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COASTAL ENGINEERING

Contribution of wave set-up into the total water level in the Tallinn area

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Abstract. Wave-induced set-up is a nonlinear phenomenon driven by the release of momentum from breaking waves. It may cause a systematic rise in the water level in certain coastal segments. We address the contribution of wave set-up into the formation of extreme water levels at the waterfront in the Tallinn area of the north-eastern Baltic Sea. The parameters of set-up are evaluated using the wave properties computed for 1981–2014 with a triple-nested WAM model with a horizontal resolution of about 470 m. The offshore water level is extracted from the output of the Rossby Centre Ocean (RCO) model. The maximum set-up may reach 0.7–0.8 m in some coastal sections and the all-time highest measured water level is 1.52–1.55 m in the study area. The high offshore water levels are only infrequently synchronized with extreme set-up events. Wave set-up may contribute to the all-time maximum water level at the shoreline by up to 0.5 m. This contribution considerably varies for different years. The largest contribution from set-up into extreme water levels usually occurs during north-westerly storms.

Key words: marine coastal hazards, flooding, wave set-up, water level.

1. INTRODUCTION

Effects of climate change have the most significant influence on urban areas [4] where they affect people's safety, the functioning of the existing infrastructure, new development projects, etc. A serious problem for low-lying urban areas is coastal flooding [5]. The water level at the shoreline of coastal segments that are open to high waves can be considerably higher than in neighbouring offshore locations because of wave-induced set-up. This non-linear phenomenon, hereafter denoted as wave set-up, occurs in the surf zone where the release of momentum of breaking waves may lead to an increase in the water level [13]. The magnitude of wave set-up is traditionally modelled and quantified using the variation in the onshore component of radiation stress (the tensor of excess horizontal momentum fluxes due to the presence of the waves) [13]. For open ocean coasts wave set-up can contribute up 30–60% of the total height of the 100-year surge [2]. Extreme water levels are usually produced by an unfortunate combination of high tide (or water volume of a semi-enclosed sea [12]), low atmospheric pressure, and strong wind-driven surge. As wave set-up is added on top of their joint effect, its presence may cause extensive additional flooding of affected coastal sections [1] and may provide a significant threat to people and property.

The magnitude of wave set-up crucially depends on the approach angle of waves. Waves that approach the coast obliquely mostly produce a longshore current rather than high wave set-up [3]. Therefore, if high waves always approach a certain section of the shore under relatively large angles, wave set-up usually does not cause any substantial danger [28]. The wave set-up is the largest when waves propagate (almost) directly onto the shore. This is common on more or less straight open ocean coasts [3]. The situation is more complicated in semi-sheltered areas such as the Baltic

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Sea where the wave approach angle is often highly variable [33].

The existing flooding maps, operational water level forecasts, and warning systems often ignore wave set-up. The prediction of extreme wave set-up events is particularly difficult in coastal segments with complex geometry and bathymetry [1]. In such areas the wave approach direction may be considerably affected by wave–seabed interaction and specific effects such as slanted fetch [18]. As a consequence, the highest wave set-up in such coastal segments does not necessarily occur during the strongest storms [28]. Each storm may have a somewhat different wind direction and refraction-induced changes in the wave direction depend also on wave periods. It is thus natural that the locations hosting the highest wave set-up normally vary from one storm to another. This suggests that the highest water levels at a certain distance from the shoreline (hereafter named offshore water level although it corresponds to a distance of a few kilometres from the shore in this study) are only infrequently synchronized with extreme wave set-up events.

The vicinity of Tallinn Bay in the north-eastern Baltic Sea (Fig. 1) is an example of regions with extremely complicated geometry. Its coastal sections are open to a wide range of directions and include segments that are most vulnerable to extreme events. The typical tidal range is a few centimetres and water level fluctuations in the entire region are mostly governed by atmospheric forcing. The extreme water level measured at a single location has reached 1.52 m above the long-term mean [29], or 1.55 m according to [6]. These values have been measured at the entrances of major harbours (Tallinn Old Harbour, Muuga Harbour, Fig. 2) at water depths >10 m. They are thus not affected by wave set-up and can be considered as representative for the offshore water level. Therefore, even a moderate additional water level rise may cause problems in this area. The entire study area is almost completely open to the waves excited by north-westerly and northerly winds. The adjacent Muuga Bay (Fig. 2) is open to high

