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Published in:
SCIREA journal of geosciences

DOI:
10.54647/geosciences17154

Published: 24/03/2022

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Girgibo, N., Lu, X., Hiltunen, E., Peura, P., Yang, T., & Dai, Z. (2022). A conceptual framework for the future of sea-level rise and land uplift changes in the Vaasa region of Finland. *SCIREA journal of geosciences*, *6*(1), 23-57. https://doi.org/10.54647/geosciences17154

SCIREA Journal of Geosciences

http://www.scirea.org/journal/Geosciences

March 24, 2022

Volume 6, Issue 1, February 2022

https://doi.org/10.54647/geosciences17154

A conceptual framework for the future of sea-level rise and land uplift changes in the Vaasa region of Finland

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Abstract:

This paper uses the Vaasa region of Finland as an illustrative case study to explore how the relationships between climate change, sea-level rise and land uplift may offer applications in forecasting future land uplift changes. Using a comparative literature review and analysis of open source data, a conceptual framework is developed to examine causes-effect relationships between them. The sea-level rise around the world by the end of the 21st century shows dramatic effects all over the world. However, the rate of land uplift in the Vaasa region is higher than the rate of sea-level rise. This localised finding is different from global average rates for land uplift and sea-level rise. This indicates that although climate change is global, it can lead to very different regional expressions. This paper presents a first attempt to combine sea-level rise and land uplift into a single cohesive framework to support future land uplift management. The results of this paper establish a conceptual framework for studies of vulnerability and adaptation to climate change that can benefit local, regional and global communities.

Keywords: land rising; climate change effect; coastal region; forecasting; cause and effect

Plain Language Summary (PLS)

The land uplift is a rising of land through time. Comparing land uplift and sea-level rise it was found that land uplift has higher rate of rise in city of Vaasa area where land uplift has been going on. The land uplift framework chart developed tries to generalize the overall causes of land uplift, patterns of uplift through time, how to measure land uplift and consequences of uplift. The results of this paper establish a conceptual framework for studies of vulnerability and adaptation to climate change that can benefit local, regional and global communities. One of the conclusions was that local changes are different from world climate change expectations.

Nomenclature

a = proportionality constant

Af = fast down-load factor (m)

As = slow down-load factor (m)

Bs = slow inertia factor (Y^{-1})

Bf = fast inertia factor (Y^{-1})

C = crustal change in meters

E = eustatic sea level rise in meters

h = sea level rise in meters

H = global mean sea level

N = number of articles and books used for synthesis

s = the shoreline sea level corresponding to h and t

S = shoreline sea level displacement in meters

t (years) = in the variable time

T = global mean temperature

T_o = initial equilibrium temperature value

Tf = the standard time for maximal uplift rate given by the reference

Ts= time in years for the maximal uplift rate set by the calculator (us)

U = average glacio-isostatic uplift in meters

Uf = fast glacio-isostatic uplift

Us = slow glacio-isostatic uplift

$Utot$ = total glacio-isostatic uplift

1. Introduction

The relationship between climate change, land uplift and sea-level rise is complex and the outcomes differ from place to place. Land uplift is defined as the change in land at the shoreline to give more land or change harbours [Okko (1967) and Girgibo (2021a)]. The sea-level rise is due to the increase in the volume of water contained in water bodies. This causes flooding and land swamping if the rise is significant. Sea-level rise is facilitated by greater solar irradiance due to climate change (Rahmstorf 2007).

Climate change is due to the 20th century human (anthropogenic) pollution (IPCC 2007). This is the majority scientific view, outweighing the counter belief that there is no climate change effect, or if there is, it is caused by natural effects. Climate change is a current issue that touches all aspects of the environment: land, water, ecosystem, weather, solar radiation and other areas of life (Hannah, 2011; IPCC, 2007; IPCC, 2019; IPCC 2021).

The greenhouse effect theory underpins the climate change issue. Anthropogenic pollutions, notably carbon emissions, cause different greenhouse gases to be trapped in the higher atmosphere. They act as a glass structure in the higher atmosphere, reflecting the latent heat emitted from the earth´s surface and facilitating the heat accumulation in the surrounding atmosphere (Hannah 2011). This is the global warming that is evident in rising average ambient temperatures. The consequences are a disturbance in ecosystems and melting of accumulated glacial ice, leading to sea-level rise and the associated effect of land uplift, felt most keenly on the shoreline.

The scientific evidence of the global threat of sea-level rise due to climate change is overwhelming (Dasgupta and Meisner, 2009). The rate of rising has been accelerating. from 1961 to 2003 the sea level rose 1.3 to 2.3 mm per year, averaging 1.8 mm per year. However, in the period from 1993 to 2003 the level rose by between 2.4 to 3.8 mm per year, averaging 3.1 mm per year (IPCC, 2007; Dasgupta and Meisner, 2009). These same sources forecast that the sea level will rise up to 1.0 m in the 21st century. The main causes of this rise are melting ice sheets in Antarctica and Greenland, water volume expansion due to water temperature increase (ocean thermal expansion) and/or glacial and ice-cap melting (Girgibo, 2021a; Dasgupta and Meisner, 2009). If we do not consider storms, it is shoreline land areas under the greatest threat of flooding and inundation from sea-level rise. The contemporary threat of sea-level rise has been examined extensively (Church and White, 2011; Ablain, M. et al., 2019; and IPCC, 2019).

According to Dasgupta and Meisner (2009), the biological or physical effects of sea-level rise on coastal regions can be: a) inundation, flood and storm; b) wetland loss; c) erosion; d) saltwater intrusion; e) coral bleaching (from higher sea-water temperature); f) ocean productivity change; and g) species migration. These effects can be especially catastrophic for developing nations. If the same authors´ most extreme forecast of a sea-level rise of 1.0 m were to occur in countries of the developing world, it would submerge 194,000 square kilometers of land and displace at least 56 million people. An increase in temperature can give rise to storm surges and a 1 ^{o}C temperature rise can cause a 3 – 5 % increase in wind speed (Dasgupta and Meisner, 2009). Consequently, the rising global temperature can bring about a high number of cyclones or storm surges. Floods and storms all over the world can be expected if climate change continues unabated. Gathering and analysing local data is an essential requisite for understanding the effect of climate change in specific regions.

The city of Vaasa is in the Pohjanmaa region on Finland´s western coast and the area closest to Vaasa is known for its archipelago and became a protected area as a UNESCO World Heritage Site in 2006. The EPI (environmental performance index) shows that Finland has a very good index compared to the world especially in air quality, sanitation and drinking water and heavy metals (EPI 2021). Studying the Vaasa region of Finland will help us to understand better the local effects of sea-level rise on land uplift and vice versa. There has been an assumption that the main cause of land uplift in the Vaasa region of Finland is the melting of the ice sheet, causing the earth core to rebound. We apply the theories of the greenhouse effect and global warming, ice melting and theoretical models of sea-level rise and land uplift to identify causality and investigate the combined effects of multiple issues, bringing them together in sharper focus. The main result is the forecast that future land uplift in the Vaasa region will surpass the sea-level rise.

Three principal research questions were set.

1. What are the key future trends and expectations for land uplift in local regions?
2. Can we fully understand the cause and effect of land uplift and sea-level rise?

3. How does climate change (sea-level rise) affect future changes of land uplift in the local area?

Four further questions were posed, designed to underpin the construction of a framework chart. First, what are the causes of land uplift? Second, what are the patterns of land uplift through time, and how should future uplift rates be assessed and calculated? Third, how is land uplift measured? Last, what are the consequences of land uplift? Most of the questions have worldwide relevance, instead of being specific to the Vaasa region.

The authors´ motivation to investigate land uplift and sea-level rise is derived from the forecast that in the local Vaasa region land uplift is expected to be the dominant movement (Nordman et al. 2020). In contrast, in most other areas of the world it is sea-level rise that is forecast to dominate. This highlights how the repercussions of climate change and its relationship with sea-level rise and land uplift can be very different and locally specific. The authors were inspired to investigate this further and, in particular, test the forecast for the Vaasa region. Additionally, the aim is to suggest potential solutions for coping with the challenges of land uplift and rising sea levels. There are knowledge gaps associated with the certainty of forecasting in both the Vaasa region and the world in general, and there is no framework for world land uplift management. This study´s forecast for the Vaasa region, its framework chart development and comparison between climate change, sea-level rise and land uplift in some areas of Nordic can be considered as contributions to fill these knowledge gaps.

2. Materials and Methods

The applied methodology is a qualitative study from literature data for empirical model validation. Specifically, framework chart development, theoretical data analysis calculations and empirical model with data validation will be conducted based on the literature data.

2.1. Climate change impact on sea-level rise

According to Rahmstorf (2007), there is a clear relationship between temperature change and sea-level rise:

$$dH/dt = a\,(T - T_o) \tag{1}$$

where, H = is the global mean sea level, t = is time, a is the proportionality constant, T = is the global mean temperature, and T_o = is the initial equilibrium temperature value (or baseline temperature of a 30-year average at which sea level is stable, as determined by the National Research Council, 2012).

Ice melting in ice sheets and ice caps leads to rise in sea level. It creates flooding in some places, so land near the shore maybe replaced by water, offsetting the effect of land uplift. But the land uplift and sea-level rise are not necessarily balanced, so the effects of these changes will vary (Nordman 2020), hence the coefficient a varies with regions, where 3.4 mm/year per ^{o}C is found in the relationship between global temperature and sea-level rise.

