Estimating Affected Croplands and Potential Crop Yield Loss of an Individual Farmer Due to Floods

Shima Nabinejad, Holger Schüttrumpf

Abstract**—**Farmers who are living in flood-prone areas such as coasts are exposed to storm surges increased due to climate change. Crop cultivation is the most important economic activity of farmers, and in the time of flooding, agricultural lands are subject to inundation. Additionally, overflow saline water causes more severe damage outcomes than riverine flooding. Agricultural crops are more vulnerable to salinity than other land uses for which the economic damages may continue for a number of years even after flooding and affect farmers' decision-making for the following year. Therefore, it is essential to assess what extent the agricultural areas are flooded and how much the associated flood damage to each individual farmer is. To address these questions, we integrated farmers' decision-making at farm-scale with flood risk management. The integrated model includes identification of hazard scenarios, failure analysis of structural measures, derivation of hydraulic parameters for the inundated areas and analysis of the economic damages experienced by each farmer. The present study has two aims; firstly, it attempts to investigate the flooded cropland and potential crop damages for the whole area. Secondly, it compares them among farmers' field for three flood scenarios, which differ in breach locations of the flood protection structure. To achieve its goal, the spatial distribution of fields and cultivated crops of farmers were fed into the flood risk model, and a 100-year storm surge hydrograph was selected as the flood event. The study area was Pellworm Island that is located in the German Wadden Sea National Park and surrounded by North Sea. Due to high salt content in seawater of North Sea, crops cultivated in the agricultural areas of Pellworm Island are 100% destroyed by storm surges which were taken into account in developing of depth-damage curve for analysis of consequences. As a result, inundated croplands and economic damages to crops were estimated in the whole Island which was further compared for six selected farmers under three flood scenarios. The results demonstrate the significance and the flexibility of the proposed model in flood risk assessment of flood-prone areas by integrating flood risk management and decision-making.

Keywords**—**Crop damages, flood risk analysis, individual farmer, inundated cropland, Pellworm Island, storm surges.

I. Introduction

ECONOMIC assessment of flood damages has been increasingly paid attention by decision makers since it helps them to take policies with the aim of protecting flood-prone areas and/or reducing the damages. Avoiding expected losses may have a major impact on decisions regarding technical flood protection or even economic activities. The latter is of high importance for farmers especially those living in the coastal regions since coasts are threatened by sea level rising and storm surges which have been increased in recent years due to global climate change [1], [2]. More important is the large amount of saline water that enters into the area in the time of flooding. As a result, croplands may be inundated and the crops cultivated are damaged depending on their tolerance against salt stress. Therefore, it would be of interest to estimate the inundated cropland and associated crop yield loss for each farmer.

Most studies have considered agriculture as a whole sector in their flood risk analysis [3], [4]. One of the disadvantages regarding to this approach is to develop only one depth-damage curve. Thus, they calculate flood damages based on water levels without paying attention to differences between vulnerability of agricultural components. To overcome these drawbacks, there has been a major emphasis on influential flood parameters on agricultural components [5]-[8]. Although the above-mentioned studies provide valuable insights regarding to agricultural damages, it seems to us, an important step is still missing in order to consider farmers as the central decision makers of agricultural sector and damages they experience. Thus, there is a key need to equip each individual farmer with valuable information regarding crop yield losses. Taking all into account, the goal of this study is to establish a model based on farmers' decision-making and flood risk analysis which can provides each individual farmer with negative consequences associated with flooding. The structure of this paper is as follows: Section II presents an overview of the research methodology, important factors related flood damages to agriculture, and the study area. Results and discussion are presented in Section III followed by the conclusions section.

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II. Methodology

A. Flood Risk Analysis

In order to focus on the damages and risk resulted from flood as a natural disaster, an analytical approach is required, which combines the hazard properties with the vulnerability of the elements exposed to flooding. A holistic flood risk analysis not only provides information and quantifies probabilities of flood, but also identifies the consequences by integrating four main components, namely, structural failure analysis, hydrodynamic analysis, analysis of consequences and risk for the area under study. In this framework, both structural and non-structural measures are taken into account.

While the former protect the area by reducing the probability of flooding, the latter involves human-flood interactions that may either be influenced by flood or have an impact on that.