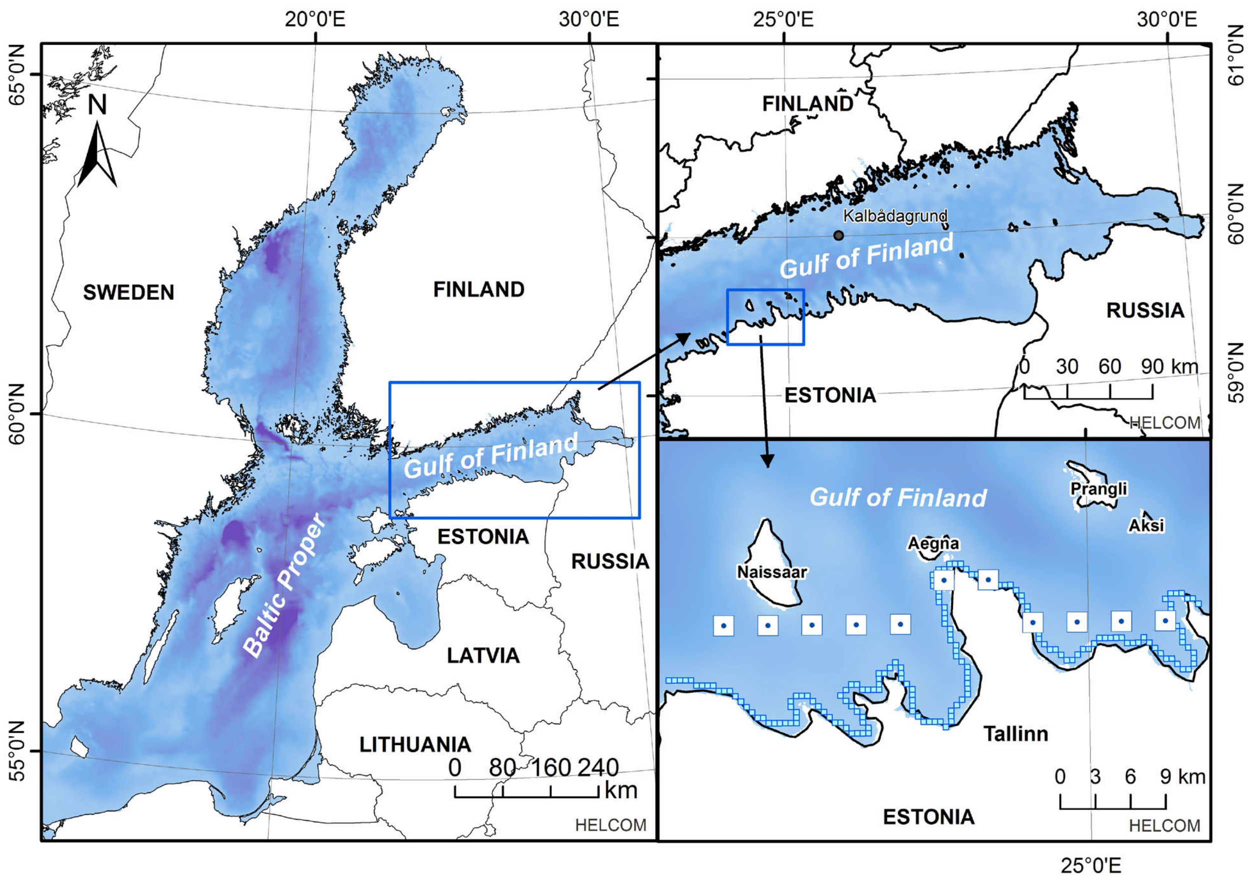

Fig. 1. Computational areas of the triple-nested wave model applied to the Tallinn Bay area. The small squares along the coast in the lower right panel indicate grid points of the wave model used in the analysis. The cells are numbered sequentially starting from the westernmost point (Fig. 2). The offshore water level is represented by 11 grid cells (white squares) of the RCO circulation model.

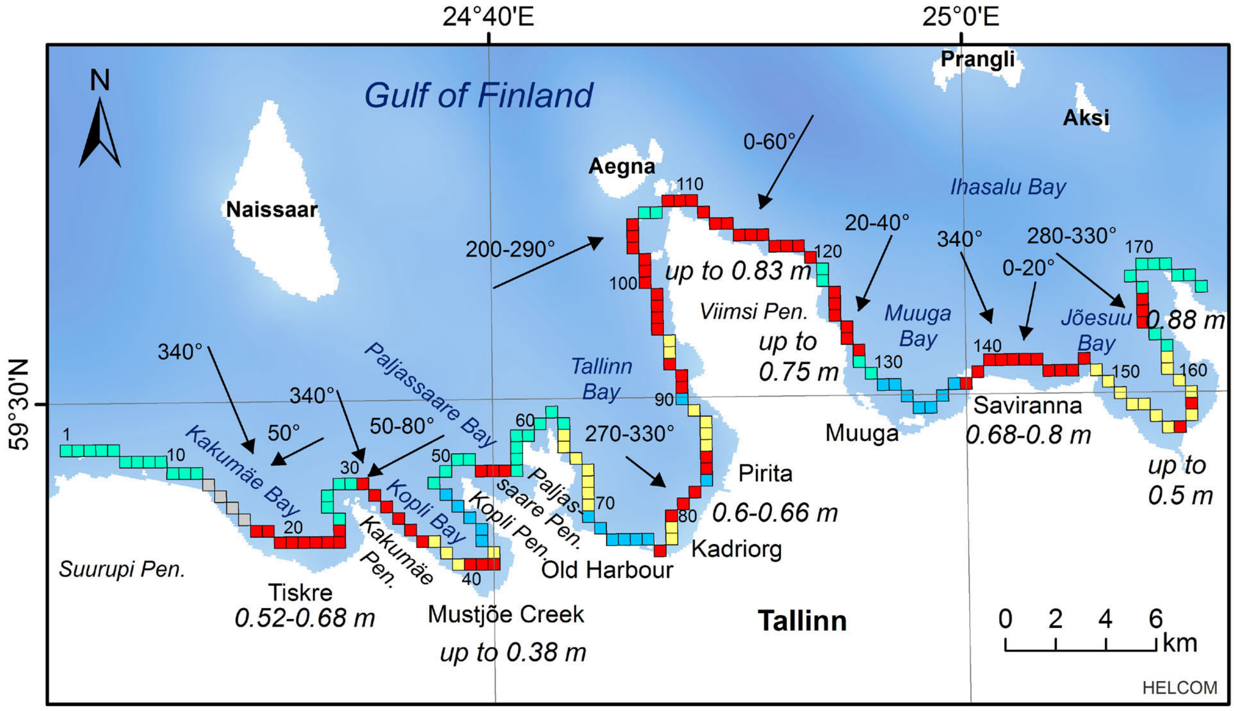

Fig. 2. Coastal sections potentially affected by high wave set-up (red squares) in the urban area of the City of Tallinn. The arrows indicate the associated directions of wave propagation. Yellow squares indicate coastal stretches where the maximum wave set-up is <20 cm, green squares are areas where high wave set-up is evidently not possible because of the convex shape of the shoreline, and blue squares refer to areas containing various engineering structures. Extended from [28] to cover areas to the east of the Viimsi Peninsula.

waves from the north-east. The maximum wave set-up may reach 0.7–0.8 m according to simplified reconstructions of wave fields in [28], and thus may substantially contribute to the resulting water level near the bayheads or along almost straight sections of the study area.