The sea-level rise in the equilibrium state can be obtained from Equation 1 as.

$$H(t) = a\int_{to}^{t} \left(T(t') - To\right) dt' \tag{2}$$

Table 1 summarises IPCC (2007 & 2013) data derived from modelling designed to quantify the future relationship between temperature and sea-level rise. This illustrates the direct link between the best estimate forecast temperature change (2090-2099) in ^{o}C and the corresponding sea-level rise in meters. Knowing the actual local area temperature change will help provide a better understanding of the forecast sea-level rise in the region, which gives insight into the future land uplift that can be expected.

Table 1. Projected global average surface warming and sea-level rise at the end of the 21st century (IPCC, 2007 & 2013).

	Temperature Change (in °C at 2090-2099 relative to 1980-1999) [a]		Sea-Level Rise (in meter (m) at 2090-2099 relative to 1980-1999)	
			Model-based range excluding future rapid dynamical changes in ice flow	
Case	Best estimate	Likely range	Range	Central estimate

Constant year 2000 concentrations [b]	0.6	0.3 – 0.9	NA	NA
Scenario 1	1.8	1.1 – 2.9	0.18 – 0.38	0.278
Scenario 2	2.4	1.4 – 3.8	0.20 – 0.45	0.325
Scenario 3	2.4	1.4 – 3.8	0.20 – 0.43	0.315
Scenario 4	2.8	1.7 – 4.4	0.21 – 0.48	0.345
Scenario 5	3.4	2.0 – 5.4	0.23 – 0.51	0.370
Scenario 6	4.0	2.4 – 6.4	0.26 – 0.59	0.425

Notes:

[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several earth system models of intermediate complexity and a large number of atmosphere-ocean general circulation models (AOGCMs).

[b] Year 2000 constant composition is derived from AOGCMs only.

Scenario description – these scenarios were used in IPCC (2007) study by various past and forecast description to vary between them (See IPCC, 2007). IPCC (2007) scenarios refers were here in the table as: B1 scenario = Scenario 1, A1T scenario = Scenario 2, B2 scenario = Scenario 3, A1B scenario = Scenario 4, A2 scenario = Scenario 5 and A1FI scenario = Scenario 6.

2.2. The relationship between sea-level rise and land uplift

Based on Okko (1967), the shore-line displacement along the Finnish coast combines of land uplift and eustatic changes in the sea level. Theoretically, ′′when the sea level changes insignificantly, land uplift causes a seaward displacement of the shore. A sinking sea level would add the apparent rate of this displacement′′ (Okko, 1967). In additions, land uplift shows the rate at which the crust is draws away the Earth′s centre or from a given point. The stable isotope study on southern Alaska shows that the uplift in the area has been occurring for millions of years (Bill et al., 2018).

According to Okko (1967), in some places land uplift exceeds the sea-level rise. In others, the two compensate for one another, and in some areas the sea-level rises are higher than land uplift. Figure 1 shows the theoretical model of the relationships between isostatic land uplift and sea-level rise. It depicts a previous model, dating back to 1967, attempting to forecast what we now know as the reality of the current situation. The diagram in the top left of Figure

1 depicts sea-level rise (h meters) from h_0 to h_4 during periods t_0 to t_4. Then, the sea-level remains stable during the same fifth period from t_4 to t_5. During the same five periods, land uplift is on the right, showing the successive amount of vertical movement: the oldest uplift from t_0 is the highest on the graph. The shoreline corresponding to h_0 and t_0 is marked s_0. In diagram V of Figure 1, the coast s_4 is called the transgression coast of the first order. The point s_3 is the uppermost shoreline, the transgression coast of the second order. The coast s_0 is the coast of emergence, and its lowest part contains a transgression coast of the third order. The other proposed model was in terms of the present uplift in Fenno-Scandia in order to demonstrate a sea-level rise and a crustal uplift. It was made in Okko (1967) paper, nine curves developed from different measurements on shores of Finland showing displacement for an arbitrary sea-level rise was calculated and presented at it. See Fig. 2 and page 10 in Okko (1967).

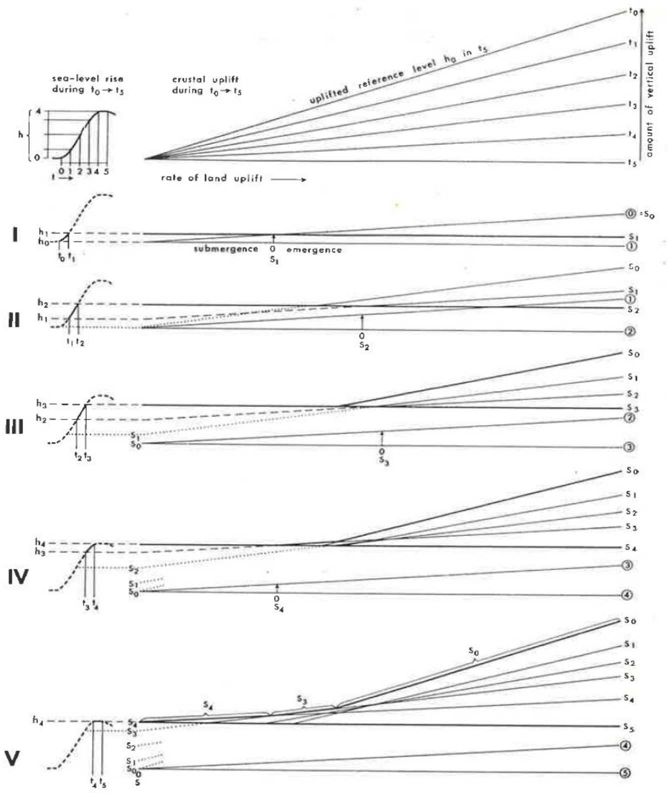


Figure 1. A theoretical model picture presenting the relationships between isostatic land uplift and sea-level rise is presented. The resulting raised shore surface is metachronous [re-presented from Okko, 1967].

A review of literature finds data relating to Finland obtained by oceanographic, hydrographic and geodetic methods. The prehistorical data were from the study of late-glacial (Late Weichselian) and postglacial shoreline displacement, using geological and archaeological methods. Table 2 lists the sources used for the literature review and summarises their key value for this study.

Table 2. The main initiation based on general sources and their use in this article as theoretical contributions.

Topic	Literatures utilised	Core subject	Issues investigated	Paper´s key findings	Conclusions made here based on this literature
Land rising	Okko (1967)	Theoretical model between sea-level rise and land uplift. Theory and definitions on land rising.	Is there the relationship between sea-level rise and land uplift?	Sea-level rise and land uplift have a close and relationship.	When calculating land uplift changes the consideration of sea-level rise is important.
	Kääriäinen (1953)	- Data and theory explanation in land uplift. An older view of land uplift.	What is the future land uplift level in Finland and Vaasa region?	The future land uplift in Vaasa will be 8.77 ± 0.30 mm/yr.	The future forecast of land uplift in the region is 8.77 – 9 mm/yr. Far future land uplift might show a decline.
	Poutanen & Steffen (2014)	Data and forecast in land uplift at Kvarken Archipelago.	Which and why will be the greater - land uplift or sea- level rise?	Future land uplift is much lower than sea-level rise in world data.	Future sea-level rise might be higher than land uplift and might differ in local areas.
	Steffen et al. (2016)	Data for land uplift and sea-level rise.	What is the uplift data relative to Baltic Sea mean level rise?	Data gained for land uplift and sea-level rise in various areas.	The data can be used for comparison data presented in this paper.
	Amante & Eakins (2009)	Data on Baltic Sea and world.	What is the topography and bathymetry data for Baltic Sea?	Data gained on Baltic Sea and world.	Data can illustrate the Baltic Sea land uplift.
Sea-level rise	Dasgupta & Meisner (2009)	Future sea-level rises will continue if no temperature decreases. Explanations about sea-level rise. The maximum sea-level rise expected in future due to climate change.	What is the expectation of sea- level rise with maximum temperature increase? How to explain sea-level rise?	If Antarctica ice sheet melts the world sea level rise will be 7 m or more.	If we do nothing about climate change, temperature will continue to increase and there will be much more flooding in most parts of the world.
	Rahmstorf (2007)	Relation between sea-level rise and temperature increase. - Formulas and calculations for temperature´s relation to sea-level rise.	What are the formulas used to calculate the relations between sea-level rise and temperature increase?	Calculations for sea-level rise and temperature increase can be used for forecasting.	Formulae can present the relation between the temperature increase and sea-level rise and can help us in forecasting future effects.

2.3. Cause-effect analysis of climate change, sea-level raise and land uplift

The historical data were used as the basis for cause and effect analysis. The principle used was to construct a diagram of the various causes and their individual effects in order to see and understand the aggregated outcome. This graphic and easily-accessible approach helps to determine the root of the problem and identify areas where data should be collected in future or where further studies are needed. Figure 2 presents the diagram depicting the world situation forecast of sea-level rise and land uplift causes and outcomes (effects).

