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Geodetic Reconciliation of Tide Gauge Network in Estonia

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Abstract

A network of automatic tide gauges (TG) is managed by the Estonian Environmental Agency. During the recent reconstruction of Estonian high-precision levelling network the local TG ties were remeasured. Estonia adopted EVRS (European Vertical Reference System) based height system in 2018. This datum change caused the previous heights (belonging to the obsolete 1977 Baltic Height System, BHS77) to increase from 14 cm to 25 cm in a north-westerly direction. Accordingly, the tide gauge records had to be corrected. This study also analyses corrected time series of 14 TG-s along the Estonian shoreline of a four years (2014–17) period. Statistical analysis reveals improvements in the consistency of the TG time-series. The standard deviation has decreased from 4.4 cm (BHS77) to 2.7 cm (EH2000), the improvements due to new adjustment in EVRS system and taking into account effects from glacial isostatic adjustment. Records of some Finnish tide gauges (located at the northern shores of Gulf of Finland) are used for verifying the study results. New, corrected data can be used for various regional and interdisciplinary studies, e.g., confirming the land uplift values along shorelines.

Keywords: tide gauge network, high-precision levelling, EVRS

1 Introduction

Vertical datums are often based on tide-gauge determination of historical mean sea level. For that purpose the mean sea level is measured during a suitable time period in order to define the reference surface for the height system. The European Vertical Reference System (EVRS) is referred to the Normaal Amsterdam Peil (NAP). It is advisable to connect tide gauges (TG) to national height network in order to monitor and predict adequately the sea level fluctuations and oceanographic processes, as well as vertical land motions (VLM) along the entire shore of a country.

Estonia is located in a VLM region, where the post glacial land uplift varies from 0 mm/year in South-East Estonia up to 3 mm/year in North-West Estonia, see Fig. 1.

TG records, complemented by Global Navigation Satellite System (GNSS) Continuously Operating Reference Stations (CORS) time series, help to determine the magnitude of land uplift velocities, thus enabling to monitor (and account for) the deformations in the vertical datum.

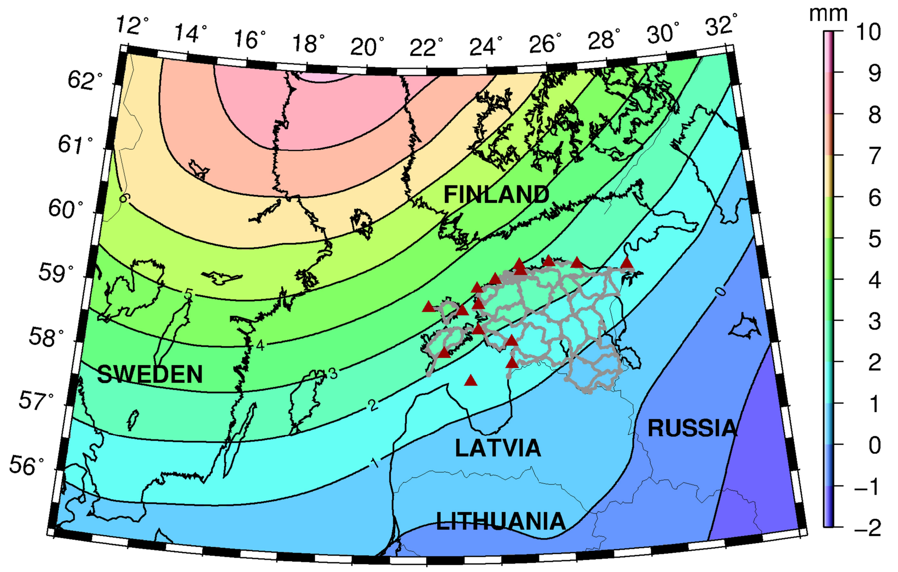

Fig. 1. The Fennoscandian land uplift (according to NKG2016LU model by Vestøl et al. (2019)) over the study area (red rectangle) and adjacent regions. The red triangles denote Estonian tide gauge stations, the gray dots denote levelling benchmarks along the national high-precise levelling routes.

