Aalto-yliopisto
Insinööritieteiden
korkeakoulu

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Artificial waves in natural waters – analysis of the hydro-environmental effects

Thesis submitted in a partial fulfillment of the requirements
for the degree of Master of Science in Technology.

Espoossa 24.3.2016
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Title of thesis Artificial waves in natural waters – analysis of the hydro-environmental effects

Degree programme Civil and Environmental Engineering

Major/minor Water and Environmental Engineering **Code** Yhd-12

Thesis supervisor Professor Harri Koivusalo

Thesis advisor(s) D.Sc. (Tech.) Juha Järvelä, D.Sc. (Econ.) Atso Andersén

Date 24.03.2016 **Number of pages** 62+13 **Language** English

Abstract

The hydrofoil method is an artificial wave production solution that is based on a hydrofoil system drawn underneath the water surface. The method can be utilised in producing surfable waves in any natural water basin. The equipment for the hydrofoil method does not require modification of the environment thus decreasing the hydro-environmental effects of the solution. However, as produced wave and water flow propagate towards the shoreline and the lake or sea bed, risk of erosion occurs thus causing a risk of hydro-environmental effects. The objective was to identify these hydro-environmental effects and potential measures to minimise the effects. The study combined literature analysis with numerical data analysis. Simulation modelling results together with examples from the literature were used as a material.

Artificial wave production in natural waters can cause erosion and indirect effects such as water quality changes. The significant wave height of the swell caused by the Artwave prototype is 30-40% lower than the produced wave with a wave height of 1 meter. According to the study flow velocities decay significantly towards the lake or sea bed but do not decay towards the shoreline in the distance of 30 meters. In the depth of 4 meters, risk of erosion for easily erodible sediment is minor and for cohesive sediments and other sediments erosion is unlikely to occur. The wave power of the artificial waves is higher than average but lower than the maximum wave conditions in the Finnish archipelago area. Cumulative wave power is minor in comparison to natural storms. Artificial wave production appears to be possible without water or environmental permit but still all hydro-environmental effects must be minimised.

Potential measures to minimise the effects include adjustment of site selection, set-up and shoreline protection. If water depth is more than 5 meters it should not require any protection as the risk of erosion is minor. However, if the lengthening of the spare area or aligning the run away from the shoreline is not possible, shoreline protection is recommended. Shoreline protection measures can be soft engineering measures, such as leaving the original vegetation untouched, or hard engineering measures, such as breakwaters or other structures. Indirect effect such as water quality changes and biota response can be traced through environmental indicators. The environmental indicators help to evaluate the occurred hydro-environmental effects and assess the need for additional minimisation measures. If change in water quality is indicated, the protection measures must be re-evaluated.

When the proposed minimisation measures are conducted, hydro-environmental effects are ought to remain minor. In fact, circulation of water might have positive effect on water quality as oxygen and nutrients are put into movement. By utilising the framework formed by this study, previous measures should be examined. Especially soft engineering shoreline protection measures and environmental indicator testing that suits to the case are recommended.

Keywords Artificial waves, erosion, wave power, hydro-environmental effect analysis

Tekijä Noora Liljanto

Työn nimi Tekoaallot luonnonvesistöissä – vesiympäristön vaikutusanalyysi

Koulutusohjelma Yhdyskunta- ja ympäristötekniikan koulutusohjelma

Pää-/sivuaine Vesi- ja ympäristötekniikka **Koodi** Yhd-12

Työn valvoja Professori Harri Koivusalo

Työn ohjaaja(t) TkT Juha Järvelä, KTT Atso Andersén

Päivämäärä 24.3.2016 **Sivumäärä** 62+13 **Kieli** Englanti

Tiivistelmä

Siivistömenetelmä on surffattavien tekoaaltojen tuottamiseen kehitetty ratkaisu, joka perustuu erityiseen siivistörakenteeseen, jota vedetään veden alla. Ympäristöä ei muokata pysyvästi ja täten vähennetään vesiympäristöön kohdistuvaa haittaa. Aalto ja veden virtaus kohti rantaa ja pohjaa voi kuitenkin aiheuttaa eroosiota ja täten epäsuorat vesiympäristöön kohdistuvat vaikutukset ovat mahdollisia. Tämän työn tarkoituksena oli tunnistaa mahdolliset vaikutukset ja toimenpiteet niiden minimoimiseksi. Metodina käytettiin kirjallisuusanalyysiä, jossa käytiin läpi esimerkkitapauksia ja numeerista data-analyysiä, jossa hyödynnettiin simulointimallilla saatuja tuloksia.

Mahdollisiksi vaikutuksiksi eroosion lisäksi tunnistettiin veden laadun muutokset, morfologiset muutokset sekä vaikutukset eliöihin joko suoran kosketusvaikutuksen myötä tai epäsuorasti edellisistä vaikutuksista johtuen. Tuotetun aallokon merkitsevä aallonkorkeus on 30-40% pienempi kuin tuotettu surffattava aalto. Tutkimuksen perusteella virtaus hidastuu pohjaa kohden merkittävästi, mutta tutkitulla 30 metrin matkalla ei havaittu aallon tai virtauksen vaimenemista rantaa kohti. 4 metrin syvyydessä helposti erodoituvien maalajien eroosioriski on pieni ja muiden maalajien eroosiota ei näytä tapahtuvan. Tuotettavien aaltojen aaltovoima on suurempi kuin keskimääräinen mutta 3-4 kertaa pienempi kuin suurin mahdollinen Suomenlahden saaristomerellä. Kumulatiivinen aaltovoima on vähäinen verrattuna luonnonmyrskyihin.

Aaltojen tuottaminen ei näyttäisi vaativan vesilupaa tai ympäristölupaa. Silti on näytettävä että vesiympäristöön kohdistuvat vaikutukset on minimoitu. Vesiympäristöön kohdistuvia vaikutuksia voidaan vähentää tarkentamalla kohdealuetta, säätämällä aallontekoasetelmaa tai suojaamalla rantaa. Jos vesisyvyys on yli 4 metriä, näyttäisi siltä, että pohjan suojausta ei tarvita. Varoaluetta kasvattamalla voidaan vähentää rantaeroosiota ja vaihtoehtoinen suositus on kohdistaa veto rannasta poispäin. Ranta voidaan suojata joko pehmein toimenpitein, kuten alkuperäisen kasvillisuuden paikalleen jättämällä, tai vaativin toimenpitein, kuten aallonmurtajien avulla. Epäsuorien vaikutusten arviointiin suositellaan ympäristöindikaattorien käyttöä ja tarvittaessa suojaustoimenpiteiden uudelleenarviointia ja säätöä. Kun suojaustoimenpiteet toteutetaan, vesiympäristölle aiheutuvat vaikutukset jäävät vähäisiksi. Veden kierrätyksestä saattaa olla jopa vesiympäristölle suotuisa vaikutus kun happi ja ravinteet saadaan kiertoon. Tämän työn luoman viitekehyksen avulla on tutkittava tarkemmin edellä mainittuja toimenpiteitä. Erityisesti pehmeitä toimenpiteitä sekä kenttäolosuhteisiin soveltuvia indikaattoritestauksia suositellaan toteutettavan ja tutkittavan.

Avainsanat Tekoaalto, eroosio, aaltovoima, vesiympäristö, vaikutusanalyysi

Acknowledgements

Working within the Project Artwave has been an amazing and invaluable experience. Thank you Atso, Pauli and the whole Artwave team. Special thanks for Ville for the simulation related data and assistance.

The study was conducted under supervision of Professor Harri Koivusalo from the Department of Civil and Environmental Engineering at Aalto University. The advisors of the study were Docent Juha Järvelä from the Department of Civil and Environmental Engineering and Dr. Atso Andersén, project leader of the Project Artwave. I want to thank you all for making this interesting and innovative study possible, and I appreciate all the advice and support I was given. Furthermore, I am grateful for the Aalto University, Tekes and Maa- ja vesitekniikan tuki ry for providing the funding for my study.

I want to thank the whole Department of Civil and Environmental Engineering from the Aalto University, and also Professor Risto Willamo from University of Helsinki, for encouraging and inspiring teaching during my studies.

Mom, dad, Antti and my dear relatives and friends; I appreciate your support, encouragement and tolerance. Thank you.

Kotkassa 13.3.2016

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Notation

a	wave amplitude [m]
d	water depth [m]
F	fetch length [m] or [km]
H	wave height [m]
H_s	significant wave height [m]
$H_{1/3}$	average height of the heights of the 1/3 highest waves [m]
H_{m0}	$4(m_0)^{1/2}$, where m_0 is the variance of the wave spectrum [m]
H_{10}	average of the heights of the 1/10 highest waves [m]
H_{rms}	equals to H_{10} [m]
P_c	cumulative wave power [Wh]
P	wave power [W] or [W/m]
T	wave period [s]
U_{max}	maximum values for U_r [m/s]
U_x	horizontal velocity component [m/s]
U_y	vertical velocity component [m/s]
U_r	$(U_x^2 + U_y^2)^{1/2}$ [m/s]
Y_{max}	Water surface level on y-axis [m]

Concepts

Artwave prototype	A prototype of the hydrofoil solution with a 8 m wide wings which was built during the year 2014 and which was successfully used to create surfable waves in Kalasatama Finland, in the summer 2014.
Artwave wave	The artificial wave produced by the hydrofoil method
Capacity of the setup	The maximum amount of runs per hour, day or season. In other words, the facility to produce the artificial waves.
Cohesion	The molecular force between particles that acts to unite them
Deep water	Water depth is considered deep when $d > \lambda/2$, intermediate when $\lambda/20 < d < \lambda/2$ and shallow when $d < \lambda/20$
Environmental indicators	Simple measures of changes in the complex environment providing a practical way to track the state of the environment or appeared change
Erosion	The action of water flow and wave exposure which removes soil material and transports it to another location where it is deposited
Event set-up	Set-up which is built up for individual event, for example for a few days
Fetch length	Distance over which wind blows, the distance from the upwind shore
Hjulström diagram	A curve that shows empirical relationship between flow velocity and sediment motion.
Hydro-environment	The totality formed by the water system and the surrounding shoreline
Hydro-environmental effect	Any potential direct or indirect effect that could modify the abiotic or biotic characteristics of the surrounding water environment or the surrounding shoreline in short term or long term future

Hydrofoil method	An artificial wave generation method developed by Project Artwave where the wave generation is based on hydrofoil system
Hydrofoil system	A wing system propagating in a depth of approximately 1.5 m thus lifting water masses and forming a surfable wave
k–ω turbulence model	A two-equation turbulence model used in computational fluid dynamics.
Littoral zone	A part of a sea, lake or river that is close to the shore
Natural water body	Any ocean, sea, lake, river or pond
Project Artwave	An innovative artificial wave technology and recreation service development project that develops a technology for an original wave generation solution
RANS equations	Reynolds-averaged Navier-Stokes equations
A return	An activity where the hydrofoil system is drawn slowly from he the stop location back to the launch location
A run	An activity where the hydrofoil system is drawn fast from the launch location until the stop location and where the wave is formed and surfed
Semi-permanent setup	Set-up which is built for more permanent use, for example for one summer season
Set-up	The equipment and area required for the use of the hydrofoil method
Site	The exact location in the area, where the set-up is built up
Ship's wash	Water flow or water wave that is caused by movement of a ship
Significant wave height	Concept which is used to characterise irregular waves and defines irregular wave characteristics better than single or maximum wave parameter values. Values of determined significant wave heights are approximately half of the individual maximum wave heights

Swell	Wave or waves that no longer strengthen or get energy from the wind or by an artificial wave method, for example the waves that propagate towards the shoreline after the hydrofoil has stopped
Wave crest	The highest wave point
Wave exposure	The degree of wave action
Wave height	The vertical distance [m] between the wave trough and the wave crest.
Wave power	Erosion measure that defines the rate at which wave energy is transmitted in the direction of wave propagation across a vertical plane.
Wave trough	The lowest wave point
Wave amplitude	The vertical distance [m] between the crest and mean water level
Wave length	The horizontal distance [m] between the crests
Wave period	The time interval [s] between the arrivals of two consecutive crests at a stationary point
Wind duration	Time period during which the wind blows

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Foreword

This thesis was conducted as part of the innovative artificial wave technology and recreation service development project at Aalto University. Until December 2014 the project was called Project Artwave and since January 2015 it has been under Artwave Surf™.