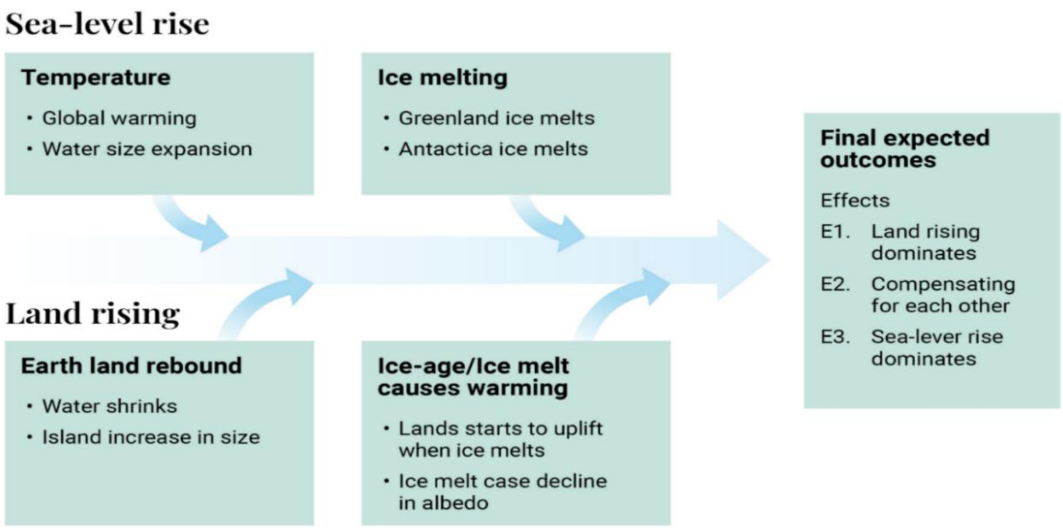


Figure 2. The world situation for forecast of sea-level rise and land uplift causes and effects (drawn by Andrei Palomäki).

The theoretical calculation of land uplift rate was also conducted based on the following model. Inclination or land uplift at the shoreline is the most evident effect of land uplift. The growth of land uplift can be affected by earthquake, although such seismic activity in Fennoscandia is not severe in global terms (Fjeldskaar et al., 2000). The inclination in land uplift occurred in Fennoscandia because the last ice age melt caused elastic uplift in the ground which had been depressed during the ice age. Påsse and Andersson, 2005, made calculations from empirical data in Scandinavia about ice affecting shore-level displacement and glacio–isostatic uplift in the area. The calculations show that the existence of a Baltic ice lake is questionable.

The formula presented by Påsse and Anderson, 2005, states shoreline displacement (S [m]) is due to the interactive vertical movements, crustal change (C [m]) and eustatic sea level rise (E [m]):

$$S = C - E \tag{3}$$

The area of former glaciated crustal change more or less is synonymous with glacio-isostatic uplift (U [m]). That means the shore-level displacement (S [m]) is expressed in Equation 4 as:

$$S = U - E \tag{4}$$

The calculations of glacio–isostatic uplift have been divided into two components: (1) the slow components (U_s) that occur most of the time and (2) the fast components (U_f) that occur at short intervals during deglaciation. Slow land uplift following unloading of ice (U_s [in m]) is calculated according to Equation 5 as:

$$U_s = \frac{2}{\pi} * A_s * [\arctan(\frac{T_s}{B_s}) * \arctan(\frac{T_s - t}{B_s})] \tag{5}$$

Where: A_s = down-load factor (m); T_s (years) = time for the maximal uplift rate -, i.e., the symmetry points of that arctan function; t (years) = in the variable time; and B_s (y^{-1}) = an inertia factor. The variables A_s and B_s are related to the specific point while T_s seems to be regional constant and is estimated to 1200 calendar years before present (BP) i.e., 10650 years if BP is counted in the conventional radiocarbon chronology (Påsse and Andersson, 2005).

Equation 6 is a general formula for the fast component:

$$U_f = \frac{2}{\pi} * A_f * \arctan [(\frac{T_f}{6.6 * A_f + 335}) - \arctan(\frac{T_f - t}{6.6 * A_f + 335})] \tag{6}$$

Where: U_f = crustal change (m) (fast uplift); A_f = down-load factor (m); T_f (years) = the standard time for maximal uplift rate given by Påsse and Andersson (2005), i.e., the symmetry points of arctan function; t (years) = in the variable time. B_f is estimated as 6.6 * A_f + 335. T_f has regional differences, varying between 11400 to 9400 calendar years BP, which indicates the fast uplift was an ongoing process during the termination of deglaciation (Påsse and Andersson 2005).

The eustatic sea-level rise is

$$E = \frac{2}{\pi} * 61 * \arctan\left[\left(\frac{9600}{1500}\right) * \arctan\left(\frac{9600-t}{1500}\right)\right] - \frac{2}{\pi} * 7 * \arctan\left[\left(\frac{11500}{350}\right) * \arctan\left(\frac{11500-t}{350}\right)\right] + \frac{2}{\pi} * 8 * \arctan\left[\left(\frac{12500}{350}\right) * \arctan\left(\frac{12500-t}{350}\right)\right] \quad (7)$$

Where: t (years) = in the variable time. The eustasy is calculated by the sum of three arctan functions. One is negative, in order to describe a retarded phase of the eustatic rise (Påsse and Andersson, 2005). The theoretical land rising calculation for the Vaasa region shows that the far-future land rising level will be the lowest, indicating that the rate of land uplift is slowing.

2.4. Steps for creating a conceptual framework

The starting point for developing the conceptual framework is the identifying the causes and effects of land uplift as shown in Figure 2. By applying diagram Figure 2 to the local region of Vaasa area in Finland, we found at least nine different causes or sources of land uplift (Kääriäinen, 1953; Fjeldeskaar et al., 2000; Hammond et al., 2016; and Girgibo, 2021a.): 1. The mass of the land and its attraction small to sea in its vicinity sinks due to the land seems to rise. 2. The ice mass in Polar Regions causes' water towards to pole then the other area land grows. 3. When the earth crust shrinks cause vertical movement. 4. The ice mass on ice age time cool down the earth crust when the ice melts start to warm up and rise. 5. Process connection to crystallization beneath the earth's crust, changes in volume taking place, cause land uplift. 6. The movement of earth crust due to periodic variation: the levelling of mountains (also cause weather formation) and flooding. 7. This was the cause of Fennoscandia land uplift, which is the ice mass, weighed the earth's crust, which is supposed to be flexible. Then the rising up to equilibrium happened when the ice melts. 8. The contents attract water, the larger the content the more water it attracts. This phenomenon depends on how much water in the content and the more water there is the more rain it attracts. 9. Causes of land rising mentioned here is by the earthquake in some areas of the world also was Fennoscandia (Fjeldeskaar et al. 2000). Even earthquake was also in some areas of Finland (Löfman 1999).

Findings during the framework development process identify several patterns of land uplift: regular growth; irregular growth; tilting of land during land uplift; and inclinations and elasticity in land uplift. Nine possible consequences of land uplift were also identified: 1. Land/island size growth; 2. The water trapped in land; 3. Drought; 4. Initiation and development of plantations; 5. Tilting of the uplift land; 6. Mountain area uplift affects sea and land surface temperature; 7. The land is not as viscous as it used to be (Fjeldskaar, 1997); 8. Sulphide-rich sediments generated by land uplift causes acidification and pollution (Boman et al., 2010); and 9. More rigid land not viscous anymore as it used to be. Figure 5 shows the framework chart developed in this article.

The procedure used in theoretical data calculations was also integrated into the conceptual framework developed. The six-step procedure used is as follows: First, using the map in Påsse and Andersson (2005) to identify the location to be analysed in the surrounding area. Second, set the time variables for analysis calculation. Third, select data from the same article for the chosen locations, data was provided by (Påsse and Andersson 2005) article for each location in map (Figure 3). Fourth, apply formulas numbered 3, 4, 5, 6, and 7 (presented below) to calculate: Us – slow uplift; Uf – fast uplift; Utot – total uplift; E – eustasy sea level; and S – sea-level displacement. Fifth, use the same formulas to calculate the data for each time selected variable and each location (make a similar table as Table 7, which is a result table in this article calculations). The sixth and final step is to use the calculated data in an Excel file to chart the change through time.

2.5. The Vaasa region and its literature data

The city of Vaasa is in the Pohjanmaa region on Finland´s western coast, bordering the Gulf of Bothnia. That particular part of the Gulf is called Kvarken and the area closest to Vaasa is known for its archipelago. It became a protected area as a UNESCO World Heritage Site in 2006, chiefly in recognition of its unusually fast land uplift and geological changes (Girgibo 2022, forthcoming). The land uplift rate in the Vaasa region is about 8.77 ± 0.3 mm/year (Kääriäinen 1953). This is much higher than the forecast world sea-level rise. Recent work by Nordman et al., 2020, compared land uplift rates and sea- level rises in coastal areas of

Finland, including the Vaasa region. They concluded that land uplift will continue to dominate the sea-level rise in the Vaasa region. This differs from the expectations for most other areas of the world. The empirical literature data compression performed for this current study confirms this expectation of the Vaasa region.

The map in Figure 3 shows the different positions of shore level curves used for land uplift calculation. The points numbered Ångermanland , S. Västerbotten, Rovaniemi and Lauhanvuori were used in the current study to calculate far-future uplift in the Vaasa region.