The reconstruction of Estonian high-precision levelling network was conducted within 2003–2016 (*Kollo et al.*, 2017). The network comprises 3144 benchmarks, with the total length of levelling lines of 4238 km, the average distance between adjacent levelling benchmarks being thus 1.4 km. The NKG2005LU land uplift model (*Ågren and Svensson*, 2007) was used to refer the levellings of different years to the common epoch 2000.0. The network adjustment yielded the average uncertainty ±1.76 mm for the resulting normal heights, see (*Rüdja*, 2016, p. 23). The new network enabled Estonia to adopt the new EVRS referred normal heights EH2000 starting from January 1, 2018 (*Estonian Ministry of Environment*, 2017). This datum change causes the previous height values (belonging to the obsolete Baltic 1977 height system BHS77) in Estonia to change considerably.

The reconstruction extended the national height network to the existing TG in a way that the distance between new benchmark and the TG station would not exceed 300 metres. This gives the possibility to refer tide gauges rigorously to the national height system and check the TG readings during the exploitation. Previously most of the Estonian TG stations were connected to some local benchmarks (LBM), which were only loosely connected to the previous national height network. In many occasions these historical connections (the typical length varies from 2 to 10 kilometres) were established by non-geodetic organisations via simplified geometrical levellings. Often there is no knowledge, whether these connections were checked by repeated levellings during the decades of exploitation.

The recent switchover to EVRS forced us to revise and recalculate TG data, i.e., due to improved connections to the national height network. The overall goal of the present data reconciliation exercise is to obtain the coherent time series for all the tide gauges along the Estonian coastline. This gives possibility to specify sea level records (and corresponding mean sea level estimates) with respect to NAP. This knowledge can also be useful for studying marine processes and for verification of near-coast satellite altimetry data (e.g., Sentinel 3, see *Birgiel et al.,* 2018, 2019) and hydrodynamic models. Previous analysis of the Estonian TG data include studies by *Jevrejeva et al*. (2000), *Liibusk et al*. (2014) and *Suursaar and Kall* (2018).

Outline of the paper is as follows. This introductions is followed by a review on interrelations between TG and vertical datum, which are then adapted to the Estonian tide gauge network. Thereafter the data used and performed calculations are explained. Conclusions and discussion conclude the paper.

2 Review on interrelations between tide gauge data and vertical datum

In this section interrelations for determining rigorous sea level heights from erroneous historic tide gauge records are reviewed (cf. Fig. 2). This includes also transfer from an old vertical datum to new one. For the sake of simplicity the discussion refers to the usage of level staffs, but can also be adapted for modern pressure sensor based tide gauges (see e.g., *Liibusk et al.,* 2013). Note also that usually the pressure sensor based tide gauge stations are also equipped with level staff, the visual readings of which are to be used for verification of the pressure gauge records and determining/elimination the sensor drift (see e.g, *Liibusk et al.,* 2013).

Tide gauge readings are expressed with respect to the tide gauge zero (TGZ), i.e., the reference value on the level staff (at the time of its installation $t_{install}$). Often the planned height H_{TGZ}^{plan} of the TGZ is aimed at to correspond to the value $H = 0.000$ m in the contemporary vertical datum. Hence, the recorded sea level heights $H_Z^{rec}(t)$ are computed from tide gauge readings dz at time-instant t as:

$$H_Z^{rec}(t) = H_{TGZ}^{plan} + dz(t). \quad (1)$$

H_{TGZ}^{plan} is determined via geometrical levelling (height difference dH) with respect to the height H_{LBM}^{old} of nearby located LBM:

$$H_{TGZ}^{plan} = H_{LBM}^{old} - dH \quad (2)$$

where the superscript *old* refers to the to the previous vertical datum and dH is the height difference between the LBM and TGZ at the time of installation of the level staff. The negative sign is assigned to *dH* in order to be in accordance with Fig. 3. The predefined TGZ remains usually unchanged for the entire life-time of level staff.