In this paper we address the contribution of wave set-up to the formation of very high water levels on the waterfront of the study area using numerically reconstructed wave properties and offshore water levels. The calculation scheme of wave time series and the method for the calculation of wave set-up height follows the material in [28]. Our focus is on the timing of the highest offshore water levels and very large wave set-up events. The study area involves also a large area to the east of Tallinn that is open to the north-east. We also further elaborate the analysis of sensitivity of the locations with the highest wave set-up in this complicated geometry with respect to the rotation of the approach direction of the largest waves from the beginning of the 1980s [28] and establish the wind directions associated with the most dangerous situations in which the total water level at the waterline considerably exceeds the all-time maximum for the offshore water level.

2. DATA AND METHODS

The study area is an about 80 km long coastal segment of Tallinn Bay and Muuga Bay from the Suurupi Peninsula to the Ihasalu Peninsula (Fig. 2). The parameters of wave set-up are evaluated from wave properties reconstructed using a triple-nested version of the WAM model with the resolution of the innermost grid about 470 m [24]. The WAM model was originally designed for open ocean conditions and for relatively deep water [9], but its latest versions reasonably replicate the Baltic Sea wave fields [6,22] and the model works properly even in Finnish archipelago areas [31,32]. To adequately represent the wave growth in low wind and short fetch conditions (which are frequent in the study area [24]), an increased frequency range of waves up to 2.08 Hz is implemented. The presence of sea ice is ignored. As there may be as many as 70–80 ice days annually [11,23], the hindcast extreme parameters of wave set-up may be somewhat overestimated. For details of the used bathymetry, the implementation, and validations of the used model version the reader is referred to [24]. The properties of simulated wave set-up statistics in Tallinn Bay are analysed in [28].

The quality of wave hindcast primarily depends on the adequacy of the wind information. Wave simulations were forced by one-point open-sea wind data for 33 years (1981–2014) according to the scheme developed in [24]. As wave set-up is very sensitive with respect to the wave propagation direction, it is important to use correct information about wind directions. Considering that atmospheric models often fail to adequately replicate wind directions in the Gulf of Finland [8], we used wind data measured at Kalbådagrund in the central part of this gulf (Fig. 1, 59°59′ N, 25°36′ E). The measurement devices were mounted on a caisson lighthouse located on the top of a shoal far offshore. The wind fields at this site are practically not affected by the shores and their use satisfactorily represents wave properties in the interior of Tallinn Bay [24]. The entire simulation interval contained 93 016 measurement instants with a time step of 3 h. In 8554 cases either wind speed or direction was missing. These time instants were excluded from the further analysis. As some of these instants involved quite strong winds, the analysis may underestimate the highest wave set-up events.

For an adequate estimation of wave set-up, we selected nearshore grid cells of the innermost wave model located as close to the shore as possible (Fig. 1) but still in a reasonable water depth so that the modelled waves were not yet breaking. The nearshore of the study area was divided into 174 sections with a typical length of 0.5 km that roughly correspond to the selected cells (Fig. 2). For each section the time series of the significant wave height, peak period, and mean wave direction were extracted from the output of the WAM model every 3 h from 1 January 1981 to 4 February 2014. The maximum simulated significant wave was usually lower than 4 m [24] but reached up to 5 m in a few locations [27]. These estimates are commensurable with the maximum measured values of 5.2 m in the open part of the Gulf of Finland at a distance of a few tens of kilometres from the study site [31]. To properly account for such wave heights, the grid points were chosen mainly in 4–8 m deep water. In a few cell locations with large bottom gradients the water depth is 20–27 m.

The joint impact of shoaling and refraction during the propagation of waves from the model grid points to the breaking line (the seaward border of the surf zone) was resolved in the framework of the linear wave theory following the approach developed in [28,33]. We assume that the numerically evaluated wave field is monochromatic, the wave height H_0 at the centre of the grid cell equals the modelled significant wave height, the period equals the peak period, and the approach direction equals the evaluated mean direction. We also assume that the nearshore is locally homogeneous along the direction of the shoreline and that the waves start to break when their height is 80% of the water depth d_{b} (equivalently, the breaking index $\gamma_{\mathrm{b}} = H_{\mathrm{b}}/d_{\mathrm{b}} = 0.8$). Then the wave height H_{b} at the breaking line satisfies the following equation [3]:

$$H_{\mathrm{b}} = H_0 \left(\frac{c_{\mathrm{g}0}}{c_{\mathrm{fb}}} \frac{\cos\theta_0}{\cos\theta_{\mathrm{b}}} \right)^{1/2}, \qquad (1)$$

where c_{g} is the group speed, c_{f} is the phase speed, and θ is the attack angle of the approaching waves. The subscripts ‘0’ and ‘b’ indicate the relevant value at the particular wave model grid cell and at the breaker line, respectively. As breaking waves are long waves, their group and phase speeds are equal: $c_{\mathrm{gb}} = c_{\mathrm{fb}} = \sqrt{g d_{\mathrm{b}}} = \sqrt{g H_{\mathrm{b}}/\gamma_{\mathrm{b}}}$, where g is the gravity acceleration. Applying Snell’s law $\sin\theta/c_{\mathrm{f}} = \mathrm{const}$, Eq. (1) can be reduced to the following algebraic equation of 6th order [28,33]:

$$\frac{H_{\mathrm{b}}^5 g}{H_0^4 \gamma_{\mathrm{b}}} \left(1 - \frac{g H_{\mathrm{b}}}{\gamma_{\mathrm{b}}} \frac{\sin^2\theta_0}{c_{\mathrm{f}0}^2} \right) = c_{\mathrm{g}0}^2 (1 - \sin^2\theta_0). \qquad (2)$$

This equation has exactly two real positive solutions if $216 g^2 H_0^2 c_{\mathrm{g}0} \sin^5\theta_0 \cos\theta_0 < 25\sqrt{5}\gamma_{\mathrm{b}}^2 c_{\mathrm{f}0}^5$. The estimate of the breaking wave height H_{b} is given by the smaller real solution [28,33].