> *“Artwave Surf™ is a project for creating technology to generate surfable waves for everyone, anywhere in the world. We combine inventiveness with mechanics and fluid dynamics to create constant waves for surfing in natural waters. If you have an urban shoreline, a river or a lake — we can deliver you the surf. Or if you dream of a bigger surf center with many simultaneous waves — just dare to ask. Our solution enables fixed and entirely mobile alternatives with no additional construction required. Once we leave there will be no permanent trace in the nature. Seriously.” (Artwave Surf 2014a.)*

The goal of Project Artwave is to develop technology settling smoothly into the natural environment and to utilise recreational potential of the water areas without harming the environment. This goal and the promise of leaving no permanent trace in the nature inspired this thesis.

This study utilised water surface elevation and flow velocity data, which were determined through flow simulation modelling. The modelling was conducted by fluid dynamics specialist Mr. Ville Tossavainen. Data provided by Ville functioned as a material in this study whereas data analysis and result interpretation were conducted by the writer of this thesis.

1 Introduction

Water waves can be utilised in surface water activities such as surfing. However, natural water waves have properties that limit the surfing possibilities. First, waves are not completely regular in their appearance (Butt and Russell 2004). This challenge limits the surfing possibilities by time. Second, waves are not regular by their size (Butt and Russell 2004). This challenge limits the surfing possibilities and leads to uncertainty and unsafety for both experts and beginners. Third, particular conditions are required in the surfable wave formation (Espejo et al. 2014). Hence, proper surf spots are rare and surf season is limited. In Finland surf spots are limited to a few spots in the archipelago and surf season is best in the spring and the fall, when the water temperature is close to freezing (Pablo Films 2015, Sellgren 2014a). Fourth, most of the popular surf spots are crowded (Barter 2013). This challenge makes surfing less enjoyable and more dangerous. Due to these challenges demand for artificial waves is significant.

Artificial waves can be customized, so they have properties that natural waves are lacking. They are regular in their appearance, predictable in their size and available anywhere. Several methods and technologies to produce artificial waves have been developed around the world (Huotari 2015). The previous wave generation solutions rely on the contours in the pool to generate the shape of the wave (Wavegarden 2015, Murphys Waves Ltd 2012, Mondy 2015, American wave machines 2014) and wave generation is dependent on bottom topography transition. Hence, the previous solutions are dependent on construction of pools or other man-made settings that modify the environment permanently. This massive infrastructure building is neither convenient nor environmentally sustainable due to several reasons. First, process is slow due to legal restrictions and permit processes. Second, land and resource use is great which causes detrimental environmental effects. Moreover, landscape and environment change permanently when massive infrastructure is built. Due to the disadvantages of the previous solutions, demand for artificial but environmentally compatible solution is urgent.

Hydrofoil method is an innovative technology for artificial wave production. The technology was developed at Aalto University which together with Tekes launched a project named Artwave in 2010. The Project Artwave is an innovation and product development project that aims to utilise recreation potential of the surface waters in a completely new manner by utilising hydrofoil method in the wave production. The equipment for the hydrofoil method does not require modification of the environment making it different from almost any artificial outdoor sport equipment (Nordic Surfers Mag 2014). The wave production method is unique and patent is granted (FI 125474 B 2015). Figure 1 demonstrates the wave production principle and Figure 2 demonstrates the required equipment the set-up of the hydrofoil method. More detailed demonstration is shown in Appendix 1.

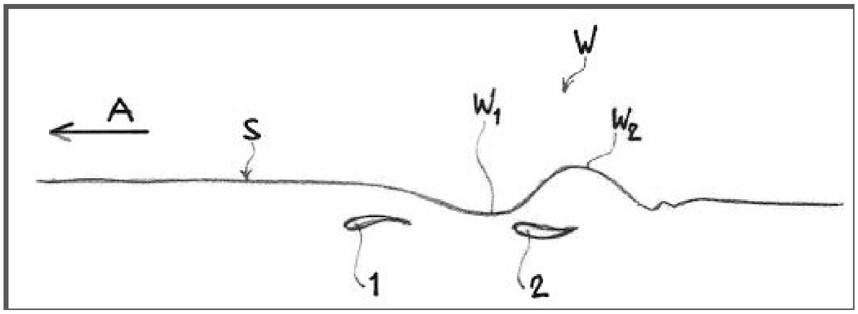


Figure 1: The wave production principle of the hydrofoil method. The surfable wave (W) is formed by two or more wings (1 and 2) propagating underneath the water surface (S). Surfable wave (W) is formed in between the wave trough (W_1) and the wave crest (W_2). Direction of the propagation (A) is identical for wings (1 and 2) and the wave (W).

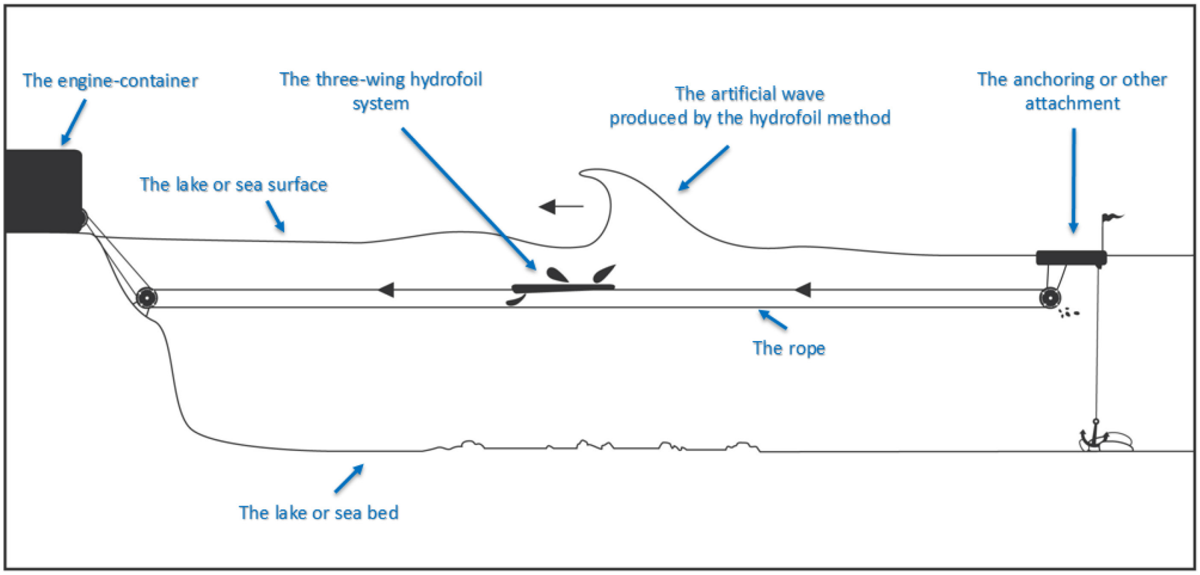


Figure 2: The required equipment for the set-up of the hydrofoil method (modified from Poranen 2014). The hydrofoil system moves as it is drawn with a rope that is controlled from the engine-container. The artificial wave is formed above the hydrofoil system.

In the hydrofoil method the wave formation is dependent on shape, adjustment and motion of the *hydrofoil system* (see Figure 2). In the hydrofoil method wave formation is not dependent on bottom topography transition. The wave generation is based on a hydrofoil system propagating in the sea or lake in a depth of approximately 1.5 m. The hydrofoil system moves as it is drawn with *a rope* that is controlled from *the engine-container*. Planned set-up for the use of the solution is shown in Appendix 1 and images in Appendix 2 demonstrate the hydrofoil solution.

Running of the hydrofoil system does not require any modification of the surrounding hydro-environment. Design and planning criteria for the hydrofoil method was that lake or sea bed and shoreline are left in their original state (Porttila 2014, Andersén 2014) and there is no need for big investments (Salomäki 2015). Also, the solution is mobile and transportable, thus minimizing the required construction and transitions of the environment (Porttila 2014). Independence of extensive structures and the utilization of a natural pool minimize the environmental and hydro-environmental effects of the developed solution. Furthermore, developers of the project avoid the installation of the solution in vulnerable waters (Salomäki 2015). Hence, the solution is artificial but still environmentally compatible.

The application of the hydrofoil method is mostly environmentally compatible. The Centres for Economic Development, Transport and the Environment (ELY Centres) observe the state of the (hydro-) environment and the changes in it. The state of the environment is monitored using variables such as biological, physical and chemical variables and by analysing interaction between them. ELY Centres also monitor the acts of the The State Regional Administrative Agencies (AVI:s). (ELY Centres 2015). AVI makes decisions on water and environmental permits. Those permits are under the Environmental Protection Act and the Water Act. AVI specifies the activities for which permits are required (AVI 2013). A permit under the Environmental Protection Act is required for activities that might lead to environmental pollution. Actions that require a water permit include water abstraction for a water supply plant, dredging and filling of a water area, building a bridge across a public waterway and insertion of a water pipe, sewage pipe or a cable under a public waterway. (Finlex 2012, Finlex 2014, AVI 2013.) It seems that the artificial wave production in natural wates does not require an environmental or water permit.

However, natural water body as an operation environment induces also a challenge for the wave production. Potential impacts on European marine sites from water-based recreation are due to nine reasons including engine emissions, sound emissions, antifouling paint leaching, sewage and other waste discharges, disturbance to species, erosion and turbidity and direct physical impact. Water quality changes are also under concern (Sanders et al. 2000). Disturbance to species, erosion and turbidity can be due to the water flow and wash propagation so they are in concern in this study, wheares others are assumed to be insignificant in the scope of this study. The implementation of *the hydrofoil method* in natural waters is environmentally admissible due to three reasons. First, water use or regulation related issues are irrelevant, since developed solution neither uses water nor affects the water level. Second, waste and water pollution related issues are not relevant since product and service development in project is assumed to fulfill all environmental aspects restricted by law, including material selections and operation principles. Underwater parts do not require chemicals or hazardous content. Third, the hydrofoil method does not modify the environment directly due to mobility and lack of required structures. But then, the hydrofoil method might have hydro-environmental effects due to the wave production. Wave production is actually an import of energy into the hydro-environment. The import of energy is considered relevant since energy cannot disappear but may only be transformed. As wave and water flow propagate towards the shoreline and lake or sea bed risk of erosion occurs which can indirectly modify the environment and cause other unknown effects. The irrelevant and relevant concerns are shown in Figure 3.