Errors may occur in the determination of the right hand side terms of Eq. (2) during measurements. These errors will also affect the recorded sea level heights, see Eq. (1). Due to the short levelling distances the dH error is expected to be insignificant, though.

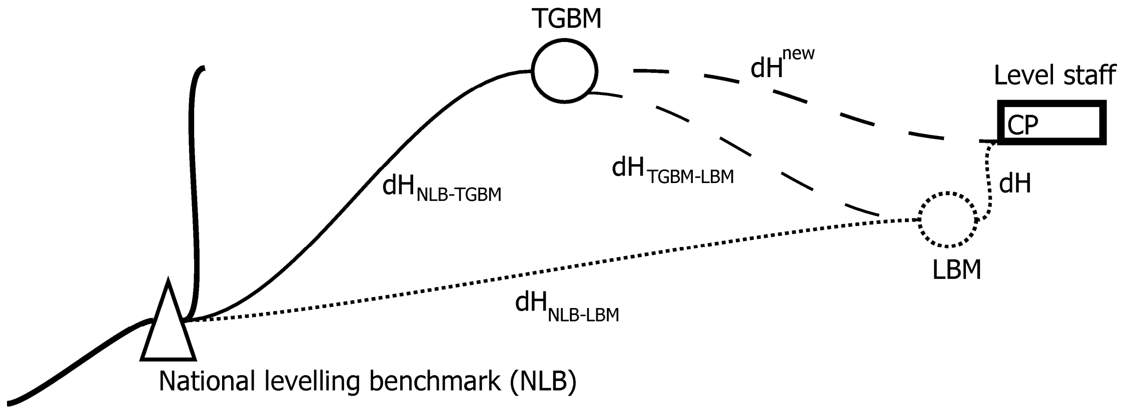

Fig. 2. Interrelations between level staff, tide-gauge benchmark (TGBM), local benchmark (LBM) and interconnecting levellings. The solid lines denote the routes of recent high-precision national levelling network, the dashed ones denote the local levellings, and the dotted line shows the historic connections between the national network, LBM and level staff.

Note that the LBM height is determined with respect to the national height network at the time of the TG installation. If the levelling is performed non-rigorously (and non-repeatedly), then the total levelling error would yield an erratic H_{TGZ}. Hence, a discrepancy du between the planned and the actual height H_{TGZ}^{actual} of the TGZ may occur. In other words this error will manifest as an offset in the TG time series. The magnitude of the discrepancy can be identified from a high-precise levelling of the LBM, e.g. with respect to the newly established national benchmark (that can also be used as the new TGBM) as:

$$du = H_{LBM}^{spec} - H_{LBM}^{old} = H_{TGZ}^{actual} - H_{TGZ}^{plan} \quad (3)$$

where H_{LBM}^{spec} is the specified height of the local benchmark at the time of new levelling (t_{lev}) and H_{TGZ}^{actual} is the actual height of the tide gauge zero. If LBM has disappeared in between the initial and recent high-precision levellings, then the du can be determined by levelling the TGZ mark from the new TGBM, i.e., by comparing the H_{TGZ}^{actual} and H_{TGZ}^{plan} directly, see Eq. (3). H_{TGZ}^{actual} can be computed as:

$$H_{TGZ}^{actual} = H_{TGBM} - dH^{new} \quad (4)$$

where H_{TGBM} is the height of the new tide gauge benchmark and dH^{new} is the new height difference between tide gauge benchmark and the tide gauge zero.

