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Tracking cliff activity based on multi-temporal digital terrain models – an example from the southern Baltic Sea coast

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Abstract. A multi-temporal digital terrain models [DTM] study of a coastal cliff section at Kaszuby Coast (northern Poland) is presented in this paper. The analytical study was based on five LiDAR-derived DTM acquired between 2010 and 2016. The main idea was to compare changes year by year or every two years (depending on the available material). The DTM were analysed using various geoprocessing techniques, and as a result the map of slope and the gradient of maximum changes in z-value were prepared. The analysis of the temporal variations of these parameters were also prepared and allowed to visualize and track the landslides that occurred within the cliff. What is more, the areas of sediment increasement and decreasement, as well as the average rates of vertical displacement within the landslides and sediment balance on the beach were estimated. The studies allowed also to discuss the interrelation between the mass wasting processes and the protective infrastructure on the seashore. The information gathered allows us to find the mechanisms and development of landslides on the steep cliff coast.

Keywords: *cliff coast; landslide monitoring; northern Poland; land-sea interaction*

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INTRODUCTION

The coastal zone of the sea is a place of special interest in natural, economic, tourism or cultural aspects (Charlier 1989; Schenewski, Schiewer 2002; Onofri, Nunes 2013; Bertina *et al*. 2015; Schluter *et al.* 2018). Therefore, attempts are made to map this area with the most accurate and corresponding to the particular requirements way. A different approach results from the natural conditions of the coast, expressed by different types of coast, as well as from the purpose of imaging (Meyer *et al.* 2008; Foyle, Naber 2012; Furmańczyk *et al.* 2014; Paprotny *et al.* 2014; Bagdanavičiute *et al.* 2015; Bugajny, Furmańczyk 2017; Deng *et al.* 2017; Grilli *et al.* 2017). Different methods are used to assess geohazards and others to assess economic potential. Among all types of coasts, the steep, cliff coasts, through the most spectacular transformations and difficulties they pose, find a particular research interest. Cliffs worldwide are subjected to various analyses and monitoring (e.g. remote sensing, geoengineering, hydrogeological, nature evaluation, risk assessment, etc.) (Young *et al.* 2009; Quinn *et al.* 2010; Montoya-Montes *et al*. 2012; Joyal *et al*. 2016; Kuhn, Prüfer 2014; Grilli *et al.* 2017; Jaeger *et al.* 2018; Prémaillon *et al.* 2018). These methods, inevitably, are aimed at quantitative and qualitative mapping of the past, existing and sometimes future situation. Within the coastal zone of the Baltic Sea, all the above assumptions are reflected.

The coastal zone of the southern Baltic Sea is subject to continuous natural processes caused by numerous factors, among which the main place should be attributed to the diversity of geological conditions both inland and offshore. Therefore, the research tasks directed at visualization of coastal changes are conducted by a number of studies aiming at the most-accessible and appropriate presentation of natural spatial and temporal data.

In many cases, an extended remote sensing analysis, which involves the implementation of multi-temporal digital terrain models is applied (Dewitte *et al.* 2008; Ventura *et al*. 2011; Joyal *et al.* 2016; Burvingt *et al.* 2017). An undoubted advantage of this method is the ability to track changes in a time-varying period. So, the aim of the study is to visualize the temporal and spatial changes within the cliff section of the part of the Kaszuby Coast, where on the basis of LiDAR data multi-temporal DTM were prepared showing the cliff top position and height differences in the coastal zone in 1–2 year cycles (between 2010–2016). The obtained multi-resolution models: (I) inform about the trend of changes that occur on particular sections of the coast, (II) enable a certain general parametrization of these changes for hazard assessment purposes, (III) inform about maximum average rates of vertical changes, and (IV) inform about certain internal landslide forms (e.g. step, scarp, crown).