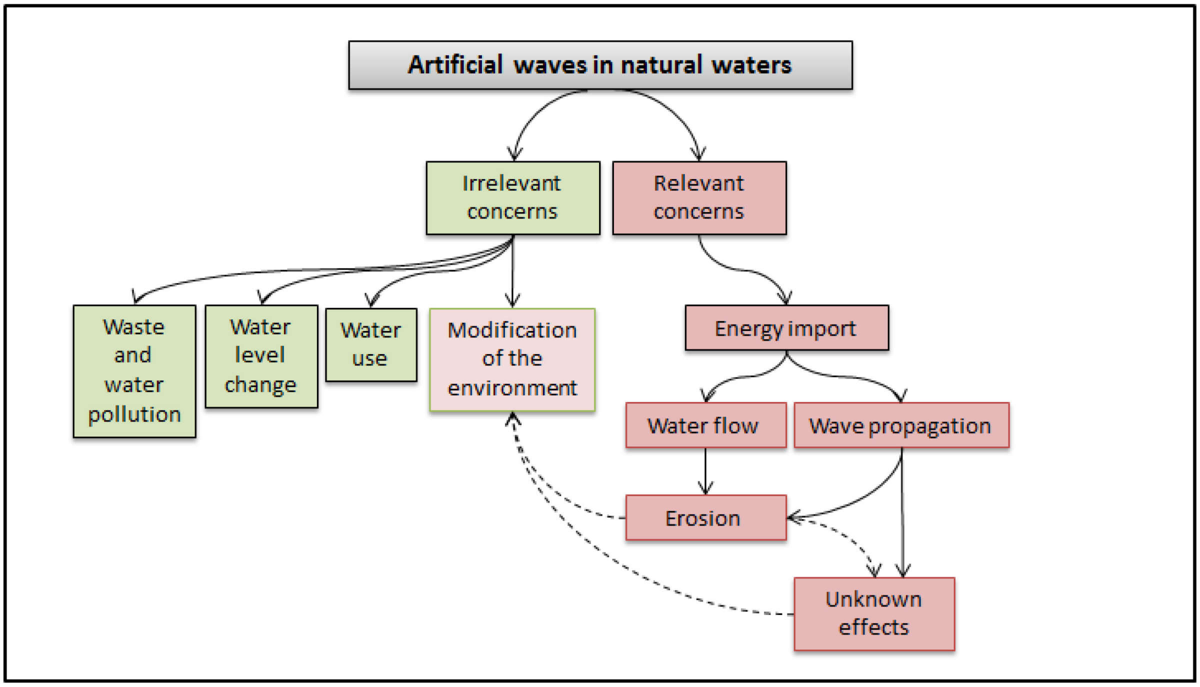


Figure 3: Irrelevant and relevant concerns of artificial wave production in natural waters. Irrelevant concerns in green, relevant concerns in red.

Artificial wave production in natural waters is not directly prohibited by law. The regulation does not refer to energy input or import, water flow generation or wave production (Finlex 2012 and Finlex 2014). However, a framework for hydro-environmentally friendly wave production is missing. The environmental or water permit would be needed if the activity might lead to water pollution, water use or water level regulation. (Finlex 2014, Finlex 2012). It means that the artificial wave production in natural waters is not prohibited by law. However, some rectrictions in the water act (Finlex 2012) apply for the artificial wave production. First, changing the hydro-environment is prohibited. Also, minimising the potential hydro-environmental effects is required. This so called “minimising rule” seems to be significant; potential hydro-environmental effects of an action might be unknown, but still the action must be implemented in a way that the potential effects are minimised. This must be taken into account while planning the measures to minimise the hydro-environmental effects.

The potential hydro-environmental effects can be minimised by different measures performed before and during the artificial wave production. When selecting the site for the execution, a few properties of the site must be evaluated. Also, set-up implementation might require adjustment in order to minimise the hydro-environmental effects. Furthermore, it was clear that some protecting measures could be necessary, but potential examples were uncertain due to the innovative and unique technology. These minimisation measures were categorized as: 1) site selection related measures, 2) operation or set-up adjustment related measures and 3) protection related measures. Figure 4 illustrates the premilinary framework for hydro-environmental effect minimisation.

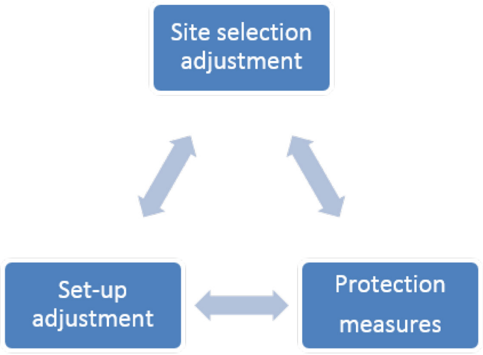


Figure 4: Premilinary framework for minimising the hydro-environmental effects and the categorization of the potential measures to minimise the effects

The topic of this study was to analyse the potential hydro-environmental effects of the hydrofoil method. The primary aims were to identify the hydro-environmental effects of implementing the hydrofoil method in natural waters and to identify approaches to minimise any potential adverse effects on waters. To assess the hydro-environmental effects and to recommend measures to minimise the effects this thesis aims to answer six research questions:

1. How do flow velocities decay with increasing distance from the wave propagation source?
2. What is the risk of erosion induced by the water flow near the lake or sea bed?
3. What is the wave power and cumulatie wave power of the waves induced by the application of the hydrofoil solution?
4. What are the potential hydro-environmental effects of artificial wave production in natural waters?
5. What are the factors behind the potential hydro-environmental effects?
6. What measures could be taken or what changes to the prototype would be necessary to minimise any potential hydro-environmental effects?

This study combines literature analysis with numerical data analysis. No similar wave production method or apparatus that utilise natural water system as operation environment have been implemented in Finland or anywhere in the world. Hence, the study utilises reference literature that deald with similar wavelike motions such as *ships wash*. Secondly, results of a simulation of the system are numerically analysed.

Demand for this study is due to both theoretical and practical reasons. First, study will give general theoretical information about artificial waves in natural waters since the topic has not been previously studied. Furthermore, by utilising the findings of this study, hydro-environmental effects can be reduced when the application of the hydrofoil method will be implemented which profits the purposes of the Project Artwave and the hydro-environment. An assessment of the ecological status of waters in Finland (Ministry of the Environment 2013) shows that 85% of the lakes and 65% of the rivers are in a good or very good state. This points out that most lakes have recreational potential due to their good water quality. Coastal waters have worse water quality (Ministry of the Environment 2013) and thus the use of coastal waters for water activities can have potential by raising awareness about the poor water quality.

Several aspects were taken into account when limiting the scope of this study. First, aquatic environments vary from oceans, estuaries, lakes, ponds, wetlands to rivers and streams. In this study coastal sea pools and lakes are taken into focus due to their feasibility for surf spot operation, but results can be applied to any natural water system with similar conditions. Second, numerical data analysis is based on prototype machinery details such as machinery size and wing positioning. In other words, the results apply for the generation of a 1 m surfing wave. In future, when waves of different sizes and shapes might be produced, machinery size or wing positioning can differ from the prototype. Any adjustment in machinery details must be taken into consideration while applying the results to machinery of any other kind. Furthermore, since simulation modelling was perfomed 2-dimensionally, simulation corresponds to hydrofoil of infinite length in the 3rd dimension. In reality, wing length of the prototype is 8 m (Tossavainen 2014b). Same wave power is distributed to a wider area thus decreasing the *wave exposure* per one meter of shoreline. Finally, water temperature and pressure are assumed to be constant. Water density is however dependent on water temperature, pressure and chemical composition (Imboden and Wüest 1995) and thus numerical analysis is unlimited.

2 Theoretical background

The developed wave production solution does not require modification of environment. However, artificial wave and water flow cause a risk of erosion in the lake or sea bed and shoreline. This section includes theoretical background about water waves and erosion.

2.1 Characteristics of the water waves

Energy is stored in waves as potential and kinetic energy. Potential energy is in the mass of water displaced from the mean sea level and kinetic energy in the motion of the water particles (Brooke 2003). Science of waves and water fluid behaviour is complex and characterization of waves requires simplifications and assumptions. General wind wave characterization parameters and relation between wind speed, fetch length and wave height are presented in following sections.

2.1.1 *Wave parameters*

Wave parameters characterise and describe waves. According to the linear wave theory, wave parameters that define wave characteristics include wave height *H*, amplitude *a*, length *λ* and period *T* (Figure 5). Linear wave theory is the core theory of surface water waves used in ocean and coastal engineering.

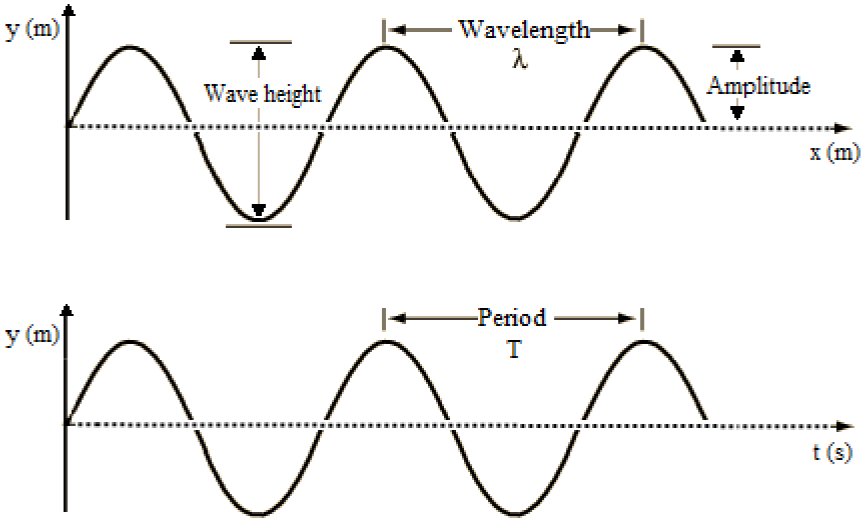


Figure 5: Wave parameters: wave height H, amplitude a, length λ and period T. Wave height H is the distance [m] in between the lowest wave point, trough and highest wave point, crest, amplitude a is the distance [m] between the crest and mean water level, wave length L is the distance [m] between the crests. Wave period T equals to time interval [s] between the arrivals of two consecutive crests at a stationary point.

The wind characteristics define wave characteristics until certain deptht of water *d*. It has been noticed, that threshold for this depth is equal to half of the wave length (Butt and Russell 2004). After the threshold, morphology of the sea or lake bed affects on the wave characteristics. Water depth is considered deep when $d > \lambda/2$, intermediate when $\lambda/20 < d < \lambda/2$ and shallow when $d < \lambda/20$. A regular wave can be speficied directly by its *H* or *a*, *λ*, and *T*

(Arntsen and Krogstad 2000).

The concept of *significant wave height*, H_s, is used in ocean wave studies to characterise irregular waves (Thornton and Guza 1983, Tucker 1991). For irregular irregular waves the wave parameters such as H varies over time and hence significant wave height defines irregular wave characteristics better than single wave parameter values. Values of determined significant waveheights are approximately half of the individual maximum wave heights (Finnish Meteorological Institute 2015a). Significant wave height can be defined as $H_{1/3}$ [m] which equals to average height of the heights of the 1/3 highest waves (Thornton and Guza 1983, Tucker 1991) or H_{10} [m] which equals to average of the heights of the 1/10 highest waves (Thornton and Guza 1983). Also, H_{m0} can also be used (Tucker 1991, Finnish Meteorological Institute 2015a) which can be calculated as follows

$$H_{m_0} = 4(m_0)^{1/2} \qquad (1)$$

where m_0 is the variance of the wave spectrum [m].