The numerical value of H_{TGZ}^{actual} at $t_{install}$ can be determined from specifying new high-precision levelling (conducted in the time epoch t_{lev}), subtracting the discrepancy du as:

$$H_{TGZ}^{actual}(t_{install}) = H_{TGZ}^{actual}(t_{lev}) - du \quad (5)$$

Over the time also the vertical land motion will affect (either increase or decrease, depending on the sign of the initial offset) the offset in the TG data series. If the specifying height difference dH^{spec} is determined years later, then du will contain also the impact of VLM. The numerical value of VLM can be deduced from existing land uplift model.

Hence, if $H_{TGZ}^{actual}(t)$ at given time moment t in the past is of interest then this can be computed retrospectively:

$$H_{TGZ}^{actual}(t) = H_{TGZ}^{actual}(t_{lev}) - du - VLM * (t_{lev} - t) \tag{6}$$

where VLM is given in the units of metre/year, and the term in the brackets is given in units of years.

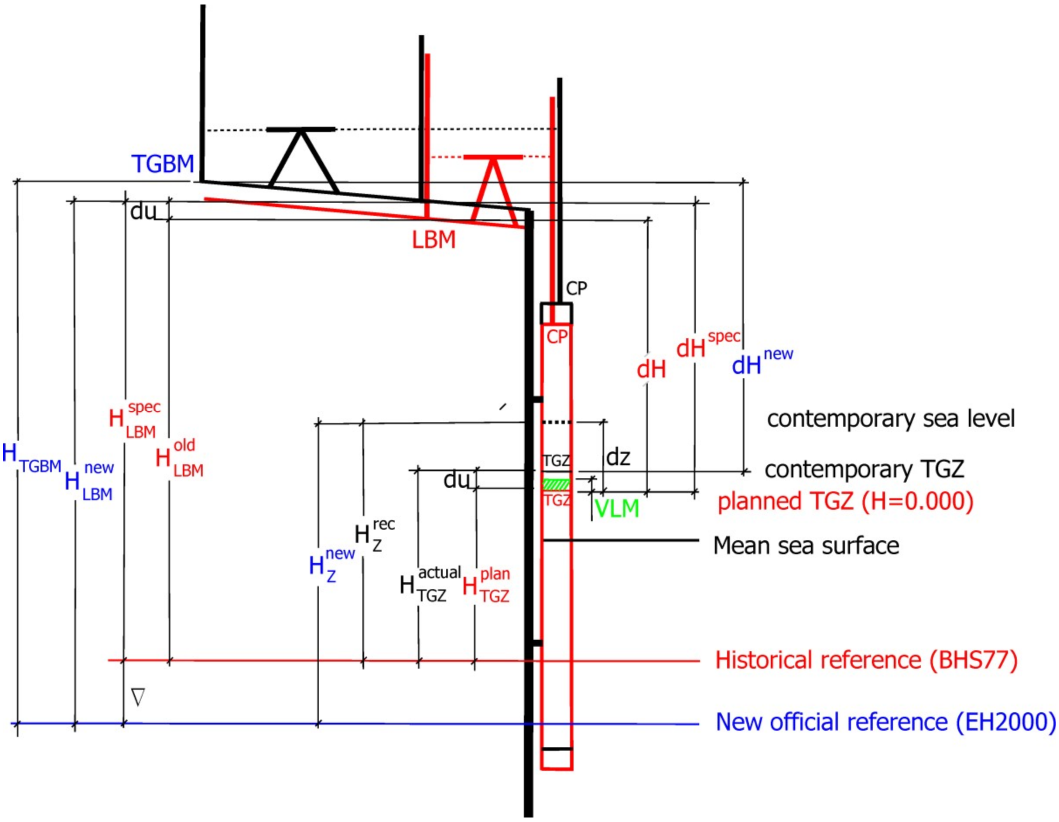

Fig. 3. Interrelations between measurable quantities and reference surfaces. The red contours reflect initial (possibly erratic) situation and the blue contours refer to new height determination. For all the used symbols see the text.