MATERIALS AND METHODS

Study area

The study area is located in the northernmost part of Poland and covers an area of morainic upland, the Kępa Swarzewska (Fig. 1). The upland within the area of interest borders the Baltic Sea to the northeast. The section of the studied coast stretches over a distance of approximately 3.8 km and is located between 18°20’05” and 18°22’40” E. The coastline in this area runs from NW to SE in the vicinity of Rozewie headland and Chłapowo village. The cliff coast in the area under discussion reaches a height from a dozen of

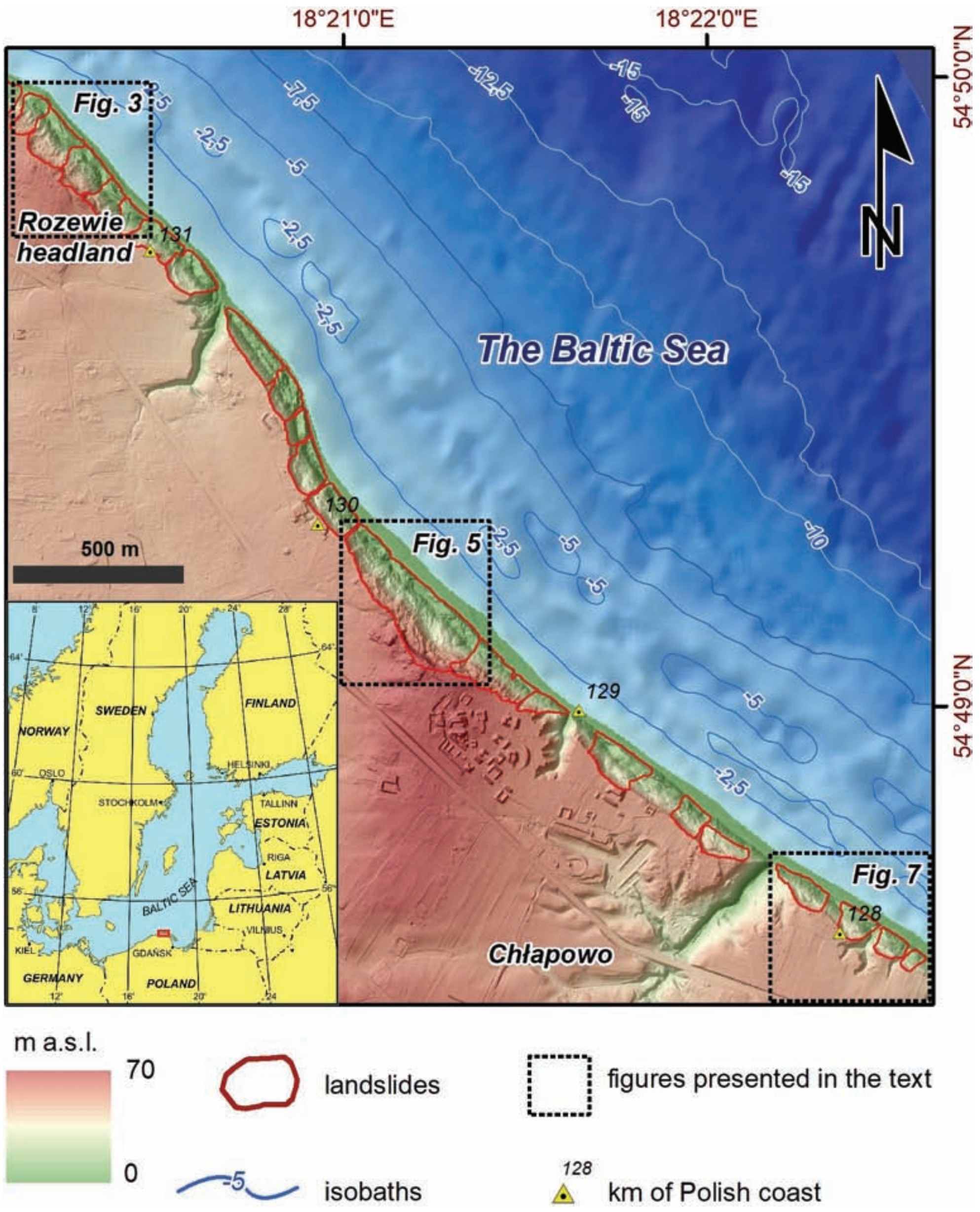

Fig. 1 Location of the study area

metres to 67 m. The edge of the upland is dissected by deep erosional ravines in several places. It extends down to sea level. The edge of the upland is almost completely free of watercourses. The ravines are only periodically, partly filled with water which flows to the sea or infiltrates into the beach sand.

The geological setting of this area closely matches its morphological feature. The surface of the upland is mainly built of Pleistocene till and sand partly covered by Holocene aeolian sand. The oldest deposits cropping out in the cliff face are of Miocene age. The geological conditions of Kępa Swarzewska upland were described several times. Thus, for a detailed information about geological conditions of the area of interest the reader is directed to the papers of Pawłowski (1922), Rudowski (1965), Kramarska (1999), Masłowska *et al.* (2002), and Uścinowicz *et al.* (2014, 2017).