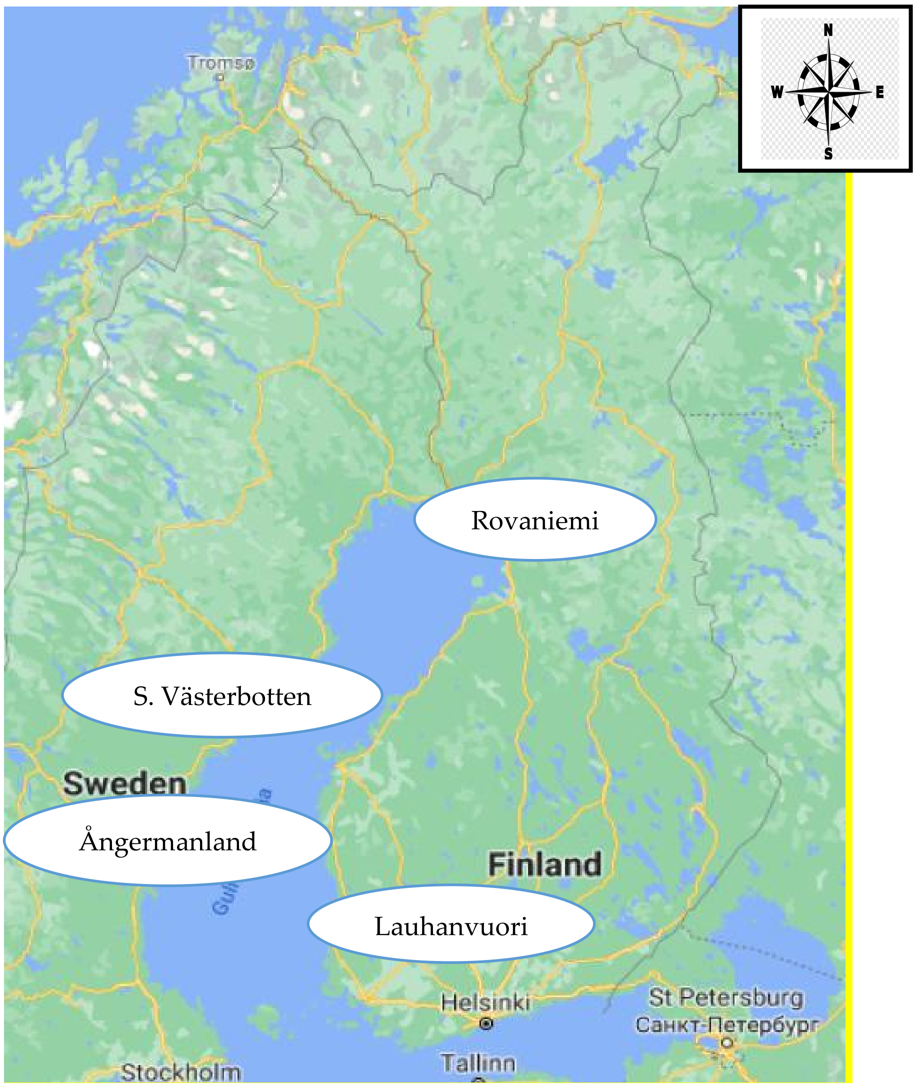
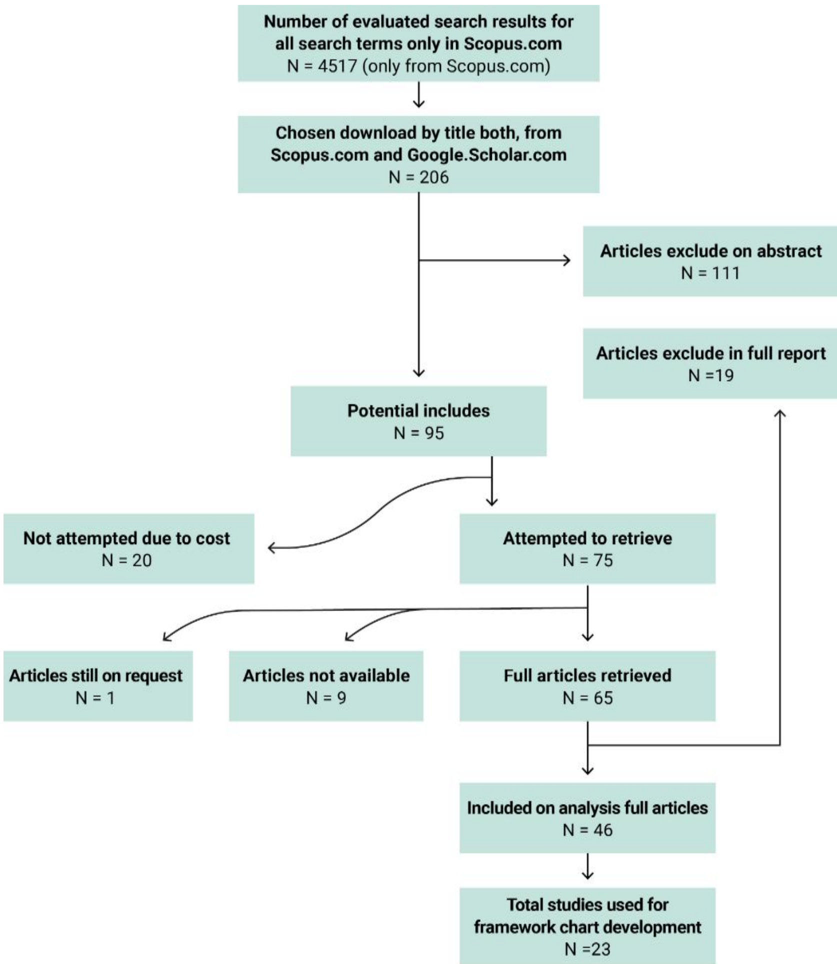


Figure 3. Positions of shore level curves are used in the calculation. Those used for Vaasa uplift calculations are locations Ångermanland , S. Västerbotten, Rovaniemi and Lauhanvuori (taken from google map and location adapted from Påsse and Andersson (2005) publications).

The data bases used in this literature review were Scopus, google scholar, science direct Elsevier journals, nature journals, google search engine. The main descriptors used for searching were: *Land rising and climate change connection, measurement of land uplift, compensation in land uplift, land uplift phenomena in Europe, Land uplift in the Vaasa region, Kvarken land uplift, and inclinations in land uplift.* Figure 4 shows the procedure used in systematic literature rereview.



A synthesis of research addressing land uplift, sea-level rise and their relationship.

Figure 4. Chart showing the flow of the literature search. N = number of articles and books used for synthesis (Brunton et al., 2006, and Booth et al., 2012). (Drawn by Andrei Palomäki).

2.6. Case study of the Vaasa region for validation of the conceptual framework

To empirically validate the conceptual framework developed previously, four specific areas on the Vaasa area– two in Sweden, two in Finland – were chosen with their data. See Table 3.

Their data relating to land uplift and sea-level rise rates in these areas were collected from various literature sources.

Table 3. The specific areas considered for theoretical data calculations for far-future forecasting and areas considered for empirical data validation analysis

The areas used in theoretical data calculation	Gereralised areas used for empirical data validation analysis
Ångermanland	Baltic Sea
S. Västerbotten	Vaasa region, Finland
Rovaniemi	Finland (generalised expectations and forecasts)
Lauhanvuori	Nordic area (Finland and Sweden)
	World (generalised expectations and forecasts)

Table 4 presents the study topics of the framework chart development, and the specific areas studied for each topic. The choice of specific area was determined during the literature synthesising and systematic literature review process.

Table 4. The specific areas considered for each section of the framework chart development.

Subsections of the framework chart development	Specific areas are considered for each subsection
1. Causes of land uplift	Generalised for whole areas of the world
2. Patterns of uplift through time	Fennoscandia and Sierra Nevada, USA
3. How to measure uplift?	Generalised for whole areas of the world
4. Consequences of uplift	Baltic sea area, Åland Islands, Sierra Nevada (USA), Kvarken archipelago, northernmost Gulf of Bothnia (Finland), Fennoscandia, North America, Yakushima rivers basins (Japan), subtropical eastern Pacific, and Vaasa region (Vassor Bay)
5. Empirical procedure based on Påsse & Andersoon (2005)	Ångermanland (Sweden), S. Västerbotten (Sweden), Rovaniemi and Lauhanvuori

Figure 5 shows the proposed framework chart.

Causes of land uplift

1. The mass of the land and its attraction small to sea in its vicinity sinks due to the land seems rise.
2. Ice mass in polar region attracts water
3. Earth crust shrinks causing vertical movements
4. Ice age ice was cooling earth crust when warm-ing the land starts to rise
5. Crystallisation beneath earth's crust
6. The movement of earth crust when there is perriodic variation
7. Contents attracts water
8. Ice-age pressing earth crust when melts the land starts to rebound
9. Earth quick cause land uplift sometimes

Patterns of uplift through time

Steady decline in uplift rate: theoretical calculations suggest rate of land uplift in Vaasa region will slow in future

Irregular uplifts. e.g. Sierra Ne-vada irregular uplift 2011–2016 high uplift source of uplift water withdrawal

Irregular up and down. Different rebound uplift thorugh time activated by different conditions

How to measure uplift?