Hence the true (unknown) tide gauge reading H_Z for any given time instant t can be retrospectively computed as (cf. also Eq. (1)):

$$H_Z^{actual}(t) = H_{TGZ}^{actual}(t) + dz(t) \tag{7}$$

Note that H_Z^{actual} increases with respect to the initial H_Z^{rec} (Eq. (1)) when H_{TGZ}^{actual} is numerically larger than H_{TGZ}^{plan} and vice versa.

Strictly speaking, also the tide gauge reading $dz(t)$ will inevitably have random errors, but these can not be corrected retrospectively. It is assumed, however, that the initial TG records consider drift corrections (see e.g., *Liibusk et al.,* 2013).

In a special case when the high-precision levellings are related to the establishment of new national height system, then the LBM height (and that of TG records) needs also to be corrected for the difference between new and old height systems:

$$\Delta = H_{LBM}^{new} - H_{LBM}^{spec} \tag{8}$$

where superscript *new* refer to the new height system; Δ denotes the difference between previous and new height systems at the location (φ, λ) of the particular tide gauge. If LBM has been disappeared, then the connection can be established via relevelling of TGZ. Note that due to *VLM* (either local or regional) the numerical value of Δ may vary within a country. Δ can be determined alternatively by using either the transition model between old and new height datums or a geoid model. Considering also difference between previous and old vertical datum then Eq. (7) can be elaborated into:

$$H_Z^{new}(t) = H_{TGZ}^{actual}(t) + dz(t) + \Delta(\varphi, \lambda) \tag{9}$$

where $H_Z^{new}(t)$ is corrected TG series in the new height system. We have arrived at the expression that allows to rigorously correct the historic tide gauge records for the initial errors and the difference in-between the height systems. The conversion of H_Z^{rec} into H_Z^{new} may also be needed in comparisons with tide gauge series from neighbouring countries. The above expressions describe a general case, which are to be further adapted for a case study.

3 The case study: reconciliation of Estonian tide-gauge data

A network of coastal tide gauges is operated by the Estonian Environmental Agency (EEA). Nowadays the network includes 14 tide gauge stations (*EEA*, 2018), see Fig. 1. These are established in local harbours, each tide gauge station is equipped with the level staff (which enables visual measurement of the instantaneous sea level) and continuously recording pressure sensors. The EEA is responsible for the maintenance and data analysis of the tide gauge network.

Once a year the elevations of the level staff (i.e., their contact point CP, which is usually the upper part of the level staff, from which the TGZ is determined, see Fig. 3) are spirit levelled by the Department of Hydrology of the EEA. Historically the nearby (within 200–300 metres) established LBMs were used as initial for height determination. Nowadays LBMs are not used any longer, as the renovated national levelling network is extended to the tide gauges. Estonian Land Board has re-measured the height differences between national benchmark nearest to the harbour and level staff by using high-precision levelling methodology and modern digital levelling instruments in 2017–2018. The new national benchmarks have already been adopted as initial TGBM for recent levellings of the EEA as well, cf. Fig. 2.

Monthly field checks of the tide gauges stations are performed by EEA. The visual control measurements are taken to compare the level staff readings with that of the pressure sensor at the same time instant. If the readings differ more than three centimetres (i.e. the threefold accuracy of the visual reading), then the automatic records of the preceding period are corrected retrospectively. This drift correction is due to time-dependent drift phenomenon of the used pressure sensors (for more details see *Liibusk et al.,* 2013).

This study analysed altogether 14 TG data streams for the period 2014–2017. Note that in 2013 all level staffs from EEA TG network were changed and relevelled, and thus the compatible TG records can be obtained for this 4-year period. Hourly averaged and drift corrected TG readings $dz(t)$ and the used H_{TGZ}^{plan} were received from EEA.