For the purpose of this work, more important is the geohazard characteristic of the area. The works aimed at landslide study were carried out in various ways by numerous scientific units in different periods. However, the complementary and lasting since 2015 studies conducted by the Polish Geological Survey have documented a continuous occurrence of mass movements at different scales — from simple to genetically and morphologically complex forms (Uścinowicz *et al.* 2017). The mass movements have a repetitive pattern — the complex landslides alternate in space with simple landslides (e.g. Rozewie headland and area of Chłapowo village are the places of complex landslides occurrence). These specific areas are presented on Fig. 1.

Digital terrain models and spatial analyses

The analytical study was mainly based on the spatial analyses of digital terrain models [DTM] derived from airborne LiDAR survey. The data have been made available thanks to courtesy of Maritime Office in Gdynia. The data collection (airborne survey) was conducted between 2010–2016 during the spring and autumn seasons (Table 1). The aerial LiDAR mapping was designed so that at least one flight line ran over the water, due to the need to register dunes slopes and the steep cliff face. The flights were carried out with the water level not exceeding 10 cm above the mean sea level. Airborne laser scanning was performed with an average scanning density of 8 points/m^2 and coverage between the series of at least 20%. The total width of the mapped coastal zone was about 0.5 km.

The main idea was to compare changes year by year or every two years (depending on the available material). The DTM (obtained from Maritime Office) were analysed using various geoprocessing techniques. The parameters affecting the vividness and readability of the digital model were adjusted. GIS-based features – maps of slope (gradient of maximum changes in z-value) and a set of multi-temporal digital terrain models from raster surfaces have been created. These features were subsequently used for morphological analysis and general delimitation of the boundaries of the landslides.

The average z (high) value error for an individual digital terrain model was approximately 0.15 m. The average error between the two DTM was different and ranged from 0.05 to 0.35 m. In order to limit the error of z-values on multi-temporal models, a number of control points were set to check the height differences between individual DTM. Control points were chosen in such a way that they were placed within stable, characteristic elements of the terrain. The error value was finally taken into account for the resulting multi-temporal models.

This allowed comparing models created on the basis of various measurement sessions at different times. Such methodological approach allowed to follow the changes taking place at regular intervals. For the purposes of this work we assumed the ranges between –0.5 to 0.5 m as a state of "equilibrium", whereas positive values (three classes from 0.5 to > 5 m) corresponded to height increments and negative values (three classes from –0.5 to < –5 m) to losses. Such a range has been set in order to overcome the measurement errors and for the transparency of the resulting maps. Determination of a smaller range significantly affected the fragmentation of fields corresponding to increments and losses but did not generally bring new information to the result layer. What is more, the reduction in the state of "equilibrium" range did not affect the course of major trends. Nevertheless, the ranges of height differences can be easily modified to extract the demand values.

Table 1 The list of digital terrain models used in the study

Material	Time of airborne LiDAR survey	Model resolution (pixel size) [m]	Conducted analysis
Digital terrain model	2010	0.5×0.5	Morphological analysis of changes taking place at regular intervals and the interpretation of the general course of landslide limits. GIS-based features – maps of slope (gradient of maximum changes in z-value) and a set of multi-temporal digital terrain models from the raster surfaces have been created.
	04.09.2012–29.09.2012		
	16.04.2014–22.04.2014		
	11.09.2015–07.10.2015		
	12.11.2016–22.11.2016		

All geological works require field verification. That is why the area under discussion was visited dozens of times which made it possible to identify presented landslides in the field and correlate their limits with those derived from the DTM.

RESULTS

The Rozewie cliff from the turn of the 19th and 20th centuries was protected by various types of protective constructions and since then it was considered inactive (Subotowicz 1991; Marek, Olszak 2017), but after ca. 100 years of stability mass movements were unexpectedly activated in April 2005. Just after this event one of the co-authors of this manuscript was leading the survey to Rozewie to recognize and document the process. The event in 2005 was accompanied by damage to seawall at the base of the cliff (Fig. 2 A, B). Later, the multi-temporal DTM for 2010–2012 showed that at least during this period there was a periodic renewal of mass wasting processes.