2.1.2 *Wind wave formation*

Waves result from wind blowing over an area of water surface and all water pools have different conditions, which affect the wind wave formation (Finnish Meteorological Institute 2015a). Wind waves can occur in any pool including oceans, seas, lakes and rivers and the same physical laws define wave formation and propagation principles independently from the water pool type. However, conditions such as wind speed, wind duration and *fetch length* (Vilmundardottir et al. 2010) together with the water bed topography (Butt and Russell 2004) are variables that define wind wave characteristics in natural waters. The fetch length is the distance over which wind blows, measured from the upwind shore.

Waves grow in period, height and length as a function of the wind duration and fetch lenght for any specific wind speed (Le Roux 2009). Vilmundardottir et al. (2010) assessed shoreline erosion along Blondulón in Iceland. Their study reported about relation between wind speed, fetch length and the wave height (Figure 6) when wind duration does not limit the wave formation.

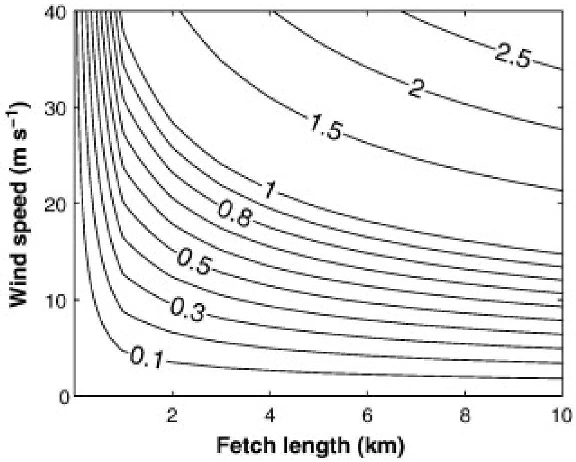


Figure 6: Fetch length F and wind speed U_{10} relation to potential wave heights H (Vilmundardottir et al. 2010)

Significant wave height H_s [m], and period T_s [s] in deep water can be calculated as follows

$$H_s = \frac{0.283}{g} {U_w}^2 \tanh\left\{0.0125\left[\left(\frac{gF}{{U_w}^2}\right)^{0.42}\right]\right\} \quad (2)$$

$$T_s = \frac{7.54}{g} {U_w}^2 \tanh\left\{0.077\left[\left(\frac{gF}{{U_w}^2}\right)^{0.25}\right]\right\} \quad (3)$$

where g [m/s^2] is the acceleration due to gravity, U_w [m/s] is average 10 min wind speed and F [m] is the fetch length. Vilmundardóttir et al. (2010) presented other formulas to approximate spectrally based significant wave height H_m [m] and wave period T_m [s] in deep water:

$$H_m = 0.0183926 {U_w}^{1.1} F^{0.45} \quad (4)$$

$$T_m = 0.5591662 {U_w}^{0.46} F^{0.27} \quad (5)$$

where U_w [m/s] is average 10 min wind speed and F [km] is the fetch length. Appendices 6a and 6b show calculated values for H_m and T_m with different F and U_{10}.

2.1.3 *Characteristics of the wind induces waves in Finland*

Water is a generic feature in Finnish landscape but due to mild winds and short fetches the waves are rather small. The country has 188 000 lakes with total coastline of 215 000 km. In addition, length of marine coastline is 46 000 km. In total Finland has a coastline of 314 000 km (Kuusisto 2006). In lakes the wind induced waves are usually limited by fetch length rather than by the windy period duration due to rather small reservoir size compared to bays and oceans (Vilmundardóttir et al. 2010). Finnish wind conditions (U_{10}) vary generally in between 0 - 20 m/s. According to Figure 6, wave heights until 1 m are possible in these conditions. In order to reach wave heights H from 0.5 - 1.0 meters, fetch length F of 4-10 km is required. This observation assumes that wind duration does not limit the wave formation. Share of 70% of Finnish lakes have a size of less than a hectare (Kuusisto and Raatikainen 1990). Hence, in most of them fetch lengths vary from tens of meters to hundreds of meters. In comparison to lakes, waves reach much higher wave heights in oceans. This is due to bigger pool sizes and fetches lengths. However, The Baltic Sea is a small and sheltered marine pool. Waves in the Baltic Sea are rather small due to short fetch lengths and numerous islands that work as natural breakwaters.

Shorelines even in marine environment might require additional attention as the artificial waves change the wave and flow conditions. For instance, in the coastline off Southern Finland easterly and westerly winds are able to generate waves as high as H_s = 5 m and individual waves as high as H = 9 m (Soomere et al. 2008, Finnish Meteorological Institute 2015b). However, these are extreme situations and waves are not expected to grow higher due to the narrow shape of the Gulf of Finland (Finnish Meteorological Institute 2015b). Long-term average H_s is much lower (Soomere and Räämet 2011). According to Figure 7, the long-term average of H_s reaches values of 0.5 m in the coastline off Southern Finland.

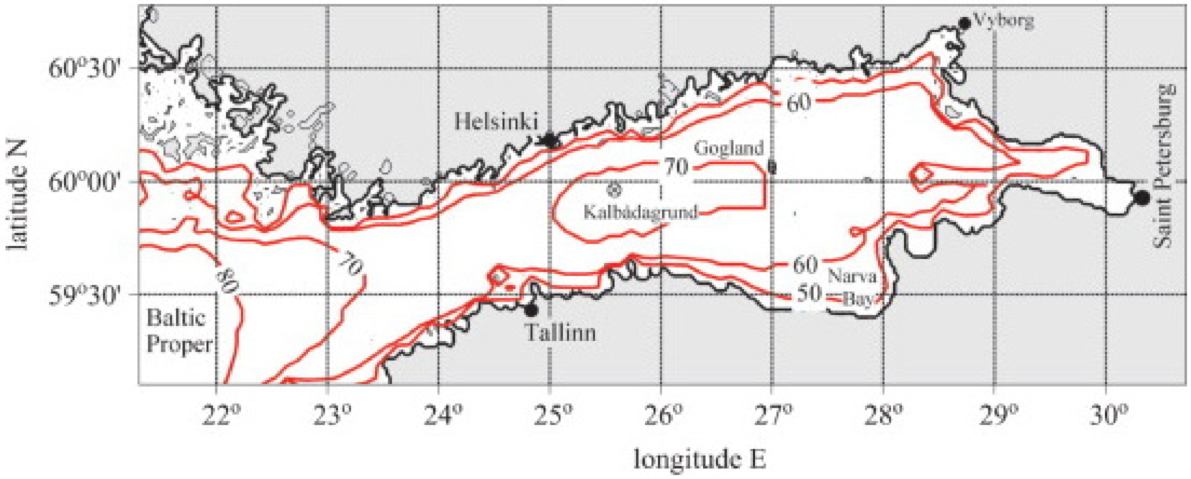


Figure 7: Spatial distribution of the long-term average of the modelled H_s [cm] (red lines) in the Gulf of Finland (Soomere and Räämet 2011)

2.2 The risk of erosion

2.2.1 *Erosion*

Erosion is a complex phenomenon influenced by several variables. It can be assessed through several approaches, depending on the water system type or area of interest. First, flow in open channels has the ability to scour channel beds, to transport eroded material and to deposit particles (García 2008). Secondly, waves scour shoreline as they collide towards it (Larson 1996, Tolvanen and Suominen 2005, Vilmundardóttir et al. 2010). Both of these phenomena are significant in the context of this study. Hence, two approaches were selected to assess influence of the factors on risk on erosion. These approaches were: 1) critical velocity approach and 2) wave power approach. Figure 8 represents these erosion assessment approaches and factors that influence erosion.

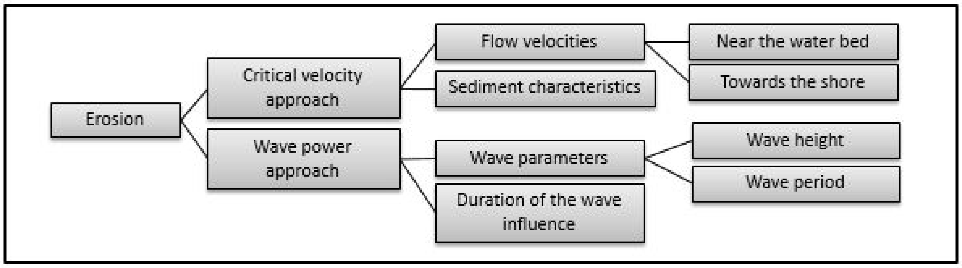


Figure 8: Erosion assessment approaches and factors that influence erosion

In the critical velocity approach the factors that influence the risk of erosion are flow velocities and sediment characteristics. This approach will be explained with more details in Section 2.2.2. In wave power approach, factors that have effect on erosion are wave parameters. The bigger the waves are, the more they erode. However, duration of the wave influence is also important factor. This approach will be explained with more details in Section 2.2.3.

2.2.2 *Critical velocity approach*

The detachment mechanism of sediment depends on water depth, flow velocities and the properties of the sediment. Water depth defines how much velocities decay before they reach the lake or sea bed. Flow velocities near the lake or sea bed define the risk of erosion. Finnish waters are relatively shallow. Share of 46% of the total lake area is less than 5 m deep (Kuusisto and Hakala 2007) and also the Gulf of Finland has rather shallow archipelago area (AVI 2012). Due to the shallow waters, it is important to analyse how the flow velocities decay with increasing distance from the wave propagation source. However, different sediment types erode at different velocities. Critical velocity approach uses empirical sediment threshold values to estimate risk of erosion under flow of particular velocities. This approach has been used to indicate erosion especially in fluvial environments where flow velocities can cause erosion in lake or river bed. (Graf 1984, García 2008.)

Erosion occurs when a critical state is reached and the initial movement of the sediment is frequently termed critical condition or initial erosion and it can be assessed through three approaches: 1) Critical velocity equations and examination of the impact of the liquid on the particles, 2) Critical shear stress equations and examination of the frictional drag of the flow on the particle and 3) The lift force criteria and examination of the pressure differences due to the gradient of the velocity. (Graf 1984.)

Sediment properties can be characterized by particle size and mineral type. Due to gravitational forces, fine-grained sediment particles transport easier than sand and gravel. For fine-grained sediment transport, size and composition are especially important (García 2008) due to *cohesiveness.* Non-cohesive soils consist of sediment particles, with large diameters, for which the attractive forces between particles are less than gravitational forces. On the contrary, cohesive soils consist of sediment particles, with small diameters, for which the attractive forces between particles are larger than gravitational forces. For clay mineral particles, with diameters less than 2 μm, cohesion increases as particle size decreases. Cohesive sediments are more resistant to erosion than non-cohesive. (e.g. García 2008 and Graf 1984.)

The relation between flow velocities, sediment properties and erosion was utilised in this study. *Hjulström diagram* shows empirical relationship between flow velocity and sediment motion (Hjulström 1935). It is widely referenced in studies in the field of sediment transport. It shows three sectors of sediment motion, depending on water velocity and the diameter of soil particles (Figure 9). The diagram was chosen for this study due to easy of its use.

