quaternary deposits. Tectonic wrenching along the Törnquist-Sorgenfrei Zone is one cause for the displacement, which due to resent investigation in the Femern Belt is recognised to have been active with tens of meters of displacement during the Eocene (-Miocene?). Glacio-isostatic adjustments are another cause for differential movements in the scale of less than few tens of meters. During the Elsterian and Saalian glaciations the ice covers are regarded to have been of considerable thickness sufficient thick for inherited displacements along the faults during loading and rebound after melting back.

At present the southern part of Lolland is regarded to subside. With the newest adjustments of the levelling in Denmark, which constitute a correction of fix-points established 100 years ago, the fix-points in southernmost part of Lolland have been corrected with 9 cm subsidence, partly due to sea level rise (5 cm/100 years) and partly due to subsidence related to the Femern Belt depression in the Baltic Sea.

The best documented neotectonic subsidence is the normal fault displacement along the Maribo fault (Fig. 23). The block to the south was downthrown for about 20 m, which resulted in the depression that became the location of the lakes at Maribo (Maribo Søerne). Due to the analysis of the PSI data a few areas are indicated to be locus of subsidence. However, no regional subsidence along the south coast of Lolland can be documented, and geohazards caused by neotectonic activity is not obvious.

Fig. 23. *Fault lineaments displacing the bedrock at Lolland. The faults partially control the destribution of the Quaternary deposits as well as some of the geomorphic features of Lolland and the islands in the Smålandsfarvandet. The general displacement of the fault block is a down-thrown off set down to the south towards the Femern Belt, which is located above the south dipping northern slope of the North Germany Basin. Modified after Pedersen & Rasmussen (2000), Klint & Rasmussen (2004, 2012), Gravesen et al.(2011).*

8. Summary

This report documents the detection of recent terrain subsidence on Lolland using persistent scatterer interferometry processing of satellite radar scanning data. The results of the analysis of the PSI data have been compared to the back ground knowledge about the geological setting of Lolland and the physiographic condition of the conditions along the southern coast line, which particularly has been the focus for flooding threatened areas subjected to tectonic or compactional subsidence.

The PSI data show local subsidence in areas with constructions over old peat filled areas. This is the case east of Rødby Havn, in northern part of Nakskov and western fringe of Maribo. The magnitude of subsidence is here 2–4 mm/ year. Furthermore the GIS-analysis of the PSI data indicate local subsidence along the Maribo Fault and the central Lolland fault, mainly concentrated in the eastern part of Lolland. The order of this subsidence is 1–3 mm/year. A few spots in the vicinity of Rødby demonstrate elevation of about 2-3 mm/year, which could be due to inherited displacements in the salt diapir in the subsurface below the village Rødby.

9. References

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