In 2013, the mentioned protective structure was expanded (Fig. 2 C, D). In 2012–2014, mass movements stopped and, at the same time, a slight marine erosion occurred on the foreground of the seawall. The years 2014–2015 and 2015–2016 are the period of relative stability of this part of the coast with addition of accretion of sandy sediment offshore (in front of the SE part of the cliff and the seawall). Such state lasted until 2017 when the sandy beach was eroded. The illustration with the use of an old topographic map (1910) as a background illustrates how close the cliff edge and the landslide are to the historical buildings in Rozewie (Fig. 3 F). The distance is only a few dozen meters. It also shows the colluvium of landslides overlapped the historical shoreline. It is due to two reasons. First, the advance of colluvial material can reach further into the sea if the marine erosion is minor in the analysed period. Second, such situation occurred also as a result of artificial works. The protective works and the raised seawall were conducted outside the historical water line.

The maximum vertical increasement within the landslide was noticed in period 2015–2016 and reached approximately 2.5 m. While the biggest decrease occurred between 2010 and 2012 (approximately 6 m). The summary picture of changes in 2010–2016 is illustrated in Fig. 3 and Table 2.

Fig. 2 Damaged (A, B – photo: L. Jurys) and the rebuild and expanded (C, D – photo: M. Olkowicz) seawall at Rozewe headland