The magnitude of du was determined from the comparison of the new and historic levellings by using Eq. (3), for the resulting numerical values cf. Table 1. The land uplift estimates (see the VLM term in Table 1, also Eq. 6) were obtained from the *Ågren and Svensson* (2007) model. Estonia adopted the new EVRS referred normal heights EH2000 starting from 2018. This datum change causes the previous height values (belonging to the obsolete Baltic 1977 height system) in Estonia to increase from 14 cm to 26 cm in a north-westerly direction (correlates with the land uplift phenomenon in Fig. 1), i.e., from the periphery of the Fennoscandian postglacial rebound toward its epicentre. The corrections Δ (cf. Eq. 8) are based on height differences of LBM (or TGZ) in the BHS77 and EH2000 vertical datums (Table 1). The corrections were as well checked to be consistent with the computed height transition model BHS77-EH2000 (*Rüdja*, 2016) and the vertical datum fitted EST-GEOID2017 model (*Ellmann et al.*, 2019, Fig. 11).

Table 1. The numerical values used in Eqs. (6) and (9) for the Estonia TG stations. The TG stations are listed starting from the eastmost one moving westwards along the shoreline, cf Fig. 1.

TG station	du at 2017 [cm]	VLM [mm/year]	Δ Difference EH2000-BHS77 [cm]	STD of dz 2014–2107 [cm]	MSL in EH2000 2014–2017 [cm]	MSL in BHS77 2014–2107 [cm]
Narva-Jõesuu	-1	2.0	19.2	10.7	29.1	9.9
Kunda	+3	2.7	21.6	10.6	26.0	4.4
Loksa	+2	3.1	23.1	10.1	25.9	2.8
Pirita	0	3.2	23.7	9.6	19.8	3.8
Rohuneeme	+1	3.4	24.2	10.4	21.5	-2.7
Dirhami	0	3.5	24.2	10.2	20.3	-4.3
Ristna	0	3.8	25.9	10.1	21.3	-4.8
Heltermaa	0	3.2	23.2	11.3	20.2	3.4
Haapsalu	-1	3.1	22.8	10.6	21.2	-1.6
Virtsu	+1	2.6	20.8	10.4	21.5	0.7
Roomassaare	0	2.6	18.9	10.4	20.8	1.9
Pärnu	+1	2.0	18.8	11.6	24.7	5.9
Ruhnu	-2	1.7	17.2	11.6	25.0	7.8
Häädemeeste	0	1.7	17.0	10.6	23.5	6.6
				$\overline{MSL}$ **[cm]**	**22.8**	**1.9**
				STD_{MSL}**[cm]**	**2.7**	**4.4**

The estimated du, VLM and Δ (see Table 1) allowed the TG time series to retrospectively correct by using Eq. (9). This yielded reconciled $H_Z^{new}(t)$ in the new national vertical datum EH2000.

4 *Computations of mean sea level*

The reconciliated $H_Z^{new}(t)$ were quality checked in several tests and analysis. The standard deviation (STD) of the readings reflects the inner consistency of the time series (for the entire period 2014–2017) at each tide gauge station, see Table 1 and Fig. 4 for the details. In general the STD remains within 10-12 cm, whereas the larger STD is associated with the rougher sea conditions at individual TG station. The smaller STD may also reveal sea sheltered locations of certain tide gauges.

The $H_Z^{new}(t)$ was then used for computing the annual mean sea level estimates for each TG station. Thereafter all the TG stations in the network were involved to compute the overall STD for the 4-year period as follows:

$$STD_{MSL} = \sqrt{\frac{\sum_{i=1}^{N}(MSL_i - \overline{MSL})^2}{N-1}} \tag{10}$$

where MSL_i denotes the MSL value for the entire period 2014–2017 at an i-th TG station, $\overline{MSL}$ denotes the averaged MSL for all TG stations in the network, and *N* denotes the number of TG-s (*N*=14 for Estonia).

The STD_{MSL} estimates as of 2.7 cm and 4.4 cm were achieved for EH2000 and BHS77, respectively. The STD of the nationwide mean sea level estimates (cf. Table 1) indicates the external consistency of the reconciled TG readings.