A straightforward estimate of the maximum wave set-up height can be derived using the concept of gradual wave breaking in the nearshore, or equivalently, assuming that the breaking index $\gamma_{\mathrm{b}} = 0.8$ remains constant in the entire surf zone. In such ideal conditions the maximum wave set-up height is [3]

$$\bar{\eta}_{\max} = \frac{5}{16} \gamma_{\mathrm{b}} H_{\mathrm{b}} = 0.25 H_{\mathrm{b}}. \qquad (3)$$

Similarly to [28], we only consider waves that approach the seaward border of the surf zone from the direction of ±15° with respect to the normal to the coast as a potential source of high wave set-up.

The largest danger occurs if the maximum wave set-up occurs simultaneously with very high offshore water levels (interpreted here, as mentioned above, as water levels modelled using an ocean circulation model at a distance of a few kilometres from the shoreline). The water level time series (once in 6 h) is extracted for 11 offshore locations (Fig. 1) from the output of Rossby Centre Ocean (RCO, Swedish Meteorological and Hydrological Institute) model. The principles, implementation, and forcing of the RCO model have been comprehensively described in the scientific literature [14–16], and we provide here only a few core features of this model. Its horizontal resolution is 2 × 2 nautical miles (about 3.7 km). We use the output of the model run for May 1961–May 2005 that was coupled to a sea ice model. The water level of the model is steered using boundary information in the northern Kattegat. The model is forced with a meteorological data set with a horizontal resolution of 22 km [21] and generally represents both the time series and statistics of water levels well. It reasonably replicates the wind-driven gentle slope in the average water level towards the eastern and northern ends of the Baltic Sea but partially fails to reproduce the largest storm surges in the western Baltic Sea [17].

3. SYNCHRONIZATION OF HIGH WAVE SET-UP AND WATER LEVEL

The all-time highest simulated wave set-up varies from 0.26 to 0.96 m (Fig. 2). Some of the very high wave set-up values characterize areas where this phenomenon apparently does not occur because of the nature of the shore. For example, almost 1 m high wave set-up hindcast for some sections of the Suurupi Peninsula (which are open to very high waves) is unrealistic because of a steep scarp at the waterline [28]. While it is natural that predominant westerly winds may often cause high wave set-up in coastal sections open to the west and north-west [28], northerly and north-easterly winds (which are relatively infrequent in the Gulf of Finland [26]) may create almost the same values of wave set-up in coastal sections of Muuga Bay that are open to the east (Fig. 2).

The total water levels at the shoreline are evaluated by adding the instantaneous values of wave set-up to the offshore water levels simulated using the RCO model. The two time series overlap for the years 1981–2005.

The highest wave set-up almost never occurs simultaneously with very high offshore water levels (Fig. 3). The reason is that large waves that attack the northern coast of Estonia are normally excited by strong northerly winds while high sea levels are produced by persistent westerly winds. This feature is mirrored by the different appearance of the relevant scatter diagrams (Fig. 3) for coastal sections that are open to different directions. The correlation between the instantaneous values of these two components of the total water level is fairly weak at all sites presented in Fig. 3. For locations open to the west or north-west the highest modelled offshore water levels (1.4–1.6 m) occur simultaneously with comparatively large wave set-up values (up to 0.5 m). For locations open to the east the largest offshore water levels are associated with very low wave set-up values (normally a few centimetres; only in one occasion 0.3 m). On the one hand, this feature indicates that the contribution of wave set-up into the total water level at the shoreline is normally negligible in the coastal segments that are open to the easterly directions. On the other hand, wave set-up may substantially contribute to the coastal flooding in all sections that are exposed to the westerly winds.

A similar asymmetry becomes evident in the formation of the total water levels that are comparable with the maximum offshore water level. The shoreline water levels higher than 1.4 m in sections that are open to the east are mostly formed by the relevant offshore water levels and contain only a minor contribution from wave set-up. In such sections almost all very high wave set-up events occur when the offshore water level is modest (Fig. 3).

The situation is considerably different in sections that are open to the west. The overall shape of the ‘map’ of the frequency of occurrence of different offshore water levels and wave set-up values has an elongated shape and extends from the origin to the water levels of about 1 m and wave set-up values of 0.4 m. High offshore water levels (>1 m) are often accompanied by wave set-up values ≥0.3 m.

4. CONTRIBUTION OF WAVE SET-UP INTO EXTREME WATER LEVELS

The total water level at the shoreline was evaluated for each 6-h time interval as the sum of the offshore water level from the RCO model and the highest wave set-up during this interval. The largest resulting values in 1981–2005 varied between 1.6 and 2.3 m along the study area (Fig. 4). The contribution of the offshore water level was in the range of 0.8–1.7 m. This constituent exclusively governed the all-time maxima of the total water level in about half (99 out of 174) of the coastal sections. This means that waves either approached the coast under large angles or propagated towards the open sea during the extreme offshore water level events.

While Fig. 3 reveals that the high offshore water levels were never fully synchronized with extreme wave set-up events, Fig. 4 suggests that these two quantities often exhibit antiphase behaviour in some sections open to the east. Still, wave set-up substantially (up to about 0.5 m) contributes to the total water level in a part of such coastal segments (Fig. 4, Table 1). The largest total water levels only insignificantly exceeded the all-time highest offshore water levels in these sections because during easterly winds (when the approaching waves were high) the offshore water level remained well below the all-time highest values.