1. The use of tide gauge
2. Levelling
3. GPS Stations
4. Uplift history by apatite cooling history (rock mineral age)

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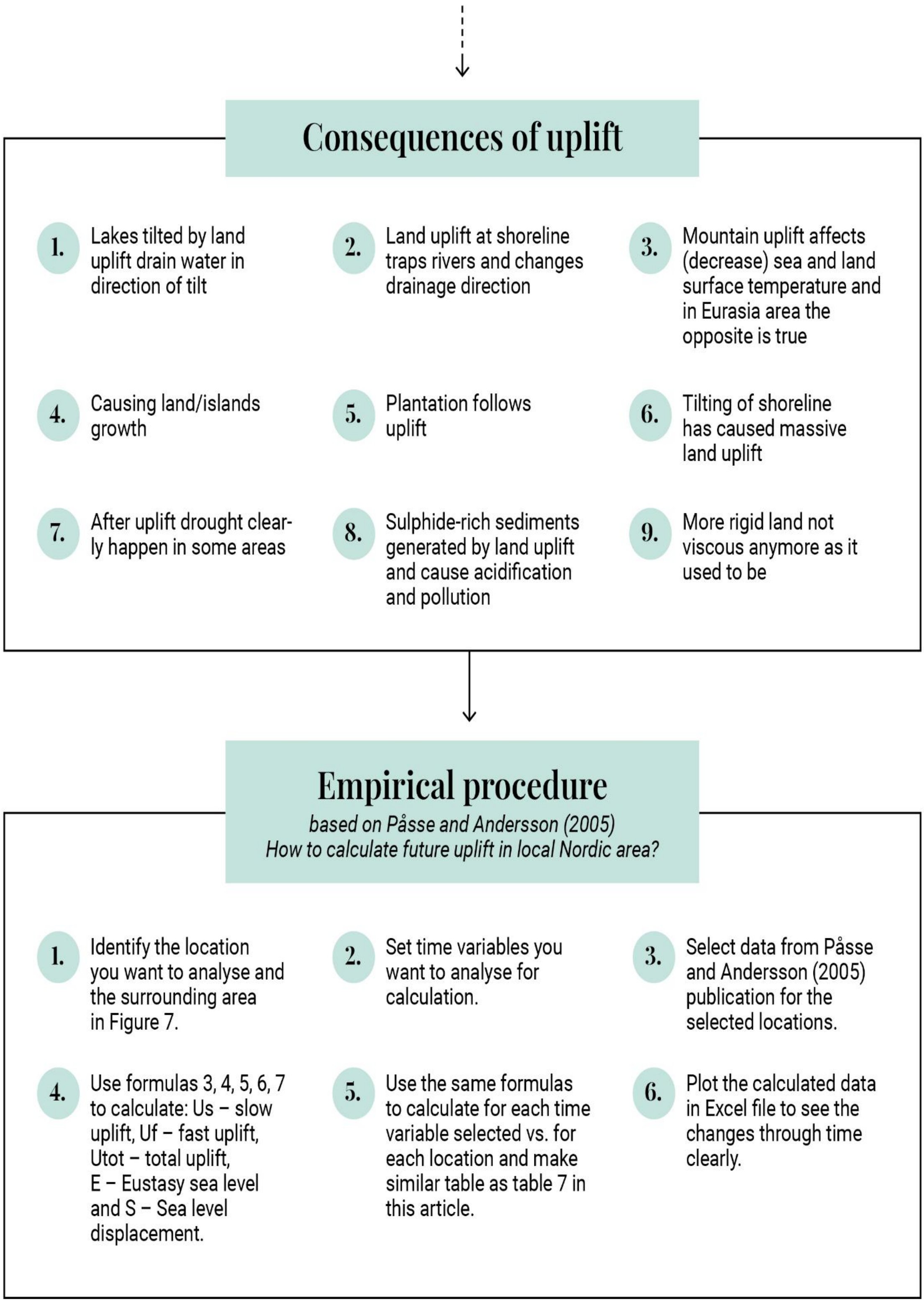

Figure 5. The theoretical framework of land rising: causes, measurement methods, patterns, consequences of uplift and how to calculate future uplift in local area derived from different sources (drawn by Andrei Palomäki).

Sea-level rise generally dominates land uplift in most areas of the world, so the current situation and forecast are for more flooding, especially in most coastal areas (IPCC, 2007 and IPCC, 2019). This is unsurprising, given the rate of climate change. Church and White, 2011, evaluated the global average sea-level rise in 1993 – 2009, after correcting for glacial isostatic adjustment. The values were 3.2 ± 0.4 mm/year from satellite data and 2.8 ± 0.8 mm/year from the in-situ data. This rise is much higher than the land uplift effect in most areas of the world. The authors of that study also asserted that sea-level continues to rise now and will do so for centuries to come. Rising temperatures due to climate change also make ocean thermal expansion an important element, adding to the sea-level rise from melting land ice (Church and White, 2011). Thus, the conclusion here, based on various literature, is that sea-level rise is expected to be much higher than land uplift in most places of the world.

According to Okko (1967), there are three possible outcomes: flooding, balanced land uplift and sea-level rise or land uplift. This current paper sets out to establish which of these is the likely outcome in the Vaasa region. Figure 6 depicts the two ends of the spectrum. On the left, land uplift is greater than the sea-level rise. The opposite scenario is shown on the right, where the sea-level rise floods the lands near the shore. In between these two extremes is a third outcome where the two movements broadly compensate for each other.

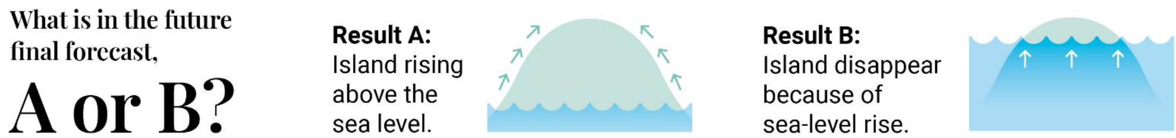

Figure 6. The comparison between the outcomes expected due to land uplift and/or massive sea-level rise due to climate change (drawn by Andrei Palomäki).

3. Results

This result section presents two main outcomes. First, temperature and sea-level rise and the theoretical calculation for future land uplift in the Vaasa region. The second deals with whether land uplift in Vaasa will be greater or lower than sea-level rise, or if they will compensate for each other.

3.1. Temperature and sea-level rises and theoretical calculation for future land uplift

Table 5 shows temperature and sea-level rise expectations in the local Vaasa region, several wider areas of the Nordic area and the world in general. The Vaasa region sea- level rise is lower compared to some of the data presented in this table. Furthermore, calibration of the regional coefficient *a* in the model equation (1) shows that the average rate of the sea-level rise in the Vaasa area (1.81 mm/yr ^{O}**C**) is lower than that of the global value 3.4 mm/yr ^{O}**C**. This also indicates that climate change impact on the Vaasa region is less intense than that on global areas.

Table 5. The relations between future temperature increase and sea-level rise is considered areas. Based on formula 1 and 2 the proportionality constant was calculated.

Areas	Future temperature increase (^{O}C)	Sea level rise (m/yr)	Proportionality constant (mm/yr ^{O}C)
Baltic Sea	2 – 6 [1]	0.003 – 0.0035[3&4]	1,354166667
Vaasa archipelago	2 – 6 [1]	0.0028 – 0.0084[2]	2,333333333
Finland	2 – 6 [1]	0.00284 – 0.00515[2]	1,664583333
Nordic (Finland and Sweden)	2 – 6 [1]	0.003 – 0.006 (1993 – 2003) [1]	1,875
World	2 – 6 [1]	0 – 1 (at end of 21st century) [1]	3,4

Notes: IPCC (2007) [1], Johansson (2014)[2], Johansson et al. (2004)[3], Yle News (2016)[4], and global forecasts IPCC (2013)[5].

Table 6 presents the locations used in calculations and the years used for different time variables. Years of t1= 5,000, t2 = 10,000, t3= 15,000 and t4= 20,018 years from the current time (year 2018) were used. Table 6 presents as well the theoretical calculations inputs presented by Påsse and Andersson, 2005. Columns: Time variable – are years label chosen for calculations. Years – particular years chosen in calculation. Location number – are the number of different locations chosen in calculation form Figure 3. Locations names – the name of locations around the Vaasa region chosen from Figure 3 for calculations. Data from Tables 6 data were the inputs used to calculate the theoretical far-future land uplift and sea-level rise results for the Vaasa region, presented in Table 7. Equations numbered 3-7, presented earlier in the materials section, were used for the calculations. The descriptions of the character As, Bs, Af and Tf presented in next Table 6 can be found in the descriptions of equations 3-7 in this article (as well in the nomenclature).

Table 6. The relevant locations for Figure 7 and 8, t (time in years) and Ts (slow time values) used for calculation and data for theoretical calculations (taken from Påsse and Andersson, 2005)

Time variable	Years
Slow time = Ts	20,018
time1 = t1	5,000
time2 = t2	10,000
time3 = t3	15,000
time4 = t4	20,018

Location name	As	Bs	Af	Tf
Ångermanland	330	8800	132	9600
S. Västerbotten	328	9200	132	9600
Rovaniemi	290	9500	100	9700
Lauhanvuori	288	9500	95	10000

Table 7 presents the Vaasa region calculations for far-future land uplift and sea-level rise. They cover: Us = slow uplift; Uf = fast uplift; Utot = total uplift; E= eustasy sea-level rise; and S= sea-level displacement.

Table 7. Theoretical calculations for far-future land uplift and sea-level rise in Vaasa region. Based on Påsse and Andersson (2005) theoretical calculated data. Us = slow uplift; Uf = fast uplift; Utot = total uplift; E= eustasy sea-level rise; and S= sea-level displacement.

		Theoretical calculated data				
Location name	**time in years**	**Us**	**Uf**	**Utot**	**E**	**S**
Ångermanland	time1	166,04	-0,05	165,94	0,71	165,28
Ångermanland	time2	67,8	0,738	68,538	0,354	68,184
Ångermanland	time3	27,6	0,5	28,1	-0,2363	28,3363
Ångermanland	time4	0	0,177	0,177	-0,177	0,354
S. Västerbotten	time1	159,6	-0,05	159,55	0,71	158,84
S. Västerbotten	time2	64	0,738	64,738	0,354	64,384
S. Västerbotten	time3	26,01	0,5	26,51	-0,2363	26,7463

S. Västerbotten	time4	0	0,177	0,177	-0,177	0,354

Rovaniemi	time1	137,62	-1,13	136,49	0,71	135,78
Rovaniemi	time2	55,49	0,559	56,049	0,354	55,695
Rovaniemi	time3	22,14	0,379	22,379	-0,2363	22,6153
Rovaniemi	time4	0	0,284	0,284	-0,177	0,461

Lauhanvuori	time1	136,67	- 1,07	135,6	0,71	134,89
Lauhanvuori	time2	55,11	0,511	55,621	0,354	55,267
Lauhanvuori	time3	21,99	0,36	22,35	-0,2363	22,5863
Lauhanvuori	time4	0	0,27	0,27	-0,177	0,447

Figure 7 is a graphical presentation of the land uplift data in Table 7. It depicts the slow, fast, and total uplift forecasts for years time1, time2, time3 and time4. It is evident that slow uplift is much higher than fast uplift which is the major contributor to total uplift. The key message from the graph is that land uplift will decline significantly through time at all four considered locations.