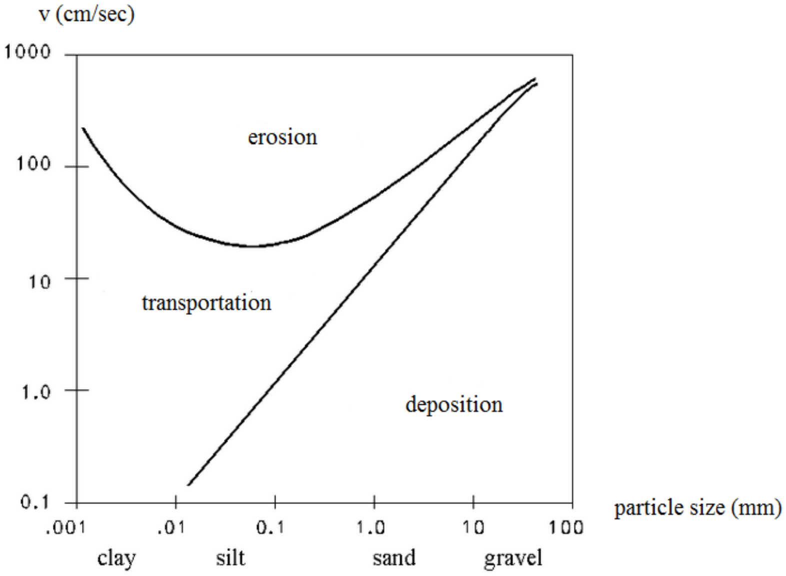


Figure 9: Hjulström diagram. Modified from Hjulström (1935)

Figure 9 illustrates the relation between flow velocity and particle size to erosion, transportation and deposition. Following notions can be discovered: Sediment is eroded after certain threshold of velocity is exceeded. As long as the flow velocity is below 25 cm/s, risk of erosion is low. The particle size of the most fragile matter is about 0.1 mm which corresponds to fine sand. This means that sediment with particle size 0.01 - 0.1 mm in diameter erode at the lowest velocities. With finer particles cohesion develops, so silt and clay tend to require higher velocities than their size would suggest. Coarser particles become increasingly heavy and therefore harder to transport. High velocities result in sediment transport within the fluid while low velocities result in sediment deposition. Once set in motion, fine particles can be transported even with low velocities. Larger coarse particles are deposited rapidly as velocity falls. Hence, transport only occurs at high velocities. These notions that are presented in this section were applied in the numerical erosion analysis.

Organic soils such as peat (Fin. turve) and sludge (Fin. lieju) are exluded from the Hjulström curve (see Figure 9). However, those soil materials are common in Finnish waters. Marttila and Kløve (2008) determined a critical flow velocity value of 0.15 m/s above which a peat layer will be eroded.

2.2.3 *Wave power approach*

Wave power approach is used to analyse erosion and wave exposure in shoreline. Shoreline erosion can be induced by natural storms or by anthropogenic activities. Wave power P defines the rate at which wave energy is transmitted in the direction of wave propagation across a vertical plane (Vilmundardóttir et al. 2010, Tolvanen and Suominen 2005).

In the wind waves the amount of energy transferred depends on the wave parameters (Brooke 2003). Wave power in deep water (for depths at least two times the wavelength) can be calculated with the wave power equation (Vilmundardóttir et al. 2010, Tucker 1991, Jadidoleslam et al. 2016). This equation follows the linear wave theory and is expressed as follows

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_E \qquad (6)$$

where T_E is the energy period [s], H_s is the significant wave height [m], ρ is the density of the water [1000 kg/m^3] and g is the acceleration due to gravity [9.81 m/s^2]. This equation gives the wave power P [W/m] per 1 m of a shoreline.

These aspects and the wave energy equation that are presented in this section were applied in erosion analysis along with the Hjulström curve shown in the previous section. With these two approaches erosion in shoreline and lake or sea bed were analysed numerically.

3 Description of the hydrofoil method

In this section the technical description of the hydrofoil method, including wave machinery details, wave generation principles and properties of the produced wave, are presented. These characteristics are relevant since they explain the peculiarities of the waves induced by the particular artificial wave generation solution. These peculiarities are presented to specify differences and similarities between natural and artificial wave properties and to present wave properties characterization principles and assumptions applied in this study. This section also describes *the Artwave prototype*, prototype of the hydrofoil system, and the premilinary framework for minimising the hydro-environmental effects.

3.1 Wave production method and required infrastructure

The method is based on a hydrofoil system propagating below the water surface in a depth of approximately 1.5 m. Wave production infrastructure requires a container on the main setup station, anchoring components on the opposed station, and underwater parts in between the stations. As the hydrofoil system propagates, it puts water into motion and lifts water masses upwards thus forming a wave. The hydrofoil system is a compound of wings attached to a trunk. Water flow behaviour and machinery stability are dependent on wing size and positioning. (Tossavainen 2014b.)

When forming the wave, several phases are required. Wave production technique was divided into four phases and named accordingly: 1. *stationary phase*, 2. *surfing phase,* 3. *halt phase* and 4. *reversing phase*. Figure 12 shows a sideview that demonstrates these phases. Each *run* begins at a *launch location* and stops at a *stop location* thus forming a *surf area* in between the launch location and stop location and *a spare* area in between the stop area and the shoreline. Figure 10 represents the physical domain with an underwater hydrofoil moving in the depth of 1.5 m and Figure 11 shows the surf area, spare area and launch and stop locations from aerial perspective.

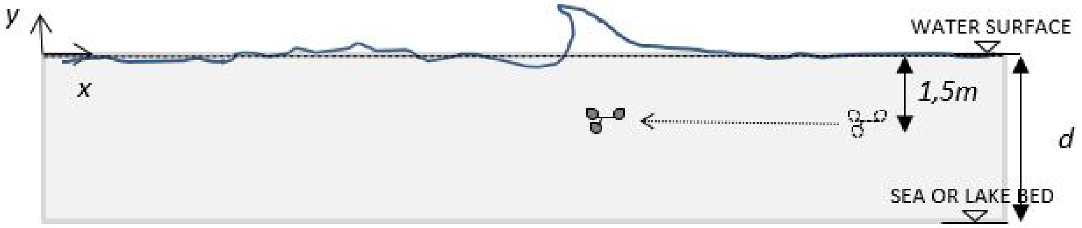


Figure 10: Sketch of the physical domain of an underwater hydrofoil moving towards the shoreline in the depth of 1.5 m

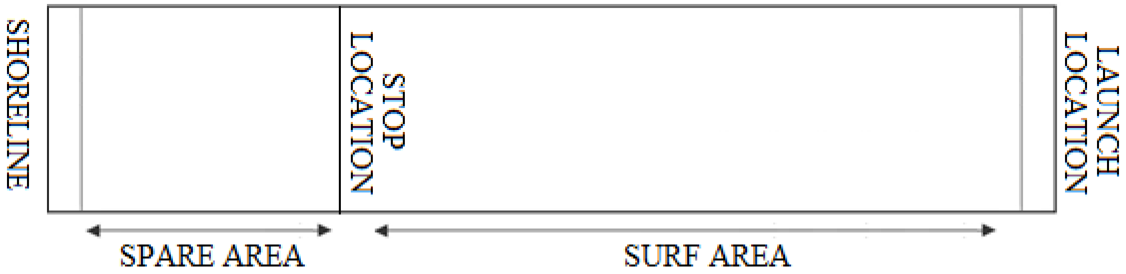


Figure 11: Surf area, spare area and launch and stop locations from aerial perspective

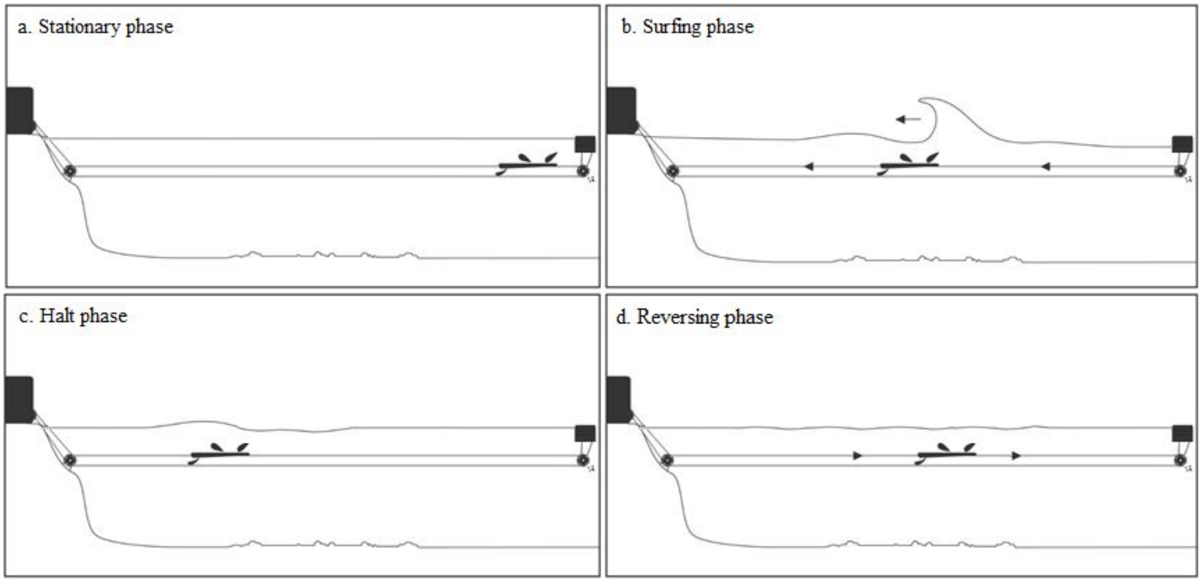


Figure 12: Sideviews from phases a-d (modified from Poranen 2014). A run begins as the machine is in stationary position (a) in the launch location (see Figure 11). After short acceleration until target speed is achieved, constant speed phase (b) lasts until machine and wave reach the stop location. In a halt phase (c), the machine is stopped. In the reverse phase during the return (d) hydrofoil system is returned back to the launch location.

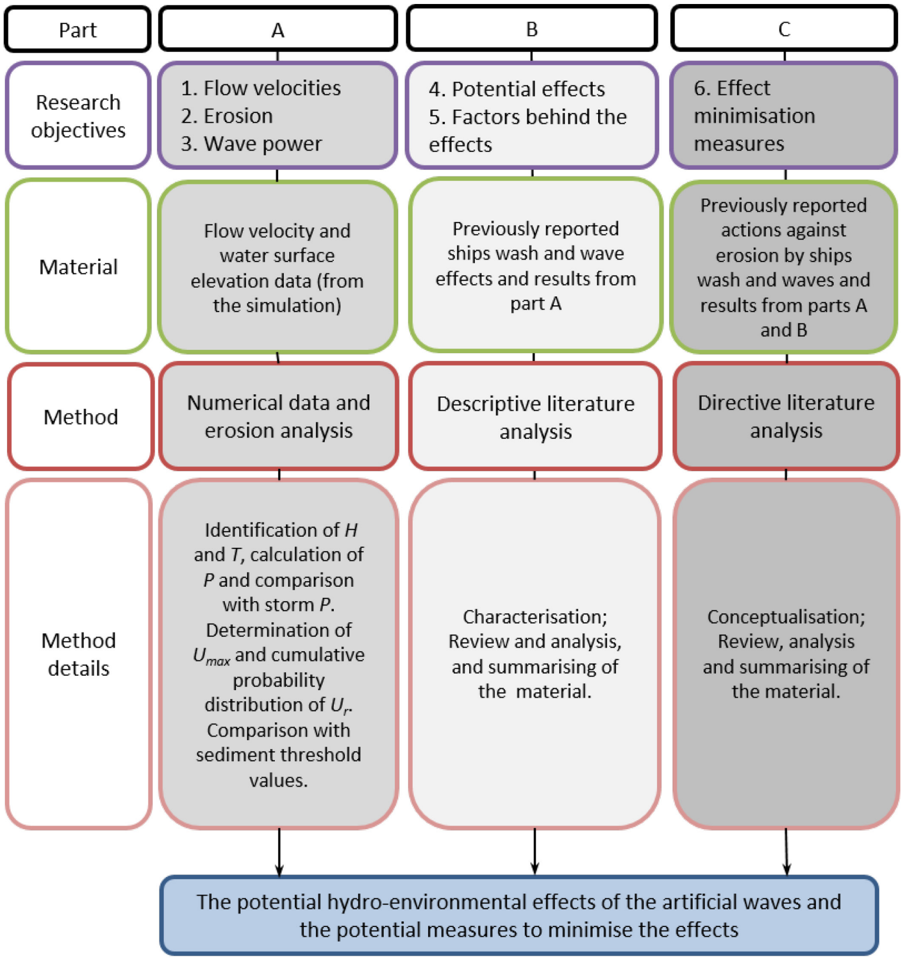
In the constant speed phase wing machinery proceeds with a speed of approximately 3-4 m/s meaning that the speed of the wave is also approximately 3-4 m/s and wave height is approximately 1 m. Surfing happens in this constant speed phase. After the halt phase wave is propagating towards the shore with changed wave parameters during the return machinery speed is rather slow, approximately 1 m/s thus not forming wave (see 5.1).