The proportion of wave set-up in the relevant annual maxima of the total water level presents another perspective on its contribution to dangerously high water levels (Fig. 5). In coastal sections that are open to the north-west the annual highest total water level systematically exceeds the similar maximum of the offshore water level (Fig. 5a, b) because of a substantial contribution from wave set-up (which is comparable with the annual highest wave set-up). In sections that are open to the west the contribution of wave set-up to

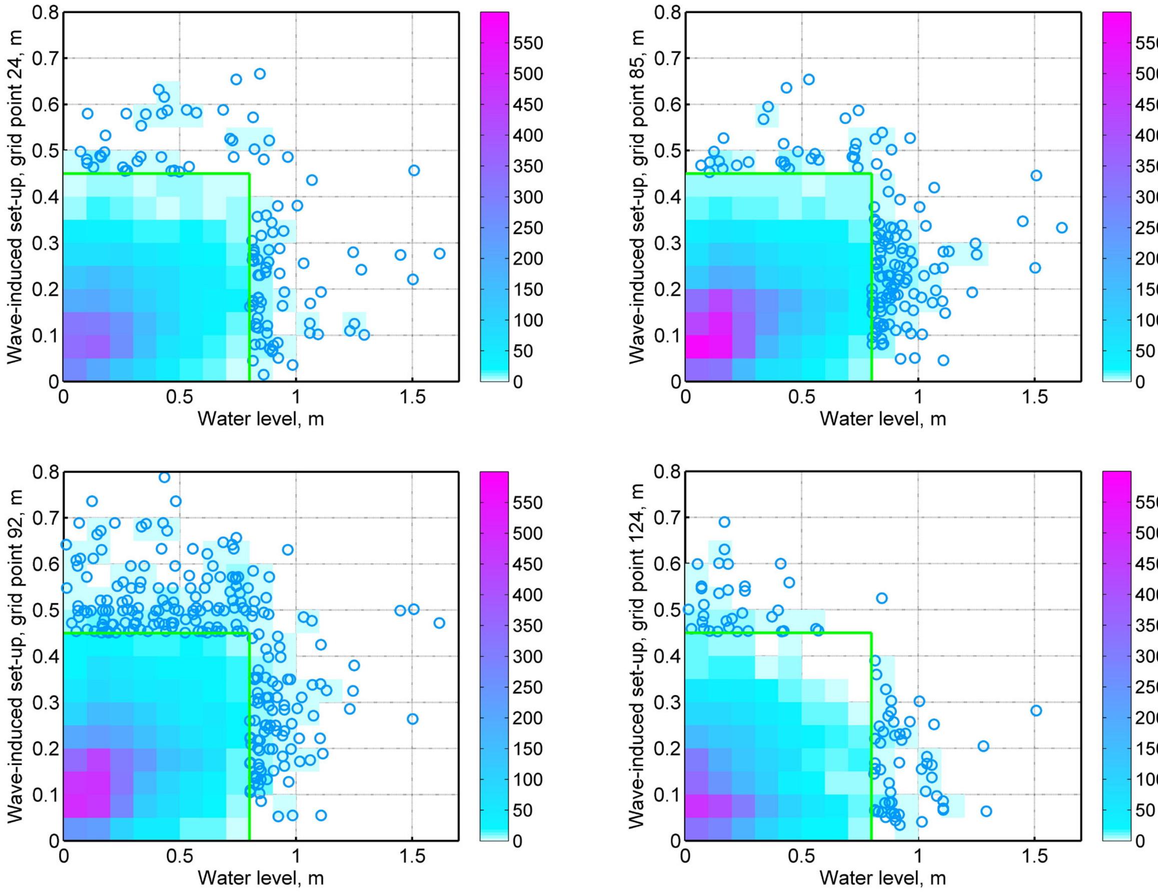

Fig. 3. Scatter diagrams of the occurrence of different offshore water levels and various wave set-up values at four representative sections of the study area: section 24 (Tiskre, a bayhead open to the north-west and partially to the west), section 85 (Pirita Beach, open only to the north-west), section 92 (western coast of the Viimsi Peninsula, open to the west), and section 124 (eastern coast of the Viimsi Peninsula, open to the north-east). The colour code corresponds to ≥ 2 occasions (otherwise the area is left white) with a particular wave set-up (with a step of 0.05 m) and water level (with a step of 0.1 m). Single cases of wave set-up >0.45 m and water levels >0.8 m (outside of the rectangle bordered by green lines) are represented as separate circles. The situations with zero wave set-up (waves propagating offshore) and cases with offshore water levels below the long-term average are not shown.

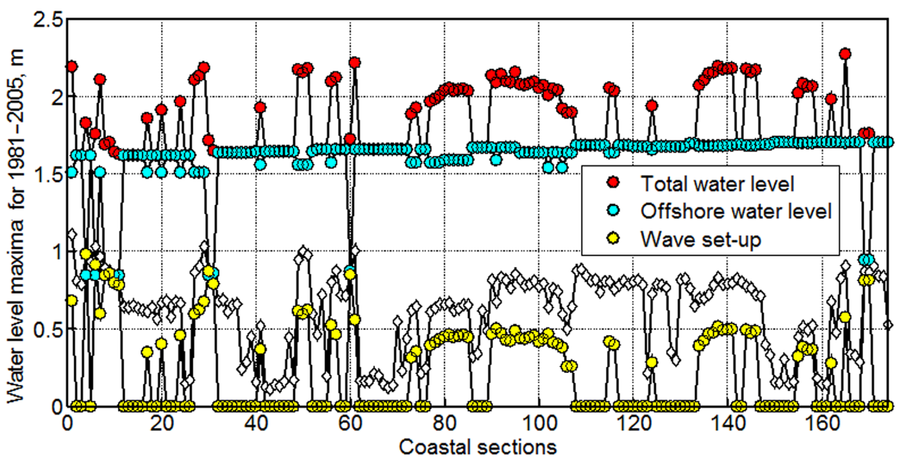

Fig. 4. The contribution of the hindcast instantaneous offshore water level and wave set-up into the all-time highest water level at the shoreline. The modelled all-time offshore water level maximum (not shown) varies insignificantly (from 1.6 m to 1.7 m) along the shore. White diamonds indicate the all-time highest wave set-up values. See Fig. 2 for the numbering of coastal sections.