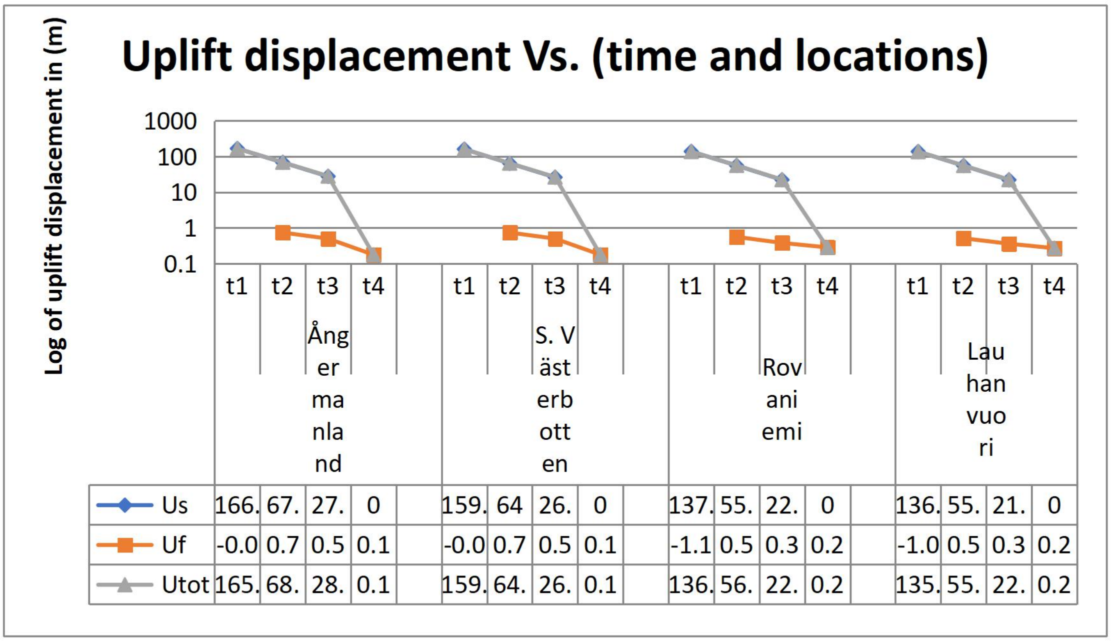

Figure 7. Graph of calculated forecasts of Us - slow, Uf – fast and Utot – total uplifts in different locations for all time variations t1, t2, t3 and t4 (see table 6 for explanations of times).

Figure 8 depicts the future sea-level displacement calculations for the four locations, as presented in Table 7. The total land uplift from Figure 7 is also included in Figure 8. Crucially, it shows that in the far-future (t4 = 20,018 years after 2018) the sea-level rise is expected to be higher than the total land uplift in the Vaasa region. This is an important finding because if on-going climate change facilitates sea-level rise it may surpass the land uplift rate even sooner than this forecast timescale.

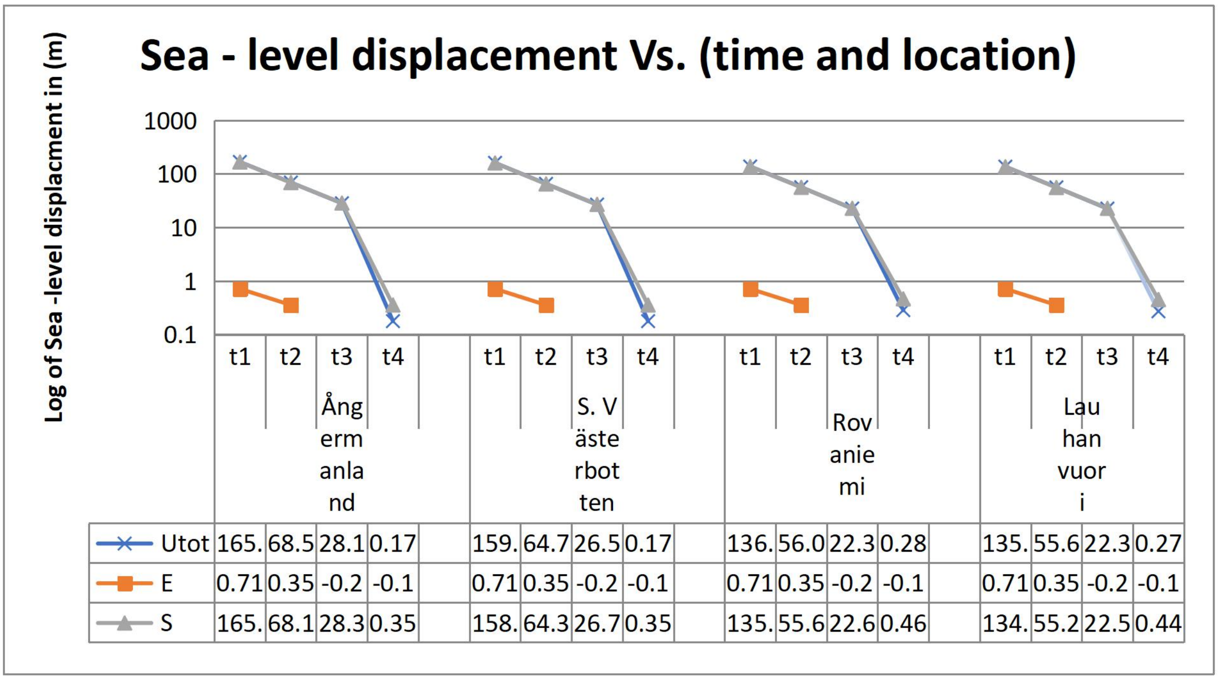

Figure 8. Sea-level and total land uplift in different locations for all time variations t1, t2, t3 and t4 (see table 6 for explanations of times). Utot = total uplifts; E = eustasy sea-level rise; and S = sea-level displacement

3.2. Comparison with literature

Land uplift is caused by nine different reasons according to Kääriäinen (1953). The most significant of these in the Vaasa region relates to the cold ice mass of the Ice Age. This has pressed down the earth´s crust, which is rebounding as the ice melts. This is the most probable explanation for the current uplift in the Vaasa area (Poutanen & Steffen, 2014). According to the work of Okko (1967), land in the Vaasa area will rise by 4.3-6.1 mm/yr, while land in Finland in general will rise by 3.0-8.8 mm/yr. Various published works indicate that land uplift in Finland is stronger in coastal areas. Land uplift at Merten Talo, on the coast just north of Vaasa city, is 8.77–9.0 mm/yr (Kääriäinen,1953, and Girgibo, 2021a).

Data gathered from various sources show much difference between the expectations for the global situation and for the local Vaasa region. Land uplift is expected to be higher than sea-level rise in Vaasa and the surrounding areas of the Baltic Sea, Finland and Sweden. This is not the case for the world as a whole. Table 8 summarises the relevant forecast data gathered from the referenced literature sources.

Table 8. Comparison of published expectations for sea-level rise and land uplift in different locations

Areas	Expected sea-level rise (mm/year)	Expected land rising (mm/year)	Future expectations	Conclusion: there will be…
Baltic Sea	3 – 3.5[8 &7]	7 – 10[1,2, 3& 4]	More land rise	Higher level of land rise
Vaasa area	2.8 – 8.4[6]	8.77 – 9[1,2&7]	More land rise	Higher level of land rise
Finland	2.84 – 5.15 [6]	2 – 10[3&7]	More land rise	Higher level of land rise
Nordic area (Finland and Sweden)	3 – 6[5 (1993-2003)]	0 – 10[1&3]	More land rise	Higher level of land rise
World (some areas)	0 – 1000[5 (at end of 21 century)]	- 6 – 10[3]	Flooding dominates	Most areas flooding

Notes: Poutanen & Steffen (2014)[1]; Kääriäinen (1953)[2]; Steffen et al. (200X)[3]; Amante & Eakins (2009)[4]; IPCC 2007 [5]; Johansson (2014)[6], Johansson et al. (2004)[7]; and Yle News (2016)[8].

Figure 9 plots Table 8′s sea-level rise and land rise data (in mm/yr) for the studied areas. The figures used are the central estimates in all cases. The sea-level rise for the world must be multiplied by 100, so it is clear that, unlike in the four specific study areas (Baltic Sea, the Vaasa region, Finland and Nordic area) the expectation for the general world situation is for the sea-level rise that will vastly surpass any land uplift. If all Antarctica melts this is expected to lead to widespread flooding and even in the Nordic area sea-level rise will exceed land uplift. Although the data size is limited, it can now be proved that the relationship between the sea-level rise and land uplift data is a negative correlation (r =-0.400 with 95 % confidence interval).

Figure 9. Sea-level rise and land uplift: forecasts of annual rates, based on central estimates of Table 8´s data. See Table 9 for reference sources. World (generalized) = Means mainly those areas where there is land uplift going on.

4. Discussions

This study confirms that climate change impact on the Vaasa region is less intense than that on global areas. The framework chart developed can be used to study of vulnerability and adaptation to climate change that can benefit local, regional and global communities. There are five sections in the framework chart developed those are: cause of land uplift, patterns of uplift through time, how to measure land uplift, consequences of land uplift and empirical procedure. Thus, this framework chart helps adapt to changes due to land uplift and vulnerability to climate change. This framework chart also delivers the different patterns, which might cause land uplift in local area and how to measure this land uplift. The empirical procedure presented can be used to forecast the Nordic area land uplift change through various times, which can be regulated in the calculation equations input.