The smaller STD of the EH2000 manifests that the distortions in the vertical datum (e.g. due to the land uplift) have been properly accounted for. Also the elimination of the detected errors (cf. Table 1, column 2) in the LBM/TGZ heights contributes to the consistency of the reconciled TG time series. On other hand, the effects on the sea surface topography (SST) and eustatic sea level rise (*Liibusk et al.,* 2014) may also contribute to the STD_{MSL}.

For obtaining a more extended regional view the Estonian TG data were complemented with the Finnish Meteorological Institute tide gauge network data (*FMI*, 2018a). Six closest to Estonia tide gauge stations were used for verifying the consistency of reconciled Estonian tide gauge records. The yearly mean values were acquired, which were converted to N2000 (*FMI*, 2018b) and finally to EVRS, adding the shift of 1 cm, which is the difference between N2000 and EVRS in Finland (pers. comm. M. Nordman, 22.03.2018). The MSL and STD_{MSL} values for the selected Finnish TG stations were computed similarly to the Estonian TG stations. The separately computed STD_{MSL} for Finnish network yielded 3.9 cm.

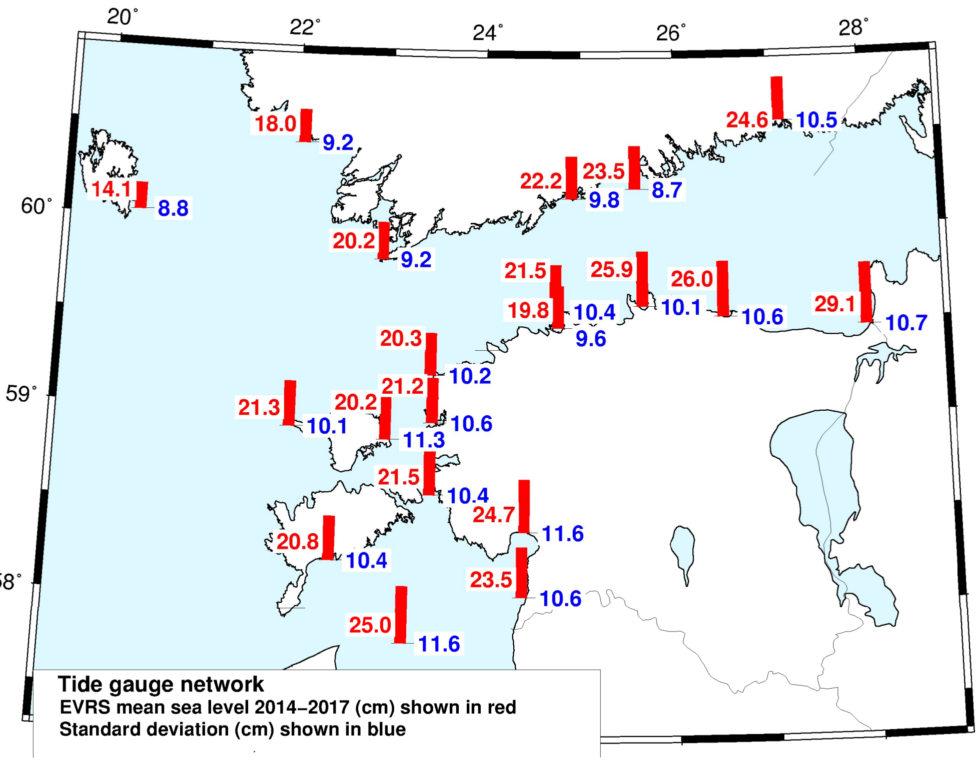

Fig. 4. The MSL (red) and STD (blue) values for the Estonian and Finnish TG stations for the period 2014–2017. STD_{MSL} is computed for the Estonian and Finnish TG networks separately.