Taking its advantages, we investigated inundated lands and associated damages experienced by each farmer in the framework of flood risk analysis as a comprehensive approach. It should be noted that, although farmers face harm in different aspects such as livestock, infrastructure, and crops in time of flooding, the focus of this study is to assess damages to crops cultivated by them due to storm surges.

B. Flood Damages to Agriculture

According to [9], [10], economic damages to agriculture can be classified into direct and indirect as well as instantaneous and induced damage. Thereafter, four different categories of damage can be recognized while crop losses and yield reduction are accounted as direct instantaneous damage occurring immediately after floods.

In economic terms, the severity of flood damage to various sectors depends on the hazard parameters and the vulnerability of the sectors. To quantify this relationship, depth-damage curves have been developed for various land use categories in which water depth on the floodplain is the most important factor. However, damage to crops is highly related to the time of flooding due to their growing cycle. Additionally, coastal regions are exposed to storm surges containing salt water. Therefore, salinity and time of flooding should be also taken into consideration as essential parameters in vulnerability evaluation of crops in the coasts.

C. ProMaIDes Description

ProMaIDes (Protection Measures against Inundation Decision Support) is a decision support system which was primarily developed for flood risk assessment in river basin areas at the Institute of Hydraulic Engineering and Water Resources Management (IWW, RWTH Aachen University) [11]. After that, the software was adapted to be applied for flood risk management in coasts [12].

One of the advantages of ProMaIDes is to integrate the main components of flood risk analysis described previously. Therefore, it helps user to select the most preferred flood protection measure according to risk criteria and associated costs for measures' implementation. Fig. 1 illustrates the modular program package ProMaIDes.

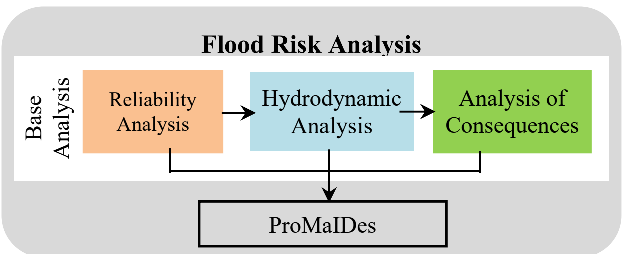

Fig. 1 Modular program package ProMaIDes and the implemented modules

D. Study Area

The study area of this research is Pellworm Island which is located in the German Wadden Sea National Park and accounted as the coastal regions of North Sea. Two severe floods, which occurred in 1362 and 1634, resulted in the deaths of many people and separation of Pellworm Island from Alt-Nordstrand. Today, this island is a municipality of the Schleswig Holstein state and Nordstrand, Hallig islands and Eiderstedt are its adjacent entities. The area of the island is 37 km^2 and it has a population of about 1158 inhabitants. The mean height of land above sea level is 0.23 m, and a 28 km sea dike with the height up to 8.8 m protects the area. Nowadays, the area of the Island is mostly covered by agricultural land and agriculture and tourism are the most important economic sectors. Fig. 2 shows the Pellworm Island and its location.

III. Results and Discussion

A. Hydrodynamic Analysis and Inundated Croplands

A 100-year storm surge hydrograph was selected as a hypothetical flooding event along the coast for the hydrodynamic simulation as shown in Fig. 3. In this study, the selected scenarios differ in the number of breach locations which are chosen based on breach development in vulnerable sections of the sea dike and the maximum width of the breach is set to 150 m. For this aim, two breaches located at the south-west coast (distance of 160 m from the initial point) and north coast of Island (distance of 239 m from the initial point) were implemented within ProMaIDes. As a result, three scenarios were developed including scenario 1 (breach at the south-west coast), scenario 2 (breach at the north coast), and scenario 3 (two dike breaches).

The topography of the area is another input which was prepared as a 50m resolution digital elevation model (DEM) in the projected coordinated system 'DHDN_3_Degree_Gauss_Zone_3' and then fed into the developed flood risk model for reliability analysis. The DEM map of the Pellworm Island is illustrated in Fig. 4. Geometry and material of the flood protection measure is also of high importance in reliability analysis, which were imported to ProMaIDes.