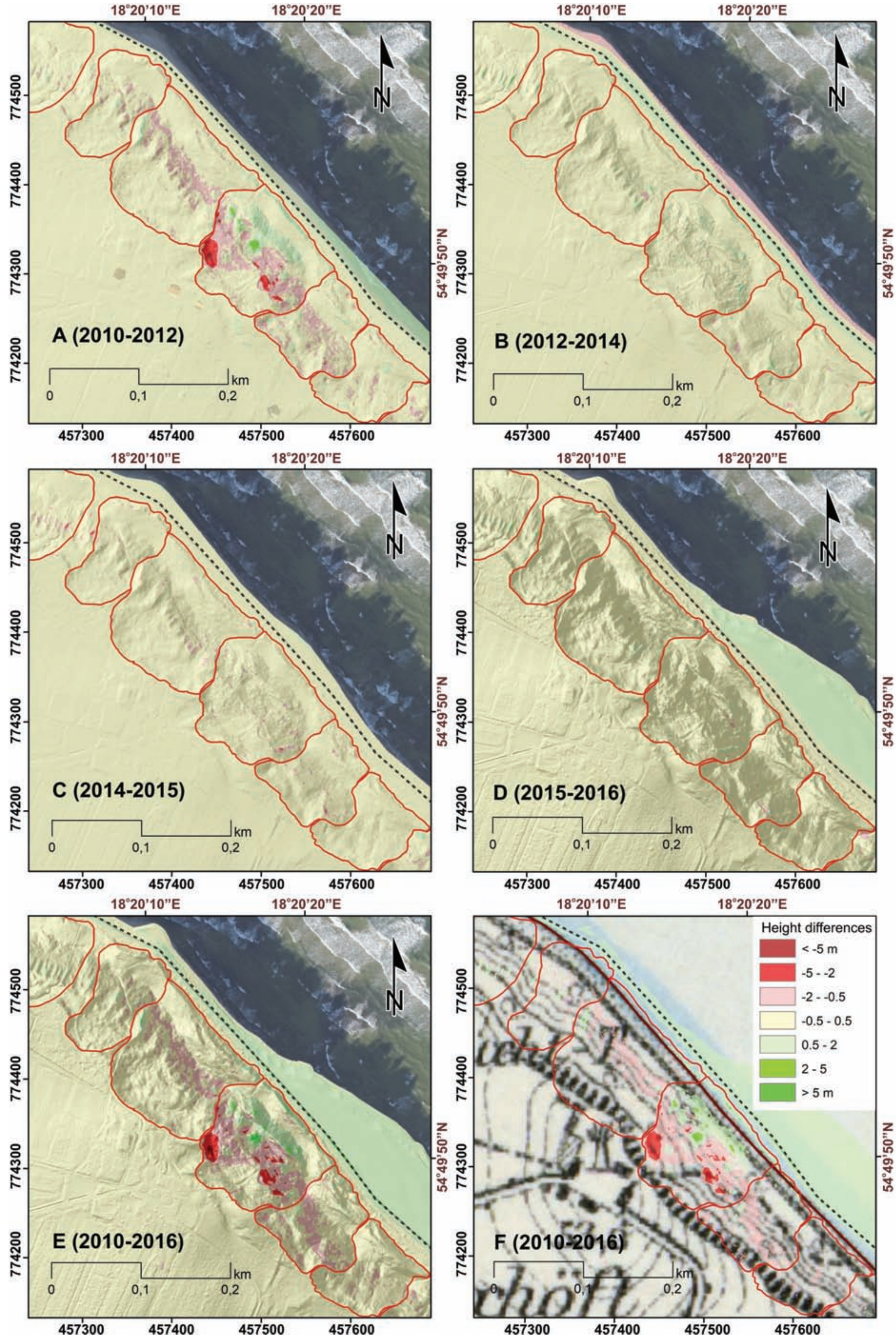

Fig. 3 The summary picture of vertical changes between 2010–2016 at Rozewie cliff section. Dashed line indicates the position of seawall. Solid brown line (Fig. 3 F) indicates the position of historical shoreline

A landslide at the Chłapowo cliff section (Fig. 4) is a large, complex landslide, both in terms of geological structure and mass wasting processes. The illustration for 2010–2012 differences shows that the landslide in terms of activity is bipartite. The SE part is definitely more active than NW part. This is also underlined by the course of landslide boundaries, especially within the main scarp, where the SE part is bent semicircularly and goes further into the land.

In contrast, the NE part of the main scarp has a more even course. The beach was accreted during this 2-year period. This results in a slowdown of landsliding in 2012–2014 period with simultaneous periodic beach erosion. The years 2014–2015 and 2015–2016 are periods of relative stability of the cliff and landslides with a variable trend of beach accretion and erosion. In 2015–2016, the increased erosion of the beach in front of the SE part of cliff section and landslide may suggest the resumption of mass wasting movements and the further retreat of the main scarp in the future. The summary picture of the changes on the background of the historical topographic map shows the scale of cliff erosion over 100 years (Fig. 5F). The characteristic elements of the landslide are 3 and sometimes 4 escarpments. Their location changes over time (i.e. it shifts inland). It is a permanent structural element that may suggest that the landslide process remains in a close and dominant relationship with the geological conditions. However, the marine erosion is of secondary importance here. The vertical increase of land within the landslide was rather equal during the whole measured period and reached approximately 2 m. While the biggest decrease occurred between 2010 and 2012 (approximately 8 m).

Table 2 Vertical displacement within the discussed sections

Area under discussion	Vertical displacement [m]	Period					Average maximum value [m/y]
		2010–2012	2012–2014	2014–2015	2015–2016	2010–2016	
Rozewie cliff section	increase ↑	3.8	2.6	1.4	2.5	3.7	1.7
	decrease ↓	6.1	1.9	2.8	1.4	6.3	2.0
Chłapowo cliff section	increase ↑	4.9	4.5	2.1	2.0	5.3	2.2
	decrease ↓	8.0	3.2	2.3	2.1	9.8	2.6
128 km of Polish coast	increase ↑	2.9	2.4	5.8	2.5	5.4	2.3
	decrease ↓	5.7	3.0	4.8	4.4	6.5	3.0

Fig. 4 Chłapowo cliff section and the landslide (photo: M. Olkowicz)