Table 1. The contribution of the offshore maximum water level from the RCO model and hindcast wave set-up into all-time highest total water levels at the Estonian shoreline of the Gulf of Finland

Location (grid cell No.)	Total maximum at the shoreline, m	Contribution from		Modelled maximum of single components	
		Offshore water level, m	Wave set-up, m	Offshore water level, m	Wave set-up, m
Tiskre (24)	1.96	1.507	0.457	1.617	0.666
Pirita (85)	2.033	1.587	0.446	1.667	0.654
Viimsi (92)	2.139	1.667	0.472	1.667	0.833
Muuga (124)	1.935	1.653	0.282	1.674	0.726

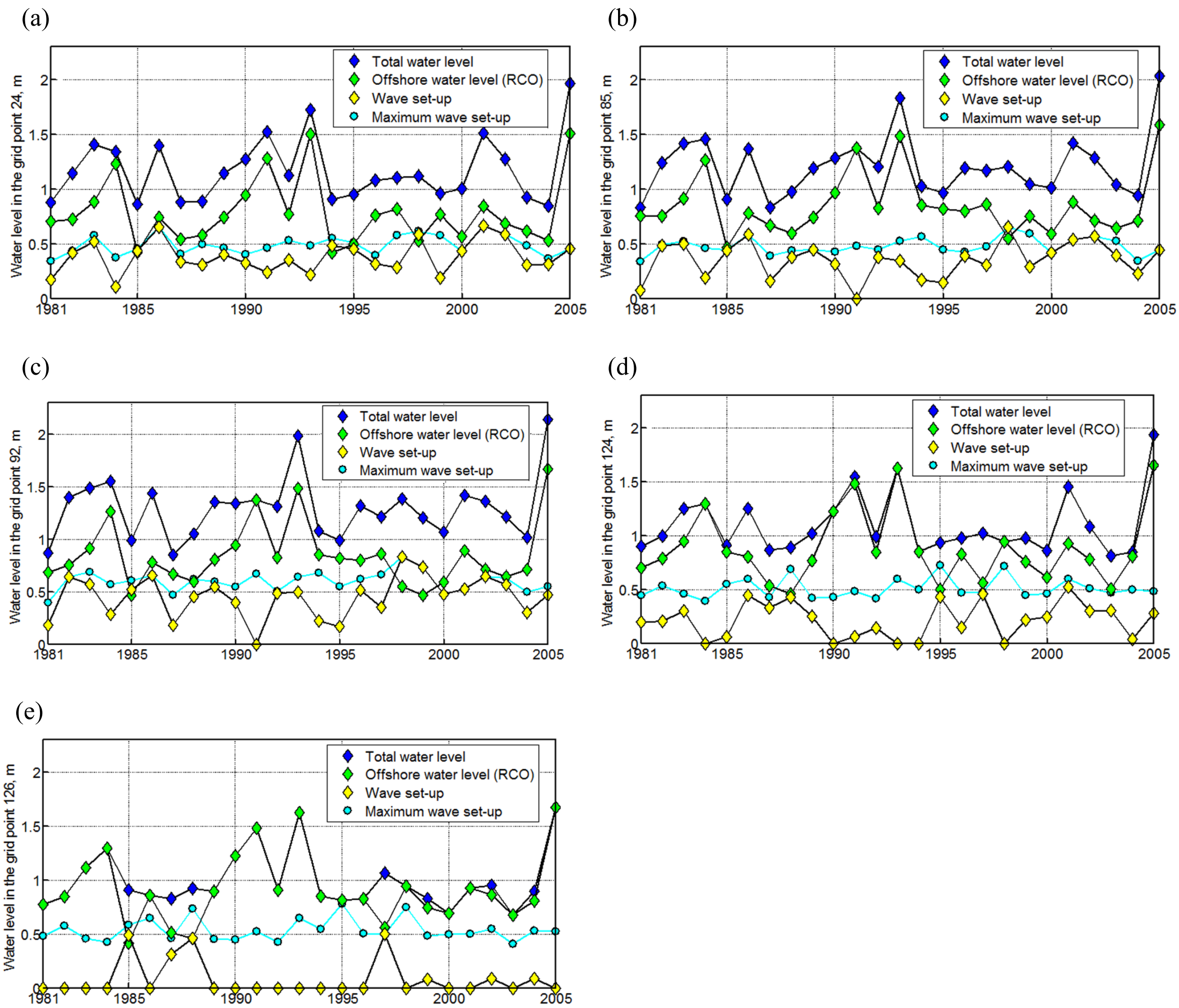

Fig. 5. The proportion of the wave set-up and offshore water level in the formation of annual maxima of the total water level at the shoreline at four representative sections of the study area: (a) Tiskre (section 24), (b) Pirita (85), (c) Viimsi (92), (d) Muuga (124), (e) a location close to Muuga Harbour (126) where wave set-up almost does not contribute. See Fig. 2 for the numbering of coastal sections.

the annual total water level maxima is clearly smaller and does not become evident in some years (Fig. 5c). In coastal segments that are open to the east (Fig. 5d, e) wave set-up infrequently contributes to the total water level maxima.

5. EVENTS RESPONSIBLE FOR HIGHEST WAVE SET-UP VALUES

In this section storms refer to all events associated with either the all-highest waves or the all-highest wave set-up values for single coastal sections of the study area between January 1981 and February 2014. The all-time highest waves were excited by six storms that all occurred in 1995 or later (Fig. 6a). The situation is completely different for storms that caused the largest wave set-up heights. The contribution of wave set-up to the annual maximum total water level substantially varies in different years. The largest contributions to the water level in sections of Tallinn Bay open to the east occurred at the beginning of the study interval in the 1980s (Fig. 5e). Our simulations confirm that this feature remains true also for the Muuga Bay area (Fig. 6b).

The all-time highest wave set-up events were much more widely distributed over different years (Fig. 6b). In total, 50 storms contributed to these events in January 1981–October 2012. Similarly to [28], a substantial number (15) of such storms occurred at the beginning of the 1980s. The stormy years 1981–1982 were apparently followed by less stormy years in 1983–1989 and then by quite a calm half-decade 1990–1994. These variations qualitatively match the course of various storm indices for Stockholm [20]. The described feature may be interpreted as indicating a rotation in the wind (and wave approach) directions in storms in the Gulf of Finland [28]. This interpretation is consistent with changes in the statistics of wind directions in the Estonian mainland [7]. The changes match quasi-periodic long-term (25–30 y) cycles in many storm-related data sets in the Estonian coastal sea [30] and may mirror the shift of North Atlantic storm tracks [10].