Preparing the required input data, the hydrodynamic analysis was performed. Figs. 5 and 6 illustrate the inundated areas under scenario 1 and scenario 3, respectively. Results of the hydrodynamic analysis for scenario 1 shows that 16.2 km^2 of the total area of the Pellworm Island is flooded with the mean water depth 0.60 m while the maximum water depth on the flood plain is about 1.55 m. Under scenario 2 in which dike breach is located in 239 m from the initial point (north of Island), inundated area, mean and maximum water depth on the flood plain were computed 16.68 km^2, 0.58 m, and 1.95 m, respectively. As expected, the inundated area in scenario 3 (two dike breaches) has been increased to 25.48 km^2 with the maximum water depth 2.1 m and average water depth 0.64 m on the flood plain.

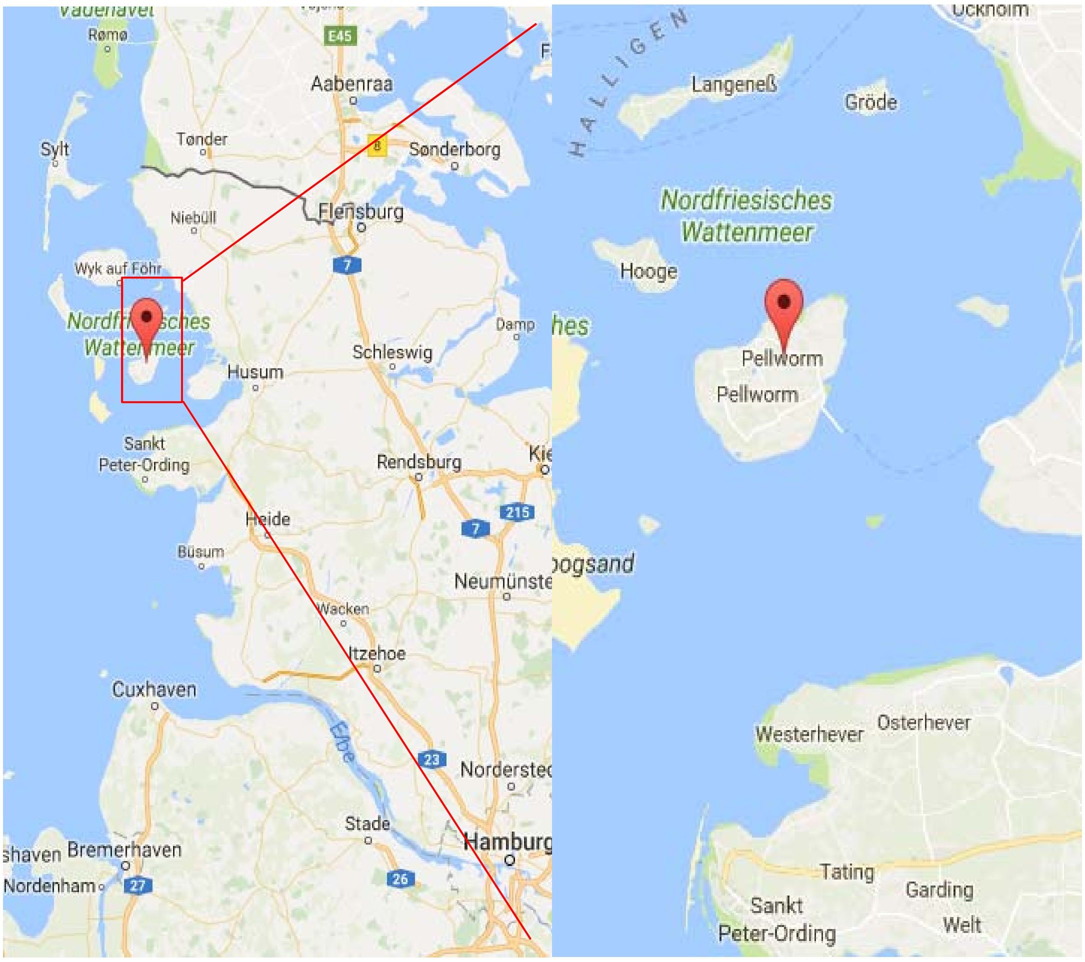

Fig. 2 Pellworm Island in Northern Germany

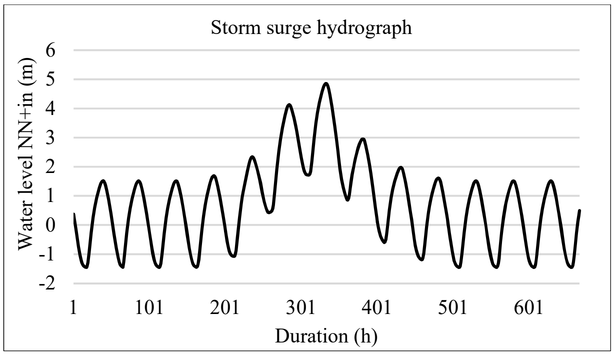

Fig. 3 Storm surge hydrograph with a 100-year return period

B. Analysis of Consequences and Farmers' Crop Damages

To estimate the flood damages to crops, various input data are required. Since the aim of our study is to investigate the extent of flooding in croplands and the associated crop damage to each famer, it is essential to prepare the land use map containing crop patterns in the area. Therefore, spatial distribution of farmers' fields and the cultivated crops were prepared in ArcGIS and projected in the coordinated system 'DHDN_3_Degree_Gauss_Zone_3'. Four crops, spring canola, corn silage, spring barley, and winter wheat were cultivated in time horizon 2010-2012 on the island, as reported by [13].