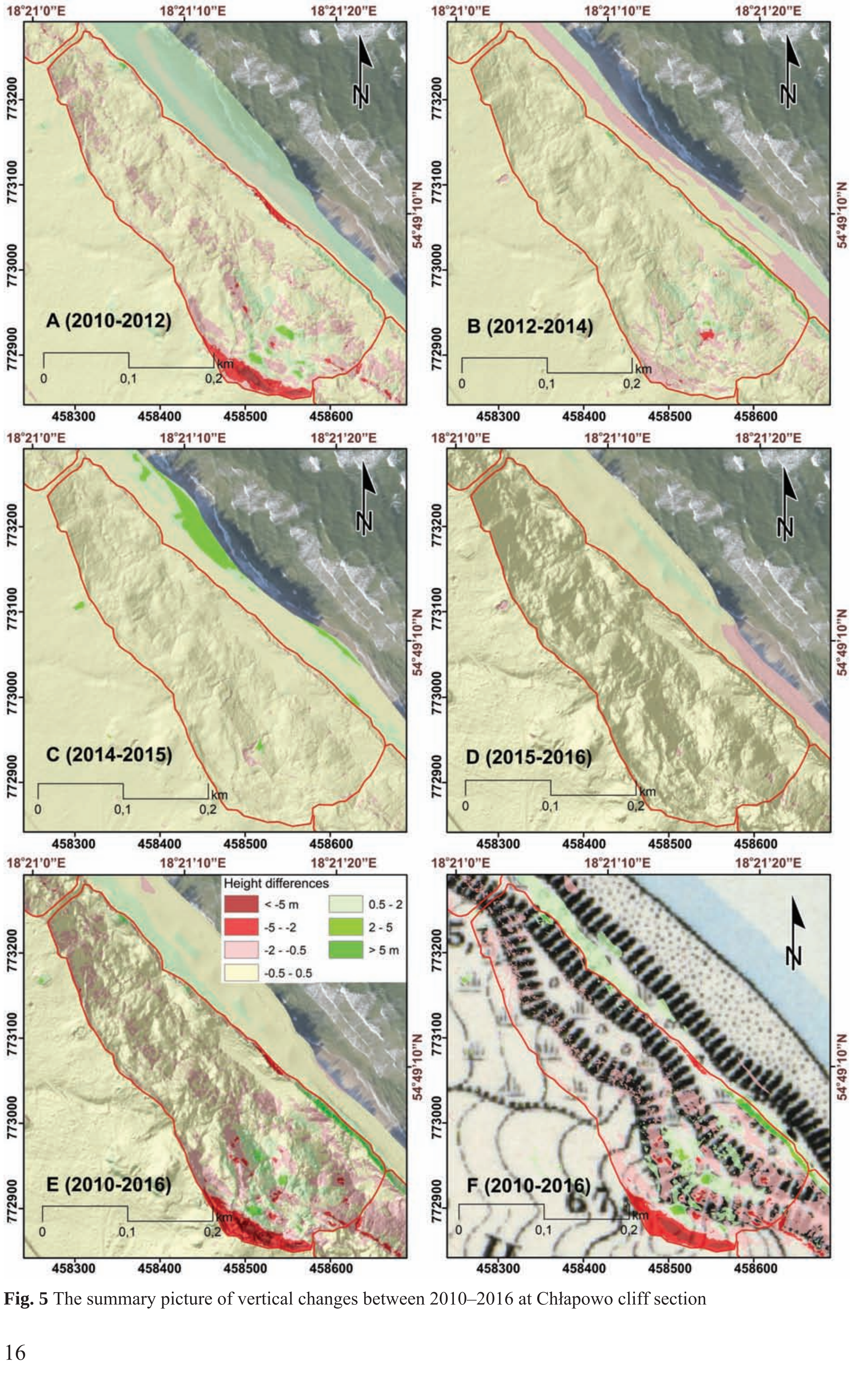

Fig. 5 The summary picture of vertical changes between 2010–2016 at Chłapowo cliff section

The summary picture of changes in 2010–2016 is illustrated in Fig. 5 and Table 2.

Another characteristic feature of this part of the coast is a landslide complex in the area of 128 km of the Polish coast. This cliff section is almost entirely occupied by mass wasting processes. First of all, the domination of marine erosion is visible, which removes colluvial material deposited at the cliff foot (2010–2012). In the next analysed period (2012–2014), erosion still interacts but with less intensity and is limited to the beach. Landslide in the NW part of the described region (Fig. 6) is inactive while the other three show little activity from the cliff top to the foot.

Mass movements within the landslide located in the NW part have been resumed in the period 2014–2015. It is a very characteristic image where the negative balance (decreasement) of rock masses (red colour) within the main scarp of the landslide is compensated by the increase, and positive balance (green colour) within the colluvium. In the period 2015–2016, mass movements were stopped again. At the same time, it should be noted that this may be related to minor beach erosion in 2014–2015 and even with the accretion of sediment in the NW part. The maximum vertical increasement of sediment within the landslides was noticed in period 2014–2015 and reached approximately 6 m. While the biggest decrease occurred also in this period and was estimated to approximately 5 m. The summary picture of changes in 2010–2016 is illustrated in Fig. 7 and Table 2.