Prototype machinery was built in several phases during the year 2014 and the proof-of-concept testing of solution was implemented in September 2014 in Kalasatama, Helsinki. In summer 2014, *the Artwave Prototype* was built and a wave with a height of approximately 1 m was generated and surfed (Sellgren 2014b). This proof-of-concept testing was implemented in a harbour basin with a protected shoreline. The wave machinery will be implemented in a completely natural water system in the summer of 2016.

4 Materials and methods

4.1 Study process and methodology

The research questions were investigated through a mixed study, which means that methodology integrates qualitative and quantitative research. The study was a combination of numerical data and erosion analysis (part A in Figure 13) and literature analysis (parts B and C in Figure 13). Since erosion was identified as one of the main factors in hydro-environmental effects, focus in numerical analysis was narrowed to erosion analysis. Other aspects, such as the further hydro-environmental effects of erosion, are not in the scope of the numerical analysis, but are included in the literature analysis. The numerical data and erosion analysis was carried out in order to answer the research questions 1, 2 and 3 as shown in part A in Figure 13. Furthermore, the descriptive and directive literature analysis were implemented in order to answer the research questions 4, 5 and 6 as shown in parts B and C in Figure 13. Through the methodology shown in Figure 13, potential hydro-environmental effects of the artificial waves and the potential measures to minimise the effects were identified to guide the users or developers of the hydrofoil method. The more precise methodology is described in the following sections.



Part	A	B	C
Research objectives	1. Flow velocities 2. Erosion 3. Wave power	4. Potential effects 5. Factors behind the effects	6. Effect minimisation measures
Material	Flow velocity and water surface elevation data (from the simulation)	Previously reported ships wash and wave effects and results from part A	Previously reported actions against erosion by ships wash and waves and results from parts A and B
Method	Numerical data and erosion analysis	Descriptive literature analysis	Directive literature analysis
Method details	Identification of H and T, calculation of P and comparison with storm P. Determination of U_{max} and cumulative probability distribution of U_r. Comparison with sediment threshold values.	Characterisation; Review and analysis, and summarising of the material.	Conceptualisation; Review, analysis and summarising of the material.

The potential hydro-environmental effects of the artificial waves and the potential measures to minimise the effects

Figure 13: Study process and methodology

4.2 Simulation of the Artwave prototype

The run by Artwave prototype and the two dimensional behaviour of water fluid during and after the run was simulated by Tossavainen (2014a). Simulation has previously been utilised in the prototype machine development process and the wave parameter assessment (Tossavainen 2014b). Simulation by Tossavainen (2014a) was conducted by using two dimensional OpenFOAM –solver tool (OpenFOAM Foundation 2015). The simulation was based on solution of incompressible Reynolds-averaged Navier-Stokes (RANS) equations, k-ω turbulence model. The k–ω turbulence model is a two-equation turbulence model that is commonly used in computational fluid dynamics. The model predicts turbulence by two partial differential equations for two variables. These variables include turbulence kinetic energy, k, and dissipation of the k into internal thermal energy, ω. (Wilcox 1998 and 2008.) Volume-of-fluid, VOF, multiphase model was used to capture air-water interface (Tossavainen 2014b).

Simulation coordinates were 2-dimensional Cartesian with zero position in water level stage in left edge of the pool and the geometry for the simulation was a pool with depth of 30 m and width of 88 m (see Figure 14). Bottom topography was plain. The grid consisted of computational cells, i.e. grid cells, with a height and width of 0.10 m. The size of the grid cells was selected in a way that one computing could be performed in one day with a PC-workstation.

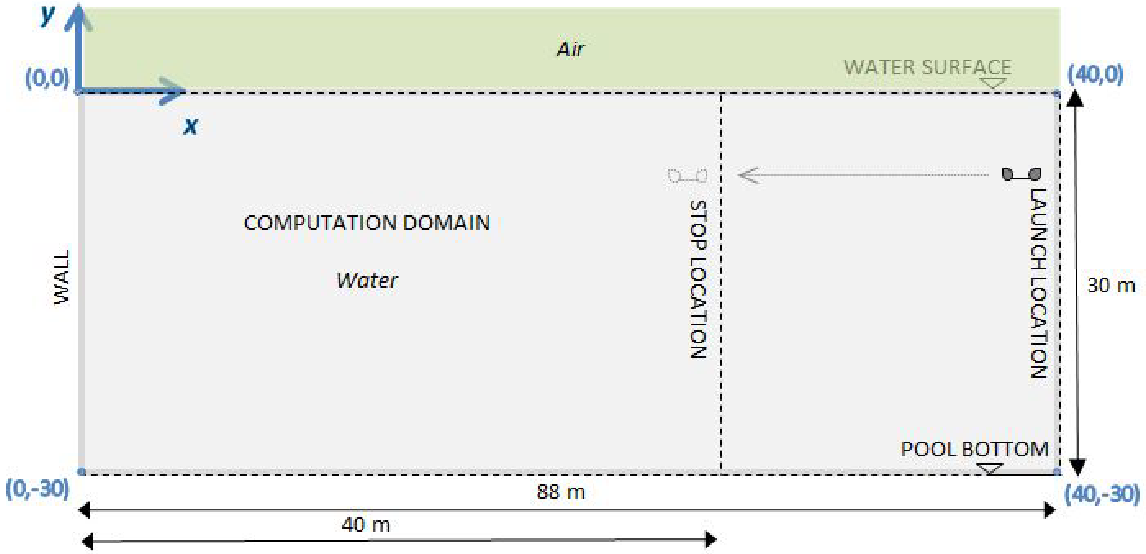


Figure 14: Sideview of the computation domain. Initial water level is in the x-axis. Simulation geometry was 30 m deep and 88 m wide. The hydrofoil system propagates in a depth of 1.5 m from a launch location to a stop location. Distance between the launch and stop locations is 48 m and the distance between the stop location and wall is 40 m. Green colour represents the air and blue colour represents the water fluid.

Scenario selected for analysis in this study was simulating a 48 m long *surf* with approximately 1 m high wave. Hydrofoil system propagated in four phases: 1) 2 s acceleration phase, 2) 10 s constant speed (4 m/s) phase, 3) 2 s decay phase and 4) machinery stopped in *stop location* X = 40.0 m at t = 14.00 s. Simulation was scaled 1:1 to represent full-size machinery and pool size.

In the current study, simulation results were utilised in the numerical data and erosion analysis. Data analysis and interpretation of the results was executed as a part of this study whereas the simulation modelling and visualization were made by Tossavainen (2014a). The results that were used in this study were water surface elevation and flow velocities after the run. Tossavainen (2014a) delivered two data sets for the purposes of the current study: time series of water surface elevation, y-coordinate of the water level in Figure 14 at every 1 s, and velocity data set including velocity values U_r, U_x and U_y, in each grid cell of the computation domain (at every 0.10 m) at every 0.04 s.

4.3 Numerical data analysis and erosion analysis

4.3.1 *Wave height and wave power analysis*

In wave power approach, analysis variables include wave height and wave period. Values of wave variables can be derived from data on the surface elevation (Thornton and Guza 1983) by Tossavainen (2014a). In this study, wave height and period were derived from the water surface elevation data for 14.00 – 60.00 s. For wave power analysis, six positions with different distances from the wall were selected. These positions and their distances from the opposing wall and stop location are presented in Table 1. Figure 15 demonstrates the selected distances and the computation domain geometry. Position represents the distance from the y-axis, and all values from the water surface y = 0 until the sea or lake bed y = -30 (see Figure 14 for the geometry) were included.

Table 1: Positions X_1-X_6 in the wave power analysis

Position	**Distance from the wall [m]**	**Distance from the stop location [m]**
X_1	30	10
X_2	25	15
X_3	20	20
X_4	15	25
X_5	10	30
X_6	5	35
Wall	0	40
Stop location	40	0

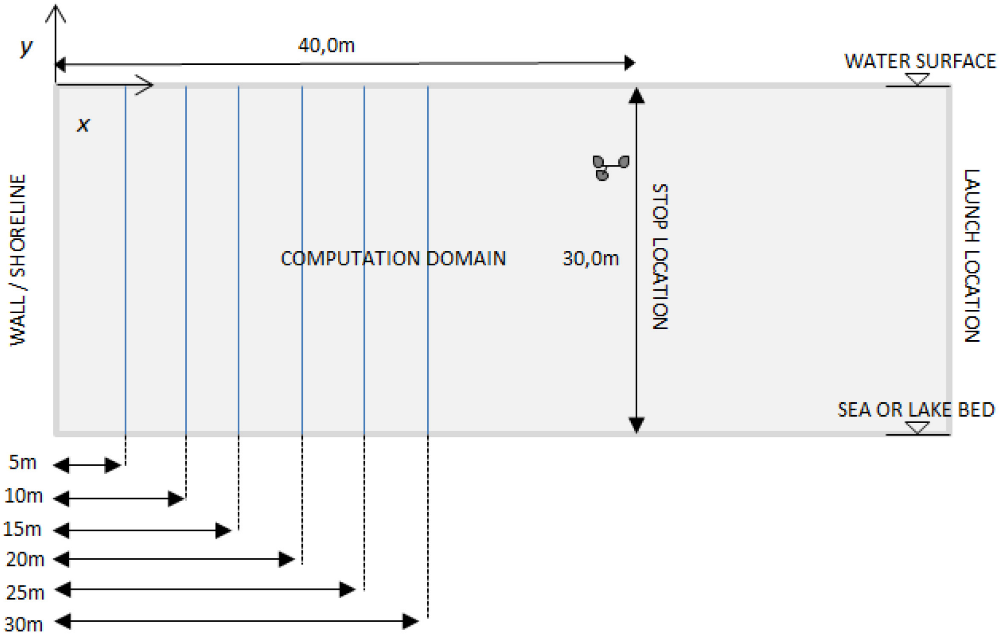


Figure 15: Selected distances and computation domain geometry in wave power analysis.

Water surface elevation as a function of time in each distance $X_1 - X_6$ was determined and converted into values of wave height and period. These values of wave height and period were used to characterise the waves. To characterize the waves also H_{max} and H_{m0} were determined. After this, wave height of the largest individual wave as a function of time was determined. Average wave period T_{avg} was determined, which was calculated as

$$T_{avg} = \frac{T_1+T_2+T_3+T_4}{4} \tag{7}$$

Where $T_1, \ldots T_4$ [s] is period of the largest wave in the position $X_1, \ldots, X_4$ and which was determined from data as follows

$$T_n = 2(t_{max,n} - t_{min,n}), \tag{8}$$

Where n is integer n = 1…4 depending on the position X_n and $t_{ma,x,\ n}$ [s] is the moment of wave crest and $t_{min,\ n}$ [s] is the moment of wave trough in the position in question. Then, wave power as a function of time was determined. Wave power was calculated with the Equation 6. Also, P_{max} as a function of time was calculated by replacing H_s with H.