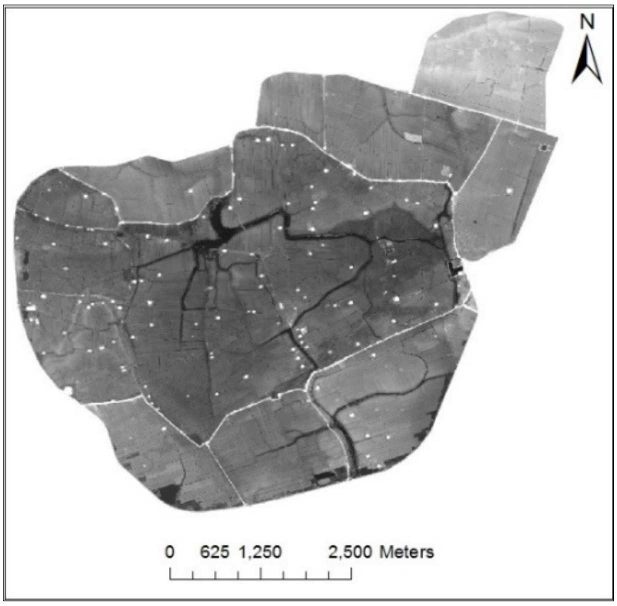

Fig. 4 Topography of Pellworm Island in ArcGIS

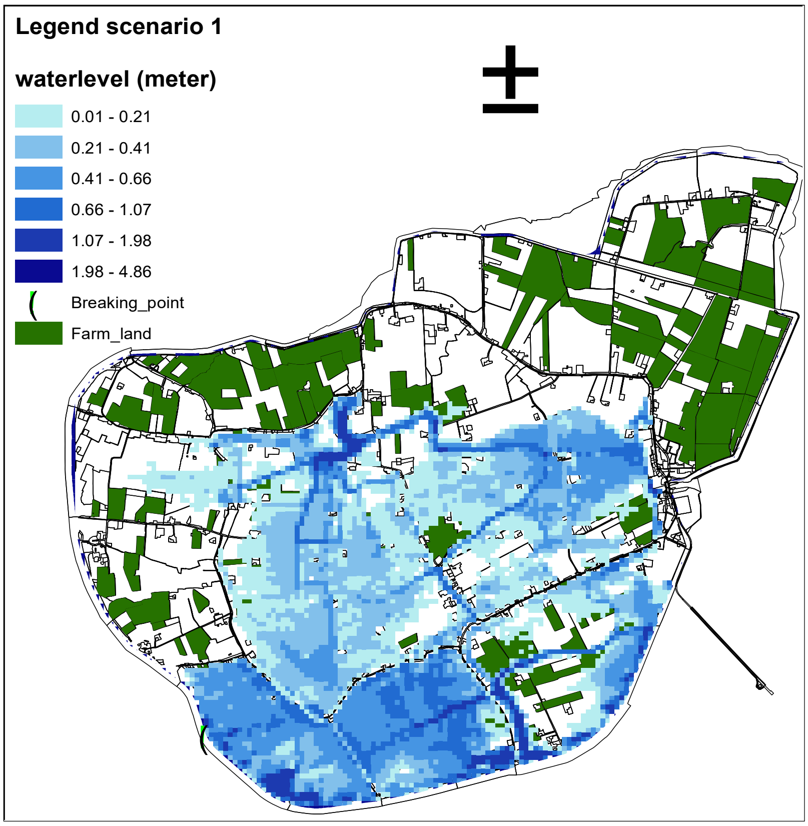

Fig. 5 Water depths for Pellworm Island under scenario 1

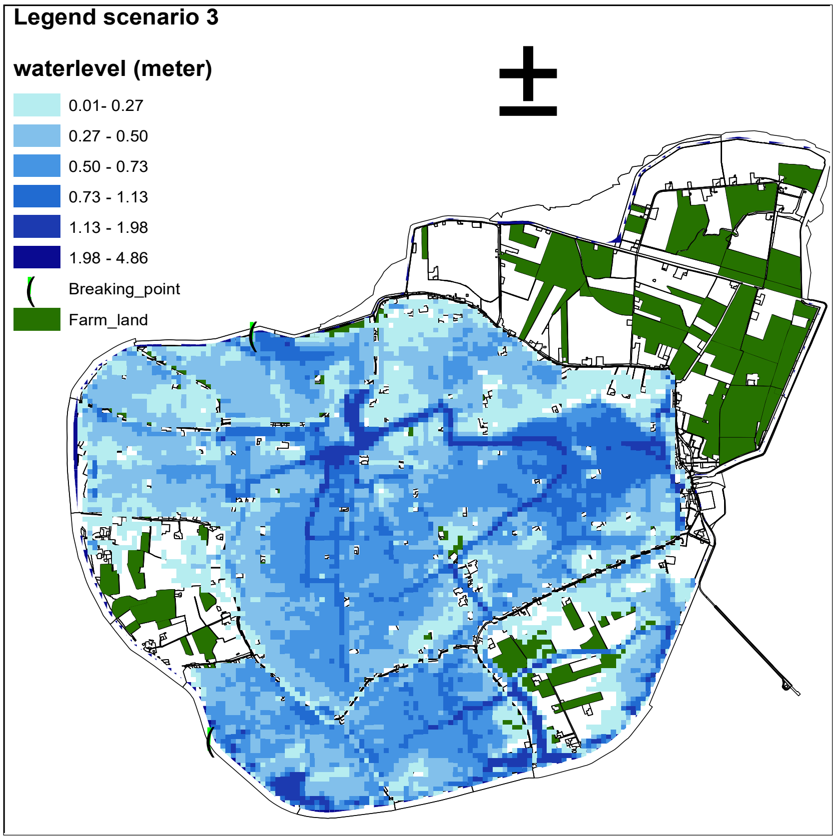

Fig. 6 Water depths for Pellworm Island under scenario 3

The monetary values of the crops were calculated based on the potential crop yields, sale price and other additional costs [14]. It should be noted that potential crop yield can be achieved under ideal growing condition such as no water and nutrient stress. According [13], the average North Sea water salinity is 44 mS/cm that causes 100% loss of crops cultivated in the agricultural land of the coast.

Figs. 7 and 8 show the potential economic damage to agricultural crops for scenario 2 and scenario 3, as examples. The cell grids of the land use map have a size of 25 m × 25m and consequently, computed damages have been reported on the cells as seen in the Figs. 7 and 8. It can be observed that spatial distribution of damaged croplands highly depends on whether they are located in the inundated areas under each scenario or not.

As expected, more crops are lost under scenario 3 since more areas are flooded and the water depths are higher. The evidence to support this claim is the Total amount of potential economic damage to crops which are about €201,694 and €287,553 for scenario 1 and scenario 2, respectively. In contrast, scenario 3 leads to higher potential damage of about €426,773 on the island.