DISCUSSION

The reasons for the formation of mass movements in cliffs built of unlithified, relatively soft rocks and rocks with low levels of diagenesis have been described several times, also with reference to the Polish coast (Uścinowicz *et al.* 2004; Dudzińska-Nowak, Wężyk 2014; Kostrzewski *et al*. 2015; Uścinowicz *et al.* 2017; Terefenko *et al.* 2018). Nevertheless, some general remarks should be devoted here in relation to these cases. The geological conditions within large and complex landslides are difficult to recognize. As it was mentioned above, the colluvial deposits mask the cliff face. Therefore, recognition of their geological structure may only take place on the basis of a few boreholes and by analogy to the nearby areas where landslides are also present, but the geological structure has been described in a reliable way (e.g. Jastrzębia Góra) (Masłowska *et al.* 2002; Kamiński *et al.* 2012). On this basis, it should be assumed that the areas in Rozewie and Chłapowo are related to the occurrence of glacitectonic deformations or thrust zones. This assumption is confirmed by analogy to the area of Jastrzębia Góra where the deformations

Fig. 6 Landslides on the area of 128 km of Polish coast

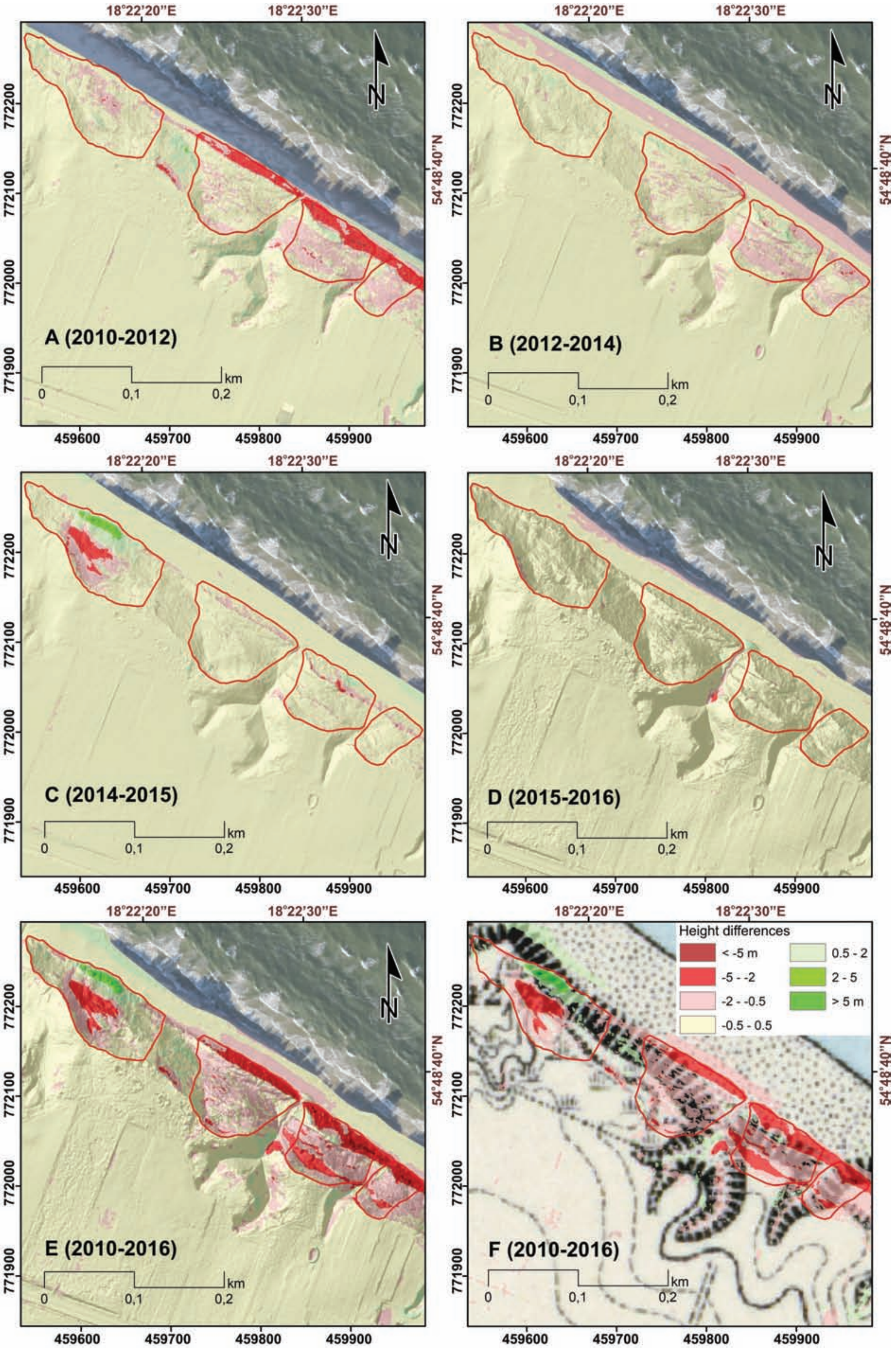

Fig. 7 The summary picture of vertical changes between 2010–2016 at 128 km of Polish coast

were described as well as due to observations of the morphology of the area. Both mentioned landslides are located within the local elevation, which would suggest a more complex style of geological structure than in their surroundings. In the case of the landslide complex in Rozewie, their renewal could also be influenced by the tectonics of the substrate. The renewal of landslides in 2005 regarded as inactive and secured by the seawall took place 6 months after the earthquake in Kaliningrad region. The earthquake in September 2004 may have weakened the structure and stability of the slope. Rainfalls in autumn 2004 and frost in the winter 2004/2005 as well as snow meltdown and spring precipitation might caused further disturbances. The observed mass movement was directed mainly downward only with a slight displacement of horizontal vectors. Such a triggering factor finds analogies in the world (Hansen 1965). We can only presume if later movements were the aftermath of the initiating event. Regardless of the above considerations, one should look for simpler solutions and assume that the main causative factors for the discussed landslides are geological, hydrometeorological and hydrodynamic conditions shaping the coastal zone.

Therefore, the question about relatively increased landslides activity in the period 2010–2012 seems justified. The seemingly simple relationship between marine erosion and the development of landslides is not reasonable here. According to some reports, the number of storm days has been decreasing since the 1990s (Formela, Marsz 2011; Bärring, Fortuniak 2009). What is more, not all landslides within the presented sections were renewed, even despite the same exposure to the marine processes. What is more, the landslide in Rozewie is protected by the seawall and yet still has some activity. Increased rainfall could play a greater role here (Jania, Zwoliński 2011), as well as hydro- and lithodynamics of the offshore area.