The theoretical calculation shows the far-future expectation land uplift in the Vaasa region. The results shows that both land uplift and sea level rise will decline significantly in far-future time (e.g. after 20,018 years starting from the year 2018). Fast uplift (Uf) is lower in its amount compared to slow uplift (Us). However, all uplifts (fast, slow and total) and sea level displacements show a significant decline in the far-future. This analysis was interpreted by using a logarithm to make the effect visible enough. Exponentials total uplift also shows a decline in all results of theoretical forecast calculation, which is made based on Påsse and Andersson (2005).

The empirical literature data validation shows the most interesting results. Except for the world expectation of a sea-level rise to be higher than the land uplift other areas analysed show higher level of land uplift compared to sea level displacement. The area expected to show land uplift higher than sea-level are: Baltic Sea, the Vaasa region, Finland and Nordic (Finland and Sweden). This very surprising compared to severely affected places by flooding such as Miami, Florida (USA) and Bangladesh. Even if the theoretical calculations show that the land uplift rate will decline in the far-future there will be a significant amount of land uplift expected at least in the Vaasa region for quite some time.

The principal limitation is that the areas studied for some of the investigation and evaluations may not necessarily represent the world´s general uplift rates. On the other hand, this can confirm that local effects are different from generalised world expectations or forecasts.

5. Conclusions

Land uplift is a process that has been ongoing for millions of years in some areas (Bill et al., 2018). There is good evidence that this might, and most probably will, continue in the future. After reviewing the different literature relating to sea-level rise and land uplift, the inevitable conclusion is that future sea-level rise will exceed any land uplift in most areas of the world. Sea-level rise might not affect the local Vaasa area, but in other parts of the world the sea-level rise will lead to much more flooding, even with the medium climate change effects that can be expected.

Poutanen & Steffen, 2014, concluded that even in the shallow sea and strong land uplift area of the Vaasa archipelago, there will not be a dry land link across the Baltic between Finland

and Sweden in the near future. They reached this conclusion using data from geophysical modelling and contemporary geodetic measurements. What is new shown in this article is that from the data gathered on the most areas, those are the Vaasa region, Baltic Sea (contradictory to the literature expectation of Baltic Sea on Poutanen & Steffen (2014)), and Finland and Nordic (Finland and Sweden), shows a much higher level of land uplift expectation than sea-level rise. In addition, it was found that there is a negative correlation between the land rising and sea-level rise. There are positive correlations between environment (water) temperature increase and sea-level rise. The theory tools used can contribute greater belief and strength in land uplift and sea-level rise theory and assumptions. Combating climate change plays a pivotal role in preventing rapid sea-level rise that threatens islands and harbours. In the far-future both land uplift and sea-level will declined dramatically based on the theoretical calculations results found and presented.

We recommend further study directed at the development of a sophisticated framework chart and other theoretical calculations that focus attention on the effect of land uplift. Further theoretical calculations to forecast far-future changes in land uplift are essential for comparison with this study´s results and to confirm changes at sites elsewhere in the world.

Author Contributions: Formal analysis, Nebiyu Girgibo; Writing original draft, Nebiyu Girgibo; Supervision, funding acquisition, writing review & editing, Nebiyu Girgibo, Xiaoshu Lü, Erkki Hiltunen, Pekka Peura, Yang, Tong and Dai, Zhenxue.

Acknowledgments: Financial support of this research was provided by Academy of Finland and University of Vaasa foundation grant. Sincere gratitude goes to Professor Marko Kohtamäki and Professor Vinit Parida. Great thanks goes to editor and proofreader David Wilcox for the language and style great improvement. We would like to thank also Andrei Palomäki at Studio Andrei for the drawings he made for us.

References

[1] Ablain, M. et al. (2019). Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration. *Earth Syst. Sci.* Data 11: 1189–1202 pp. [Cited 27 Jan. 2021]. Available at World Wide Web <URL: https://doi.org/10.5194/essd-11-1189-2019>.

[2] Amante, C. and Eakins, B.W. (2009). ETOPO1 1 Arc-Minute global relief model: Procedure, data source and analysis. *NOAA Technical Memorandum* NESDIS NGDC-24, 19 pp. [Cited 01 July 2021]. Available at World Wide Web <URL: https://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/docs/ETOPO1.pdf>.

[3] Apelgren, K. and Lernstål, Rolf (1991). Variation in Galium Palustre s. Lat. in the Baltic land-uplift area. *Nordic Journal of Botany,* vol. 10, no. 6, pp. 565-592. [Cited 01 July 2021]. Available at World Wide Web <URL: https://doi.org/10.1111/j.1756-1051.1991.tb02100.x>.

[4] Begg, D.; Fischer, S.; and Dornbusch, R. (2001). *Foundation of Economics*. United Kingdom: McGraw-Hill international (UK) Limited. ISBN: 0-07-709754-8.

[5] Bill, N.S.; Mix, H.T.; Clark, P.U.; Reilly S. P.; and Jensen, B.J.L. (2018). A stable isotope record of late Cenozoic surface uplift of southern Alaska. *Earth and Planetary Science Letters* 482 (2018) 300 – 311 pp. [Cited 01 July 2021]. Available at World Wide Web <URL: https://doi.org/10.1016/j.epsl.2017.11.029>.

[6] Boman, A., Fröjdö, S., Backlund, K. and Åström, M.E. (2010). Impact of Isostatic land uplift and artificial drainage on oxidation of brackish-water sediments rich in metastable iron sulfide. *The Elsevier Journal (Science-Direct): Geochimica et Cosmochimica Acta* Vol. 74 (2010) 1268 – 1281 pp[Cited 01 July 2021]. Available from World Wide Web <URL: https://doi.org/10.1016/j.gca.2009.11.026 >.

[7] Booth, A.; Papaioannou, D. and Sutton, A. (2012). *Systematic Approaches to a Successful Literature Review.* SAGE Publications Ltd. ISBN: 978-0-85702-134-2 and ISBN: 978-0-85702-135-9 (pbk).

[8] Brunton, G.; Oliver, S.; Oliver, K.; and Lorenc (2006). Final Report: A Synthesis of Research Addressing Children's, Young People's and Parent's Views of Walking and Cycling for Transport. London, UK: EPPI-Centre the Social Science Research Unit, Institute of Education, University of London. 131 pp. ISBN: 0-9551548-9-8.

[9] Bryhn, A.C. and Hkanson, L. (2011). Land uplift effects on the phosphorus cycle of the Baltic Sea. *Environmental Earth Sciences*, vol. 62, no. 8, pp. 1761-1770. [Cited 01 July 2021]. Available from: <URL: http://dx.doi.org/10.1007/s12665-010-0656-6>.

[10] Bryman, A. and Burgess, R.G. (1994). *Analyzing Qualitative Data*. London, UK and New York, USA: Routledge. ISBN: 0-415-06062-1 (hbk) and ISBN: 0-415-06063-X (pbk).

[11] Church J. A. and White N. J. (2011). Sea-Level Rise from the Late 19th to the Early 21st Century. *Surv. Geophys* 32: 585–602, [Cited 01 July 2021]. Available from World Wide Web <URL: http://dx.doi.org/10.1007/s10712-011-9119-1>.

[12] Dasgupta, S. and Meisner, C. (2009). *Climate Change and Sea Level Rise: A Review of the Scientific Evidence*. 48 525 pp. 118. Washington D. C., U.S. A: The World Bank Environmental Department Papers – Climate Change Serious.

[13] Ekman, M. (1995). Postglacial uplift of the Åland Islands, and the World's oldest preserved sea level gauge. *Small publications in Historical Geophysics,* No.1, pp. 1-15. Åland Islands: Summer Institute for Historical Geophysics.

[14] Environment.fi (2019). The Bay of Bothnia [online]. [Cited 21 March 2019]. Available from World Wide Web <URL: https://www.ymparisto.fi/en-US/VELMU/VELMU_research_projects/FINMARINET/Target_areas/Bay_of_Bothnia>.

[15] EPI (2021). *Environmental Performance Index [EPI)*. {Online]. EPI data information. [Cited 07 April 2021]. Available at World Wide Web <URL: https://epi.yale.edu/epi-results/2020/country/fin>.

[16] Farlex Dictionary (2018). *The free dictionary by Farlex: Causality theory (Redirected from cause and effect theory)*. [Online], [Cited 27 July 2021]. Available at World Wide Web <URL: https://encyclopedia2.thefreedictionary.com/Cause+and+effect+theory>.

[17] Fjeldskaar, W., Lindholm, C., Dehls, J.F.and Fjeldskaar, I. (2000). Postglacial uplift, neotectonics and seismicity in Fennoscandia. *Quanternary Science Review* 19 (2000) 1413 – 1422.

[18] Fjeldskaar, W. (1997). Flexural rigidity of Fennoscandia inferred from the postglacial uplift. *Tectonics*, vol. 16, no. 4, pp. 596-608. [Cited 01 July 2021]. Available from World Wide Web <URL: https://doi.org/10.1029/97TC00813 >.

[19] Genno, R. and Endo, N. (2018). Adjustment processes of mountainous rivers affected by tilting uplift: Laboratory experiments and a case study of Yakushima Island, Japan. *Island Arc*. 2019; 28: e12278. [Cited 01 July 2021]. Available from World Wide Web <URL: https://doi.org/10.1111/iar.12278 >.

[20] Girgibo, N. (2021a). *The effect of climate Change on Water and Environment Resources in Kvarken Archipelago area*. University of Vaasa Reports 20. 90 pp. 2016 – 2021. Vaasa, Finland: University of Vaasa, Tritonia, library. [Cited 01 July 2021]. Available from World Wide Web <URL: http://urn.fi/URN:ISBN:978-952-476-941-9 >.