The inclusion of the data from November 2012–February 2014 considerably modifies the pattern of storms responsible for the highest waves and wave set-up values (Fig. 6c). While until October 2012 about a third of all-time highest wave set-up values were created in the 1980s (Fig. 6b), many such values stemming from 1981–1982 were overridden from November 2012 onwards. During this shorter than 1.5-y time interval (that only includes two windy seasons) as many as 24 storms apparently created new all-time (since 1981) highest wave set-up values. The year 2013 contained 18 such storms. The total number of storms responsible for the highest wave set-up increased from 50 during the time interval of January 1981–October 2012 to 58 during the time interval of January 1981–February 2014.

As the extension of sea ice was quite limited in the Gulf of Finland in winters 2012/2013 and 2013/2014, the reconstructed wave properties apparently match well the actual wave fields. The majority of highest wave set-up values now stem from 1995 onwards (Fig. 6c). The described changes in 2012–2014 may be interpreted as

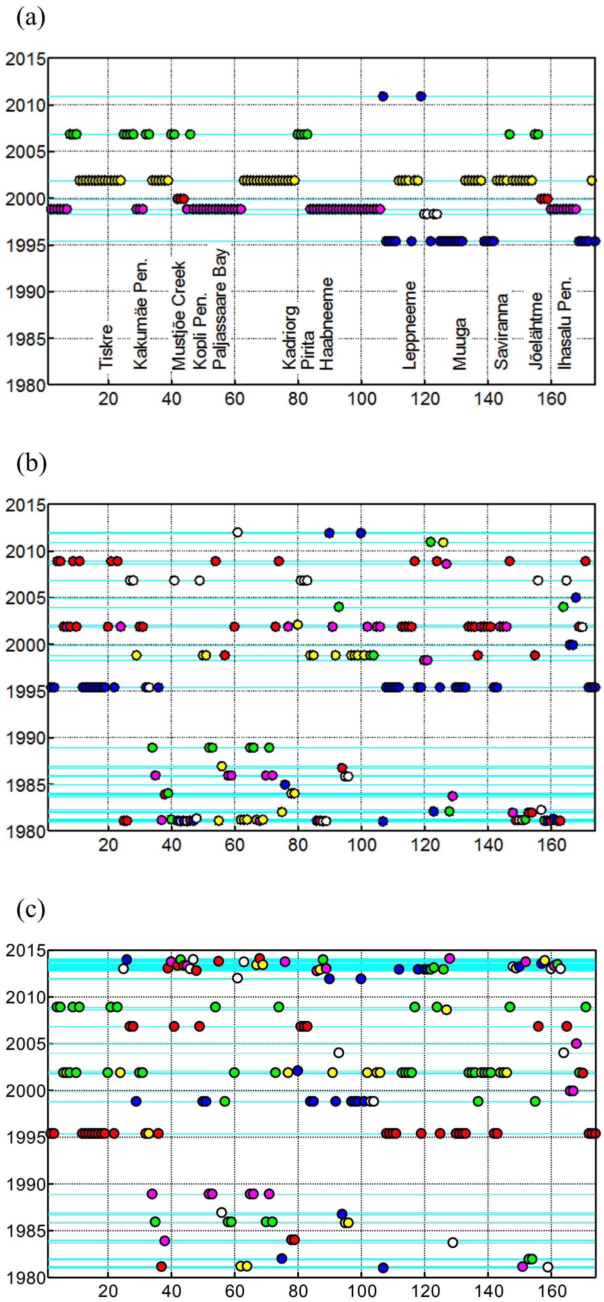

Fig. 6. (a) Six storms that caused the highest waves in different coastal sections of the study area in 1981–2014; (b) 50 storms, and (c) 58 storms that caused the highest wave set-up in these sections in January 1981–October 2012 and in January 1981–February 2014. The horizontal lines indicate single storms that produced the highest wave set-up at least in one section. Each storm is marked with a single colour. The colours vary cyclically. Note that the Kalbådagrund data set does not contain information about the wind speed during the maximum and aftermath of the extreme eastern storm on 29–30 November 2012. Therefore the largest waves approaching from the east may be missing in our reconstructions. See Fig. 2 for the numbering of coastal sections.

an implicit evidence that strong (north-)easterly winds have returned to the Gulf of Finland region. This conjecture is to some extent supported by recent wave measurements. The highest significant wave height in the Gulf of Finland (where the largest waves usually occur during westerly storms) reached for the second time its all-time maximum (5.2 m, first measured in 2001) in an easterly storm in November 2012 [19].

The temporal distribution of storms and associated wind directions during which the all-time highest total water levels were created appears greatly different from the above. Two storms were responsible for all of the overall highest water levels at the shoreline (Fig. 7). Almost all coastal sections had the overall highest water level during an exceptional storm on 8–9 January 2005 [25]. The maximum offshore water levels extracted from the RCO model reached 1.6–1.7 m in the study area. These values slightly exceed the maximum observed water levels (1.52 m [29] and 1.55 m [6]). Although the pattern of storms that were responsible for the highest wave set-up events is remarkably different (Fig. 6), in some coastal segments quite high contribution of wave set-up was apparently present during the two storms. Even if none of the 33-y highest wave set-up events occurred during the January 2005 storm, the contribution of wave set-up into the total water level was substantial (Fig. 4). The distribution of wind directions during the highest total water level occasions (Fig. 7) once more confirms that coastal sections that are open to the west or north-west are the most likely candidates for exceptional total water levels owing to simultaneous occurrence of the high offshore water level and large waves that propagate almost directly onshore.