In the context of hydrodynamics of the beach and offshore, attention should be paid to the sediment balance in an annual or several-year cycle. The occurrence of the sand cover on the beach and in the seabed, in proximity to the cliff is of great importance for its activity. An example of this is the situation on the Chłapowo cliff section (period 2014–2015) where the increase of sediment within the beach is associated with the lack of significant landsliding processes. On the opposite pole lies the situation with the area of 128 km of the coast where, with a narrow beach and some deficit of sandy material, landslide activity is noticeable (e.g. periods 2010–2012 and 2012–2014). A similar situation was described in relation to the cliffs of eastern England and Estonia (Lee 2008; Orviku *et al.* 2013).

The mentioned method of visualization of changes taking place within steep coasts has its advantages and limitations. Undoubted advantages include a good visualization of changes on a general scale and their geoprocessability. It is possible to quickly adjust the imaging ranges and their compilation with other cartographical materials. One limitation is the fact that such development requires homogeneous data obtained during expensive airborne survey. What's more, this method records larger area changes and its accuracy in relation to very local studies is limited.

CONCLUSIONS

The main conclusions can be included in the following points:

- On the basis of LiDAR data, multi-temporal DTM were prepared showing the height differences in the coastal zone in 1–2 year cycles (between 2010–2016). The vertical displacement of landslide surfaces was estimated. The maximum average increasement in elevation for the discussed area is approximately 2.3 m/y while the decreasement value is approximately 3 m/y.
- Studying the landslides developed on the steep cliff coast, special attention should be paid to the sediment balance on the beach and near shore area.
- Multi-temporal DTM demonstrate certain usefulness in determining areas of particular activity within complex landslides.
- Understanding the mechanisms steering the landslides is facilitated when data on horizontal and vertical displacement components are available. The acquisition of high resolution DTM and the information they bring on terrains prone to mass wasting processes allows identifying hazardous zones, estimate the vertical displacement and areas where the sediments are removed or accumulate and control the development of landslides for hazard assessment purposes.
- Significant differences in the intensity of processes occurring in a small area, often within one landslide, show how difficult and often hopeless the forecasting of the coastal cliff erosion rate is.

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