Finally, cumulative wave power P_c for each run, day and season was determined. When calculating the cumulative wave power, the following assumptions were: 1) Duration of wave influence after each run depends on machinery details. In this analysis, duration of 16 s was used. 2) *Capacity of the setup* depends on the length of each run. For a 50 m surf, the capacity of the setup is approximately 60 waves per hour and for a 80 m surf, capacity of the setup is approximately 46 waves per hour (Andersén 2014). In this analysis, the capasity of 70 waves per hour was used. 3) Operating time per day was assumed to be 8 hours. 4) Season duration could be anything in between a few days ("*event*") or 200 ("*semi-permanent setup*") (Andersén 2014). In this analysis, season duration of 150 days was used. Cumulative wave power P_c [Wh] was calculated with equation

$$P_c = P_{avg} T_p, \tag{9}$$

where P_{avg} [W] is the average P for each run, day or season and T_p [h] is the duration of the wave influence for each run, day or season.

4.3.2 *Velocity analysis and the risk of erosion*

Water flow behaviour and decay of flow velocities was studied by two velocity analyses; x-directional, *horizontal analysis*, and y-directional, *vertical analysis* (Figure 16). In the analyses, several positions with different distances from the stop location or from the level of the mean water surface were selected. In the selected positions, data set of velocity values in the grid cells during the time frame was gathered. Each data set included all velocity values, that occur in the selected grid cells during the time frame 14.00 – 30.00 s, from stop moment (t = 14.00 s) until wave reaches the wall (t = 30.00 s).

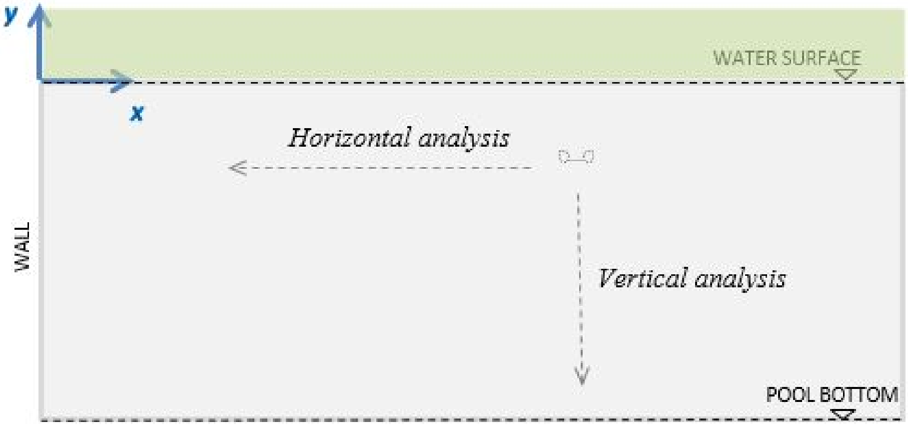


Figure 16: In the horizontal analysis how velocities decay towards the wall was analysed whereas in the vertical analysis how the velocities decay towards the pool bottom was analysed.

In the horizontal analysis, positions in different distances from the wall were selected (Table 2). Figure 17 demonstrates selected positions in the computation geometry. The positions were selected evenly at intervals of 5 m. All grid cells from the water surface until the pool bottom (Figure 18) were included in the data set of each selected position.

Table 2: Positions X_7-X_{11}, horizontal velocity analysis

Position	Distance from the wall [m]	Distance from the stop location [m]
X_7	25.1	14.9
X_8	20.1	19.9
X_9	15.1	24.9
X_{10}	10.1	29.9
X_{11}	5.1	34.9
Wall	0	40

Stop location	40	0

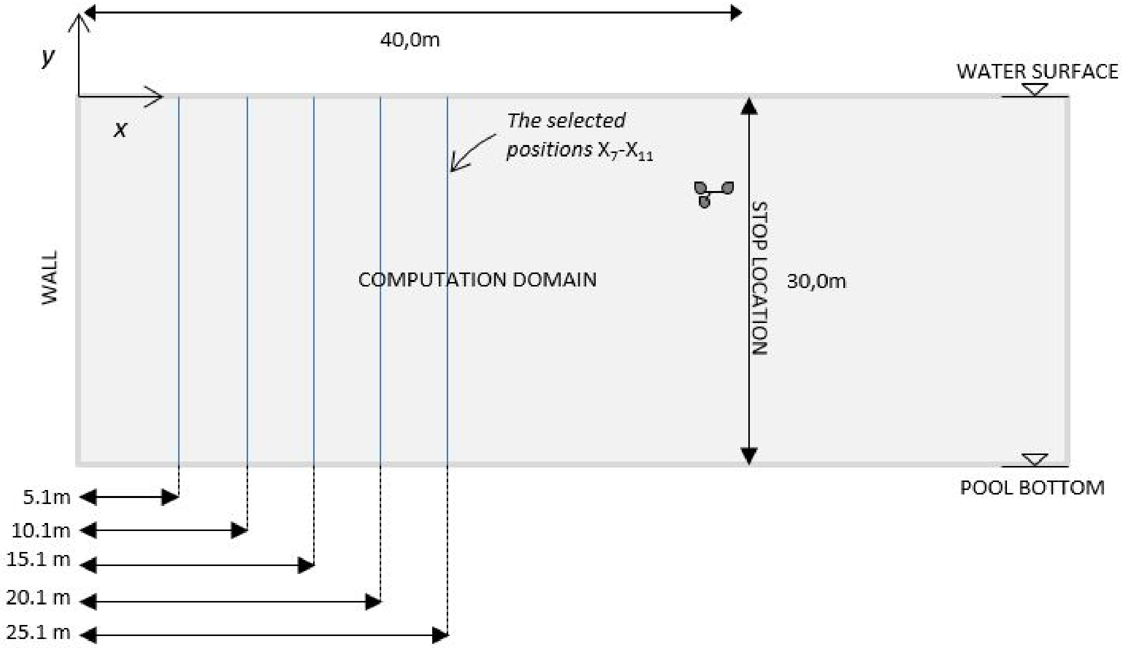


Figure 17: Selected positions X_7-X_{11} (blue lines) in horizontal velocity analysis.

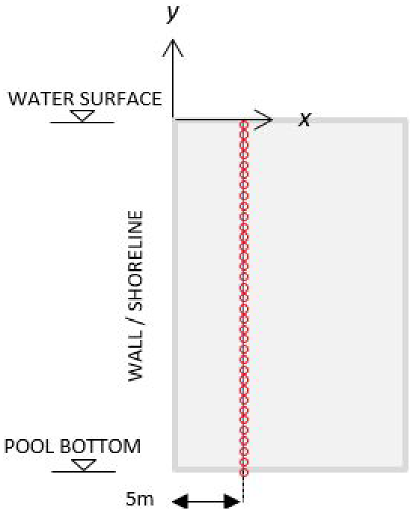


Figure 18: The selected grid cells in the horizontal velocity analysis. Red dots represent the cells selected in the analysis data set in each position. All cells from the water surface until the pool bottom were included in the data set of each position.

Moreover, in the vertical analysis, 12 positions in different depths were selected (Table 3). Figure 19 demonstrates selected depths in the computation geometry. Depths less than 2 m were outlined due to distraction of the apparatus motion in the depth of 1.5 m. In between 2-5 m positions were selected evenly at intervals of 1 m whereas below the depth 5 m positions were selected evenly at intervals of 2.5 m. This was due to the assumption that velocities decay significantly after depth of 5 m thus the interval of 1 m was considered unnecessarily dense. All grid cells from stop location until the wall (see Figure 20) were were included in the data set of each selected position.

Table 3: Positions Y_1-Y_{12}, y-directional velocity analysis

Position	Distance from the water surface [m]
$\mathbf{Y_1}$	2
$\mathbf{Y_2}$	3
$\mathbf{Y_3}$	4
$\mathbf{Y_4}$	5
$\mathbf{Y_5}$	7.5
$\mathbf{Y_6}$	10
$\mathbf{Y_7}$	12.5
$\mathbf{Y_8}$	15
$\mathbf{Y_9}$	17.5
$\mathbf{Y_{10}}$	20
$\mathbf{Y_{11}}$	22.5
$\mathbf{Y_{12}}$	25
Pool bottom	30

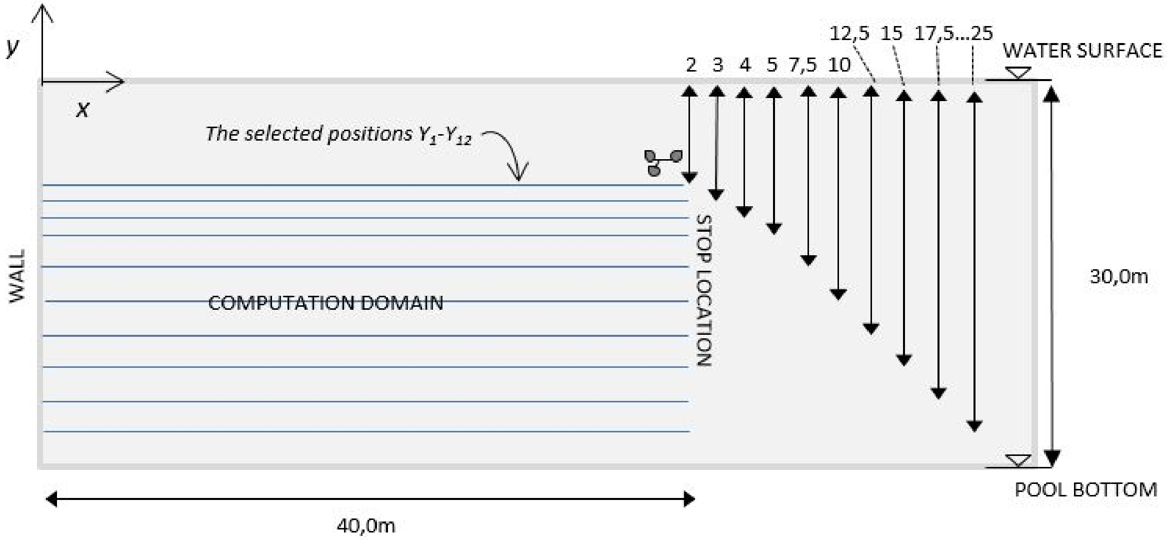


Figure 19: Illustration of selected depths and computation domain geometry. The positions Y_1-Y_{12} (blue lines) were selected for the vertical velocity analysis.