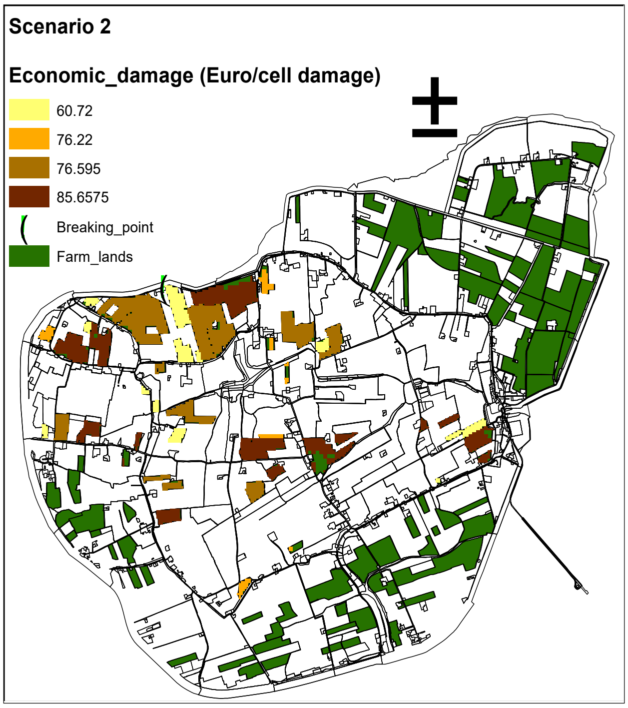

Fig. 7 Spatial distribution of crops economic damages for scenario 2

To investigate the potential economic damage experienced by each individual farmer, we selected six farmers whose lands are located in different parts of Pellworm Island, as illustrated in Fig. 9.

Fig. 10 compares potential crop loss damage (€) for the selected individual farmer. It can be seen that farmer 5 never experiences flood damages, whereas farmer 1 suffers from all three scenarios and the damage is independent of the scenario. The reason is that his cropland is located in the center of the island and is flooded under all three scenarios. In comparison to other farmers, crop loss damages to farmer 6 vary for three scenarios; scenario 1 leads to €58,125 of potential economic damage to farmer 6 whereas he experiences more potential damages under scenario 2 (€116,875) and scenario 3 (€142,500) which reveals different percentages of inundated cropland under three scenarios.