[21] Girgibo, N. (2022). *Seaside energy solutions, land uplift, and climate change in UNESCO heritage protected area: A mixed-method investigation.* Dissertation (Forthcoming). Vaasa, Finland: University of Vaasa, Tritonia library.

[22] Gleadow, A.J.W., McKelvey, B.E. and Ferguson, K.U. (1984). Uplift history of the Transantarctic Mountains in the Dry Valleys area, Southern Victoria Land, Antarctica, from apatite fission track ages. *New Zealand Journal of Geology and Geophysics*, vol. 27, no. 4, pp. 457-464. [Cited 01 July 2021]. Available from World Wide Web <URL: https://doi.org/10.1080/00288306.1984.10422265>.

[23] Hammond, W.C., Blewitt, G. and Kreemer, C. (2016). GPS imaging of vertical land motion in California and Nevada: Implications for Sierra Nevada uplift. *Journal of Geophysical Research: Solid Earth*, vol. 121, no. 10, pp. 7681-7703. [Cited 01 July 2021]. Available from World Wide Web < URL: https://doi.org/10.1002/2016JB013458 >.

[24] Hannah, L. (2011). *Climate Change Biology*. Burlington, USA: Elsevier Ltd. 402 pp. ISBN: 978-0-12-374182-0.

[25] Hansen, Kip. (2017). Sea level: Rise and fall – part 2- tide gauge [Online]. [Cited 01 July 2021]. Available from World Wide Web <URL: https://wattsupwiththat.wordpress.com/2017/10/07/sea-level-rise-and-fall-part-2-tide-gauges/>.

[26] Hela, Ilmo (1953). A study of land upheaval at the Finnish coast. *Merentutkimuslaitoksen Julkaisu* N.o. 158. Helsinki.

[27] Helmens, K.F.; Väliranta M.; Engels, S. and Shala, Shy. (2012). Large shifts in vegetation and climate during the early Weichselian (MIS 5d-c) inferred from multi-proxy evidence at Sokli (northern Finland). *The Elsevier Journal: Quaternary Science Reviews*, Vol. 41 (2012), 22-38 pp. [Cited 01 July 2021]. Available from World Wide Web <URL: https://doi.org/10.1016/j.quascirev.2012.02.008>.

[28] IPCC (2007). *Climate Change 2007: The Physical Science Basis*. New York, USA: Cambridge University Press. 996 pp. ISBN: 978-0-521-88009-1.

[29] IPCC (2013). *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York, USA: Cambridge University Press, Cambridge. 1535 pp. ISBN: 978-1-107-05799-9.

[30] IPCC (2019). *Special Report on the Ocean and Cryosphere in a Changing Climate* [Eds.: H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer].

[31] IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group - I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6 WGI).*

[32] ISO 31000 (2015). *ISO 31000 - Risk Management: A Practical Guide for SMEs*. 21 pp. Geneva, Switzerland: ISO Copyright Office. ISBN: 978-92-67-10645-8.

[33] Johansson, M.M. (2014). *Sea Level Changes on Finnish Coast and Their Relationships to Atmospheric Factors*. Dissertation, 54 pp. Helsinki, Finland: Finnish Metrological Institute. [Cited 01 July 2021]. Available at World Wide Web <URL: https://helda.helsinki.fi/handle/10138/45229>.

[34] Johansson, M.M.; Kahma, K.K.; Boman, H.; and Launiainen, J. (2004). Scenarios for sea level rise on Finnish coast. *BOREAL ENVIRONMENT RESEARCH* 9: 153 -166 pp. ISSN 1239 – 6095.

[35] Kitoh, Akio. (1997). Mountain uplift and surface temperature changes. *Geophysical Research Letters*, vol. 24, no. 2, pp. 185-188[Cited 01 July 2021]. Available at World Wide Web <URL: https://doi.org/10.1029/96GL03953>.

[36] Kunapo, J.; et al. (2018). A spatially explicit framework for climate adaptation. *Urban Water Journal*, vol. 15, no. 2, pp. 159-166. [Cited 01 July 2021]. Available at World Wide Web <URL: https://doi.org/10.1080/1573062X.2018.1424216>.

[37] Kääriäinen, E. (1953). On the recent uplift of the earth's crust in Finland. *Fennia* 77, N:o 2. Helsinki: Printed by Tilgmann.

[38] Lowrie, William. (2007). *Fundamentals of Geophysics.* Second edition. 393 pp. Cambridge, UK: Cambridge University Press. ISBN-13 978-0-511-35447-2.

[39] Löfman, J. (1999). *Site Scale Groundwater Flow in Hästholmen.* Helsinki, Finland: Posiva Oy. Posiva, 99-12 pp. ISBN: 951-652-067-7.

[40] National Research Council (2012). *Sea-Level Rise the Coasts of California, Oregon, and Washington: Past, Present, and Future.* Washington, DC, USA: The National Academies Press. [Cited 01 July 2021]. Available at World Wide Web <URL: doi:10.17226/13389>.

[41] Nordman, M.; Peltola, A.; Bilker-Koivula, M.; and Lahtinen, S. (2020). Past and future sea level changes and land uplift in the Baltic Sea seen by geodetic observations. *International Association of Geodesy Symposia.* Springer, Berlin, Heidelberg. [Cited 01 July 2021]. Available at World Wide Web <URL: https://doi.org/10.1007/1345_2020_124>.

[42] NSL-National land survey of Finland (2020). National land survey of Finland: Land Uplift, [Online]. [Cited 1 July 2021]. Available from World Wide Web <URL: https://www.maanmittauslaitos.fi/en/research/interesting-topics/land-uplift>.

[43] Okko, M. (1967). The relation between raised shores and present land uplift in Finland during the Past 8000 Years. *Annales Academie Seientiarum Fennicae, Series A, III. Geologica- Geographica* 93. Helsinki: Geological Survey of Finland.'.

[44] Poutanen, M. and Steffen, H. (2014). Land uplift at Kvarken Archiplago/high cost UNESCO World Heritage area. *Geophysica* (2014), 50(2), 49-64 pp. Masala, Finland and Gävle, Sweden: Finnish Geodetic Institute and Lantmäteriet.

[45] Påsse, T. and Andersson, L. (2005). Shore-level displacement in Fennoscandia calculated from empirical data. *Gff*, vol. 127, no. 4, pp. 253-268. [Cited 01 July 2021]. Available from World Wide Web <https://doi.org/10.1080/11035890501274253>.

[46] Rahmstorf, S. (2007). A semi-empirical approach to projecting future sea-level rise. *Science (ww.siecnemag.org)* 19 January 2007 Vol. 315 368-370 pp. '.

[47] Rajasree, B.R., Deo, M.C. and Sheela Nair, L. (2016). Effect of climate change on shoreline shifts at a straight and continuous Coast. *Journal of Estuarine, Costal and Self Science: Science Direct* 183 (2016) 221 - 234. Elsevier publications. [Cited 01 July 2021]. Available from World Wide Web < URL: http://dx.doi.org/10.1016/j.ecss.2016.10.034>.

[48] Seppä, H.; Tikkanen, M. and Mäkiaho, J.- P. (2012). Tilting of lake Pielinen, eastern Finland – an example of extreme transgressions and regressions caused by different post-glacial isostatic uplift. *Estonian Journal of Earth Science* (2012), 61, 3, pp. 149 – 161. [Cited 01 July 2021]. Available from World Wide Web <URL: http://10.3176/earth.2012.3.02>.

[49] Steffen, H.; Barletta, V.; Kollo, K.; Milne, G.; Nordman, M.; Olsson, P.; Simpson, M.; Tarasov, L; & Ågren, J. (2016). *NKG201xGIA – A Model of Glacial Isostatic Adjustment for Fennoscandia*. Gothenburg, Sweden: LANTMÄTERIET.

[50] Svensson, Nils-Olof (1991). Postglacial land uplift patterns of south Sweden and the Baltic Sea region. *Terra Nova*, vol. 3, no. 4, pp. 369-378. [Cited 01 July 2021]. Available from World Wide Web <URL: https://doi.org/10.1111/j.1365-3121.1991.tb00165.x>.

[51] Vartiainen, T. (1980). Succession of island vegetation in the land uplift area of the northernmost Gulf of Bothnia, Finland. Acta bot. Fennica 115, 1–105 pp. Acta Botanica Fennica. ISBN: 951-9469-09-5.

[52] Vestøl, Olav (2006). Determination of postglacial land uplift in Fennoscandia from leveling, tide-gauges and continuous GPS stations using least squares collocation.

Springer-Verlag: J Geod (2006) Vol. 80: 248–258 pp. [Cited 01 July 2021]. Available World-Wide Web page <URL: http://dx.doi.org/10.1007/s00190-006-0063-7>.

[53] Vestøl, Olav et al. (2019). NKG2016LU: A new land uplift model for Fennoscandia and the Baltic Region. *Springer: Journal of Geodesy* (2019) Vol 93: 1759-1779 pp. [Cited 01 July 2021]. Available World-Wide Web page <URL: https://doi.org/10.1007/s00190-019-01280-8>.

[54] Wetzel, R.G. (2001). *Limnology- Lakes and River Ecosystems*. Third edition, 1006 pp. California, USA: Elsevier Science (USA). ISBN: 0-12-744760-1.

[55] Yle News (2016). *Race Between Land Uplift and Sea Level Rise Begins in Archipelago.* [Online]. Yle News (13.06.2016; 7:00). [Cited 01 July 2021]. Available at World Wide Web <URL: https://yle.fi/uutiset/osasto/news/race_between_land_uplift_and_sea_level_rise_begins_in_archipelago/8951953>.