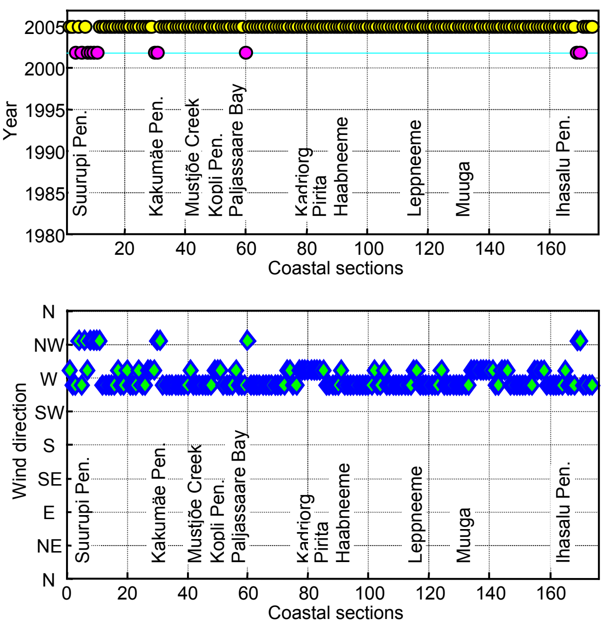

Fig. 7. Storms (above) and wind directions (below) that were responsible for the highest total water levels at the shoreline. See Fig. 2 for the numbering of coastal sections.

6. CONCLUDING REMARKS

The presented results show that wave set-up may act as an important component of marine-induced coastal hazards not only on the open ocean coasts (that are often impacted by high waves) but also on the shores of semi-sheltered relatively small water bodies such as the Baltic Sea. Similarly to the open ocean coasts [2], the extreme values of wave set-up may be over 50% of the maximum offshore water levels. The actual contribution of wave set-up to the total water levels at the shoreline is smaller in areas that are sheltered with respect to waves approaching from predominant wind directions. In these sections the high offshore water levels normally do not occur simultaneously with large wave set-up heights. Owing to such a mismatch the actual contribution of wave set-up generally does not exceed 0.5 m in the study area in the Gulf of Finland. This contribution, however, may represent a substantial hazard to certain coastal sections: the theoretical maxima of the total water level at the shoreline may reach well over 2 m in locations that are favourable for the formation of wave set-up. Wave set-up phenomena normally do not occur if the coast is protected by a seawall or by natural obstacles such as reed, bushes, or stones [2]. Still, it is likely that up to 50% of the study area may be potentially affected by high set-up [28].

The extensive alongshore variation of the wave set-up heights is a reflection of the significant dependence of this phenomenon on the match of the wave propagation direction and the geometry of the coastline. As the return period of unfavourable combinations of wave properties is considerably larger than that of just high waves or water levels, more effort is needed to establish adequate statistics of wave set-up heights. Moreover, every coastal segment seems to have its own ‘perfect storm’ in terms of wave set-up. This feature highlights the particular role of wind direction in the formation of the highest water levels. The most dangerous situations (in which the total water level at the shoreline may substantially exceed the all-time maximum for the off-shore water level) are likely to occur during (north-) westerly storms and in coastal sections that are open to the north-west.

The seeming (possibly cyclic) rotation of wind direction in strong storms and especially the return of strong (north-)easterly wave storms in the Gulf of Finland in 2012–2014 may lead to a situation where some other coastal sections will experience very large wave set-up heights. There are, however, obvious limitations for such changes in the study area. Storm tracks that cross Estonia to the south create strong northerly winds (and waves) along the northern coast but do not yield remarkably high sea level events in the Gulf of Finland. Cyclones that pass Estonia to the north yield strong westerly winds. They have a larger potential to raise sea level, but limited fetch for waves along the study area. A better 'synchronization' of a high offshore water level and large wave set-up can occur along the western coast of Estonia and along the coasts of Latvia and Lithuania.

Finally, we would like to emphasize that the presented results have been obtained using simplified schemes of the calculation of wave properties, a one-point wind data set with considerable gaps, and partially unrealistic assumptions for the formation of wave set-up on ideal beaches. In particular, no specific validation of the simulated wave properties has been performed. Therefore, the quantitative outcome of this research should be taken with caution.

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Laineaju roll veetaseme kujunemises Tallinna lahe ümbruse randades

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Laineaju ehk murdlainetes lisanduv veetõus on mittelineaarne nähtus, mida põhjustab lainete murdumise käigus vabanev impulss ja mille tõttu võib üksikutes rannaosades (kuhu suured lained saabuvad peaaegu risti rannaga) veetase rannajoonel arvestataval määral tõusta. On analüüsitud laineaju osakaalu ekstreemsete veetasemete kujunemisel Tallinna ja Muuga lahe randades. Laineaju maksimaalne kõrgus leitakse aastate 1981–2014 jaoks arvutatud tuulelainetuse parameetrite alusel. Oluline lainekõrgus, lainete tipp-periood ja lainelevi domineeriv suund on leitud lainemudeli WAM kolmeastmelise rakenduse abil. Mudelite hierarhia kasutamine võimaldab leida vajalikud suurused lahutusvõimega ligikaudu 470 m. Veetase avamerel on leitud nn Rossby Centre (RCO, Rootsi meteoroloogia ja hüdroloogia instituut) hüdrodünaamilisest mudelist. On näidatud, et laineaju võib üksikutes rannalõikudes tõsta veetaset 0,7–0,8 m võrra. Kõrgeim mõõdetud avamere veetase uuringualal on 1,52–1,55 m. Kõrgeimad avamere veetasemed ei esine üldjuhul samaaegselt ülikõrgete laineaju situatsioonidega. Laineaju roll kõigi aegade kõrgeimate rannaäärsete veetasemete kujunemisel on siiski märkimisväärne, lisades mõnedes rannaosades kõigi aegade kõrgeimatele avamere veetasemetele kuni 0,5 m. Laineaju osakaal aasta kõrgeima veetaseme kujunemisel varieerub oluliselt. Suurim tähtsus on laineajul üldiselt lääne või loode poole avatud randades ja lääne- ning põhjakaare tormidega.