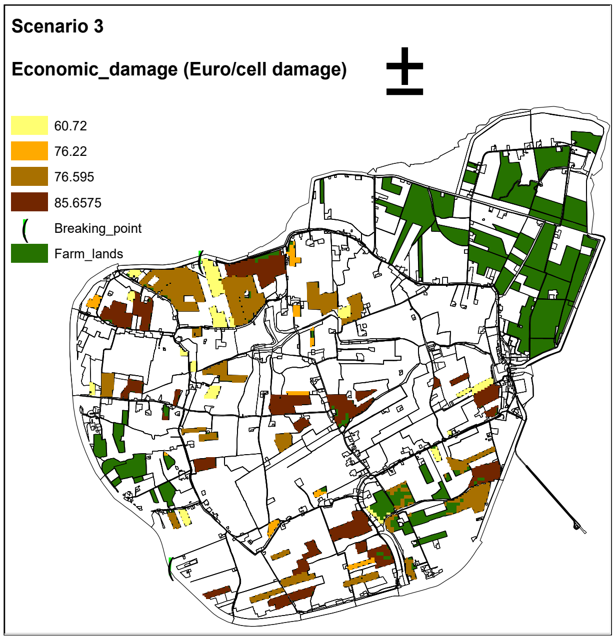

Fig. 8 Spatial distribution of crops economic damages for scenario 3

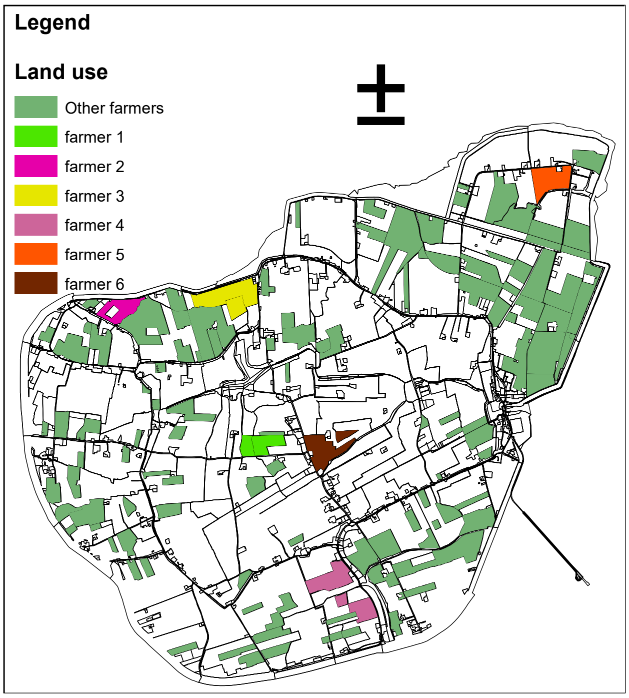

Fig. 9 Crop lands of the six selected farmers

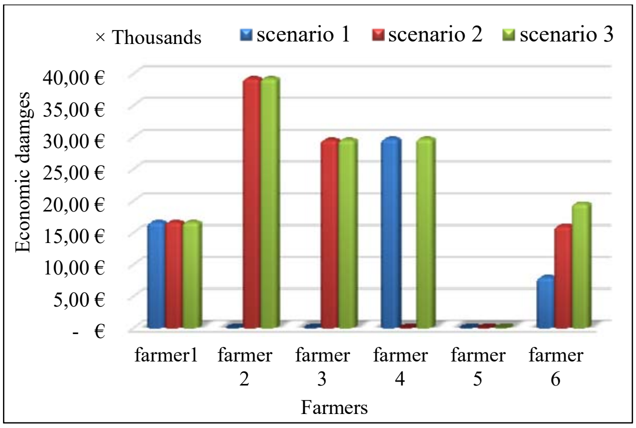

Fig. 10 Crop loss damage of individual farmer under various scenarios

In Table I, the flooded areas of all six farmers are compared for the three mentioned scenarios. As seen, except for farmer 1 whose cropland has been completely inundated under all scenarios, the others experience various inundated situations based on the location of their land.

TABLE I
INUNDATED AREA OF FARMERS' CROPLAND FOR VARIOUS SCENARIOS

Framer-id	Crop	Field area (m^2)	Inundated area (m^2) Scenario1	Scenario2	Scenario3
Farmer 1	Winter Wheat	121250	121250	121250	121250
Farmer 2	Winter Wheat	326093	0	320000	320000
Farmer 3	Maize	237293	0	215625	215625
Farmer 4	Winter Wheat	227780	216875	0	0
Farmer 5	Winter Wheat	146970	0	0	0
Farmer 6	Spring Barley	163606	58125	116875	142500

IV. CONCLUSION

Agricultural lands located in flood-prone areas are highly exposed to flooding. Especially those in the coastal regions suffer from salt content in seawater transformed by storm surges. As a result, farmers whose fields are inundated will experience crop yield loss or reduction which may be continued even in the following year. To protect the cropland or adjust farm activities in the flood-prone areas by farmers, it is essential to estimate the area of submerged field of each farmer and the associated crop damages. For this goal, we established a flood risk framework which is equipped with spatial distribution of crop patterns as farmers' decision making in the previous year. Therefore, it enables us to do a micro-scale flood risk analysis. Taking the Pellworm Island in North of Germany as the study area, we analyzed and compared how much of the cropland of each individual farmer is inundated and how much damage he has experienced. Three flooding scenarios were developed consisting of the 100-year storm surge hydrograph and two probable breach locations in distance of 160 m and 239 m in the sea dike. The inundated croplands were shown for three scenarios and the spatial distribution of crop loss damages were presented for the whole island. To identify economic damages to individual farmers, we chose six farmers whose land are located in various parts and compared their experienced damage (€) and flooded area for flooding scenarios. The key advantage of this study is to provide information for bottom-up decision-making problem to prevent or reduce flood damages. In the ongoing research, the calculated economic damage of each individual farmer is being applied for the decision-making process to investigate human-flood interaction in the frame of an Agent Based Model.

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