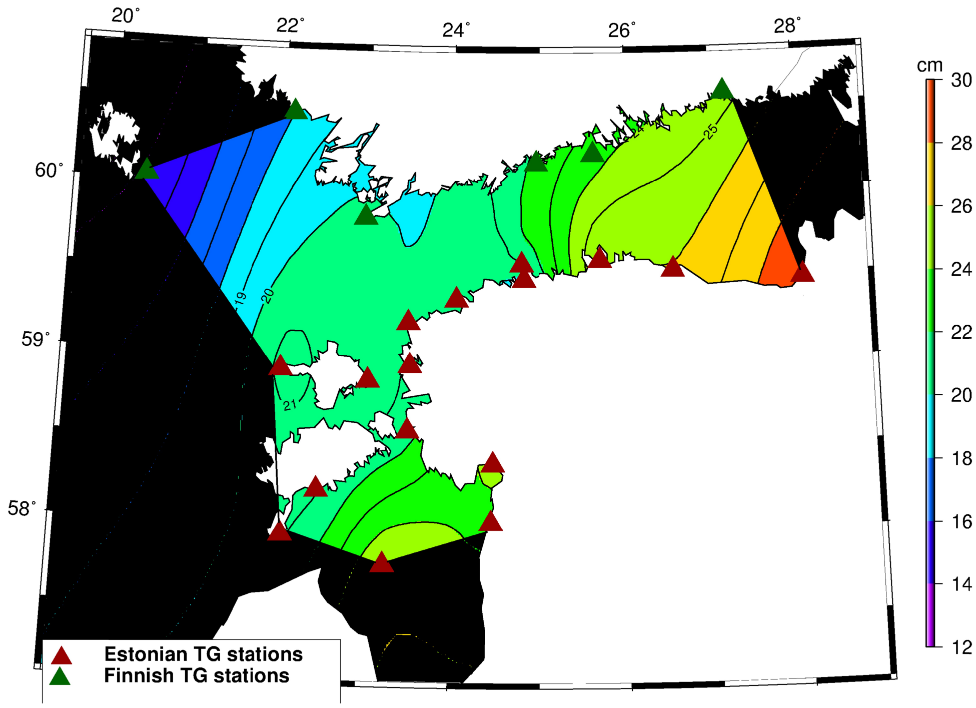

Fig. 5. Mean sea surface topography (as an average for the entire 2014–2017 period) with respect to NAP in the eastern part of the Baltic Sea. The red and green triangles denote the used Estonian and Finnish tide gauge stations.

The mean SST increases eastwards in Gulf of Finland (cf. Fig. 5). This agrees with earlier SST and sea level studies (*Ekman and Mäkinen*, 1996; *Kakkuri and*

Poutanen, 1997; *Lyszkowicz and Bernatowicz*, 2018). It can be concluded that the TG data reconciliation provides meaningful results.

5 Concluding remarks

The overall goal for this study was to reconcile the Estonian TG data. This yielded corrected and coherent sea level heights along the Estonian coastline with respect to Normaal Amsterdam Peil. This geodetic reconciliation of TG data became possible only after final adjustment of Estonian height network and adoption of the new EVRS based vertical datum in Estonia. Altogether 14 tide gauge time series were reconciliated and statistically analysed. For a more extended regional verifications Estonian data were complemented with data from the southern part of the Finnish TG network.

The re-computation yielded better compatibility of the data in the new national vertical datum. This demonstrates that EH2000 is more consistent than the previous BHS77. This is achieved by eliminating the detected levelling errors as well the impact of the postglacial land uplift.

The mean SST obtained by this study (Fig. 5) shows that the sea level increases towards eastern coast of the Gulf of the Finland, which is in accordance with the previous studies (*Ekman and Mäkinen*, 1996; *Kakkuri and Poutanen*, 1997; *Lyszkowicz and Bernatowicz*, 2018).

The obtained rigorousness of TG records is essential for regional land uplift studies, bridging the coastal gap between the land geodetic infrastructure and open sea satellite altimetry data products, validating hydrodynamic and marine geoid models. Even though the data period for this study was short, the results encourage us to extend our study to the longer time spans (up to 40 years) in future studies.

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