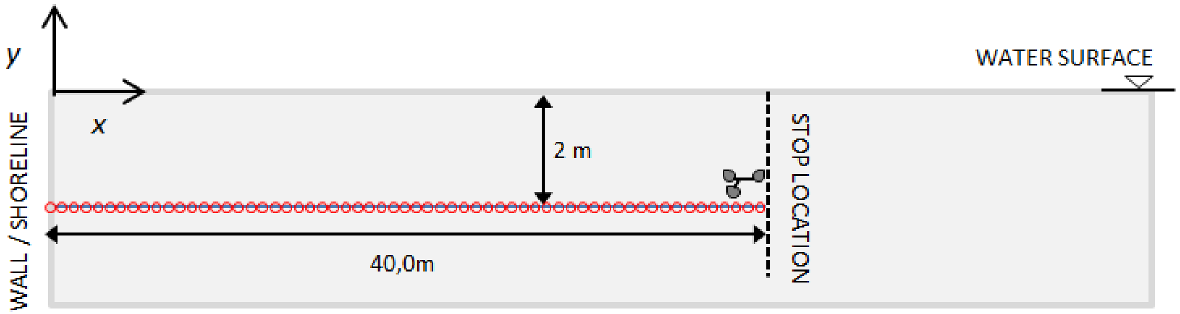


Figure 20: Illustration of the selected grid cells for the data set in vertical analysis. In the figure, example is shown illustrating the selected cells in the position Y_1. Red dots represent the cells included in the analysis data set in the depth. All cells from stop location until the wall were included in the data set of each depth.

Data sets of the velocities in the grid cells during the time frame were compiled. Velocities in the cells were analysed and positions Y_1- Y_{12} were compared. First, U_{max} in each position were determined and variation between positions was observed. U_{max} was determined as the highest velocity value during the time frame. Then, cumulative frequency of velocities were determined for U_r.

Finally, the risk of erosion in different positions with different sediment type was determined according to the critical velocity approach (see Section 2.2.2). Probabilities for U_r to exceed threshold values for erosion (Figure 21) determined for positions Y_1-Y_{12} and the differemt positions were compared in order to analyse how the velocities decay when the distance from the water surface increases. Due to uncertainty of the thresholds, absolute erosion rate is impossible to predict. However, the analysis provided a tool to assess relative risk of erosion in terms of different depths or positions.

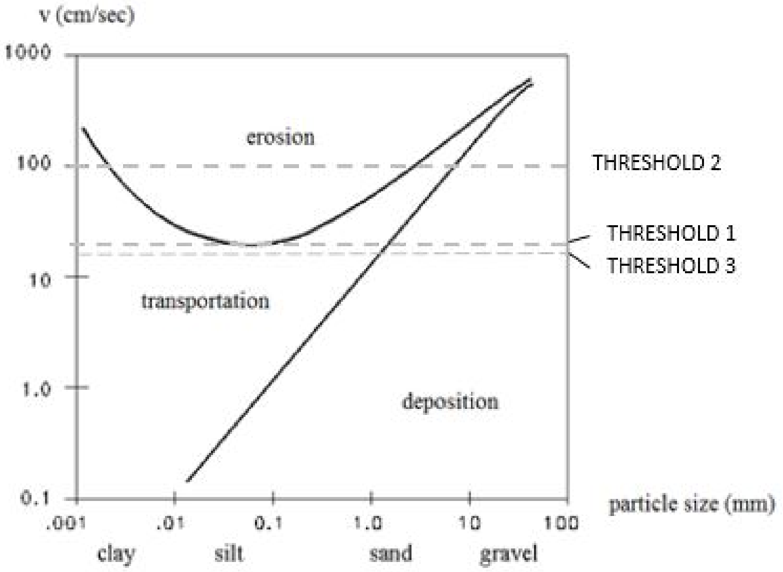


Figure 21: Selected erosion threshold velocities: threshold 1 for easily erodible sediment, threshold 2 for peat and threshold 3 for any soil material with particle size 0.005-3 mm. Modified from Hjulström (1935).

Thresholds 1 and 2 (Figure 21) were selected according to Hjulström (1935). Assumption was that velocities 25 cm/s can erode easily erodible sediment material such as silt and fine sand. Velocities of 100 cm/s cause risk of erosion for any soil material with particle size 0.005-3 mm. Threshold 3 (15 cm/s) triggering erosion of peat was chosen according to Marttila and Kløve (2008).

4.4 Descriptive and directive literature analysis

Natural wave activity due to wind or flowing water in channels can be used as a reference for the influence on water systems. Also, ship or boat activity causes effects due to the wash generation and to the propeller-induced flow velocities in the water column. Examples from a literature in these fields was reviewed and analysed and conceptualized. Focus was in the potential hydro-environmental effects of waves in natural waters and environmental characteristics influencing those effects. Analysis also focused to identify representative indicators of the potential hydro-environmental effects. Analysis method was a combination of a descriptive and directive literature analysis.

5 Results and discussion

5.1 Characteristics of the artificial wave produced by the hydrofoil method

5.1.1 *Wave characteristics*

The artificial wave produced by the hydrofoil method, *the Artwave wave,* transforms as it propagates. The wave and water flow transformation principles are similar as in natural waves. However, in comparison to natural waves, wave formation principle is different. In the artificial wave formation, different properties such as machinery details have effect on the wave size and form. In artificial waves produced by the hydrofoil method, wave formation and transformation depends on machinery details such as machinery size, wing positioning and the speed of the run. When the wave is produced with the hydrofoil equipment, bottom topography transition has no effect on size of the surfed wave.

Prototype induced wave simulation was conducted by Tossavainen (2014a). The simulation results gave information about wave formation and propagation. In the inspection of the wave formation and propagation, four specialities in relation to wave form transformation were discovered. First, in the stationary phase no wave is formed. Second, in the surfing phase wave forms locally and one individual wave is formed. Wave height is approximately 1 m (Tossavainen 2014a). Third, in the halt phase as the machinery is stopped, energy is no longer brought, and wave flattens and changes form. The individual wave flattens, breaks, and several waves propagate towards the shoreline. Finally, in the reversing phase no significant water flow or waves are formed. Table 4 and Figure 22 show wave forms in each phase.

Table 4: Wave forms in each phase

Phase	Wave form
a. Stationary phase	No wave formation
b. Surfing phase	Individual 1 m wave
c. Halt phase	Several flat waves
d. Reversing phase	No wave formation

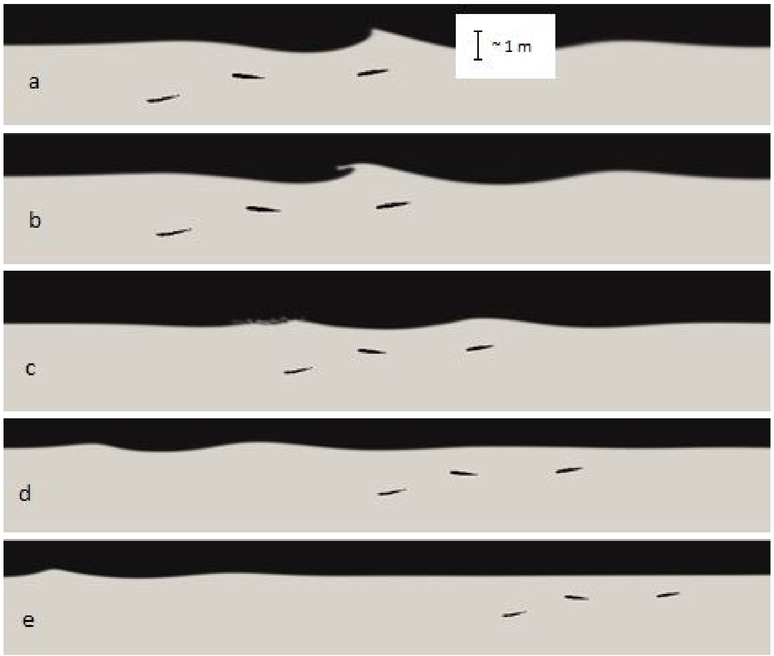


Figure 22: The wave shape alteration during the halt phase (a-b) and as the wave propagates after the halt phase (b-e). Black colour represents the air and grey colour represents the water fluid. With permission adapted from Tossavainen (2014a).

In the surfing phase flow does not spread significantly below the machinery and thereby causes no risk of erosion. However, there are two potential causes of erosion after the halt phase. After the machinery is stopped, energy is no longer given for the wave thus the wave shape alters but still continues to propagate towards the shoreline. Also, turbulent flow propagates towards the lake or sea bed under the hydrofoil system. The shoreline erosion is dependent on the wave damping and the erosion in the lake or sea bed is dependent on the decay of the water flow. These two causes of erosion are in scope of this study (Figure 23).

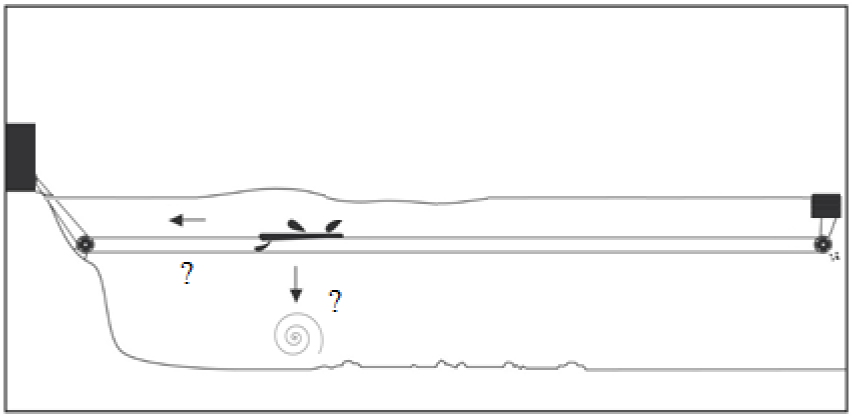


Figure 23: The potential causes of erosion that are of interest in this study. The wave can cause shoreline erosion as it propagates and collides towards the shoreline. Furthermore, water flow can cause erosion in the lake or sea bed. Adapted and modidfied from Poranen (2014).

5.1.2 *Water surface elevation and wave height*

Water surface elevation as a function of time in positions $X_1 - X_6$ (See Table 1 and Figure 15 for position definitions) are shown in Figure 24 and Figure 25. Maximum wave height (H_{max}) significant wave height (H_{m0}) and calculated average period (T_{avg}) are shown in Table 5.

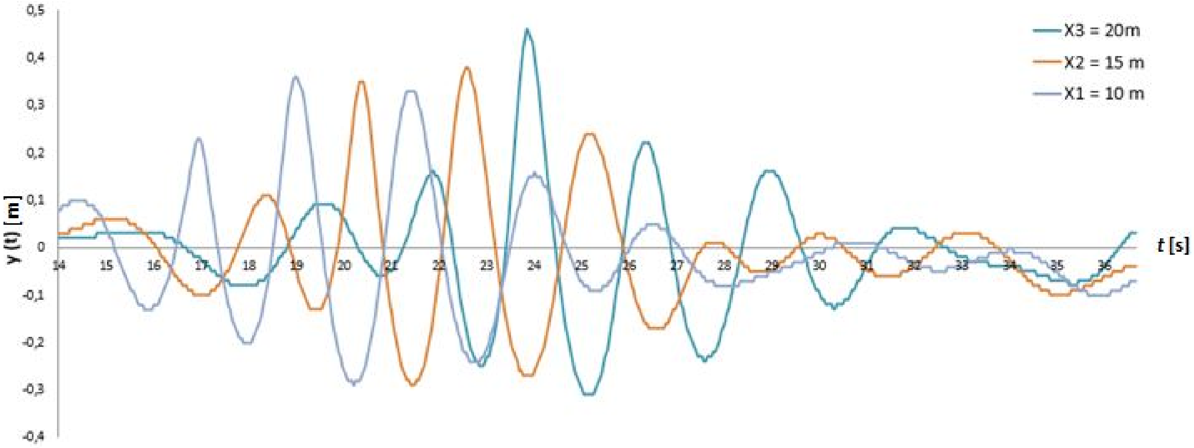


Figure 24: Water level elevation (y) as a function of time (t) in positions X_1, X_2 and X_3 (See Table 1 and Figure 15 for position definitions).

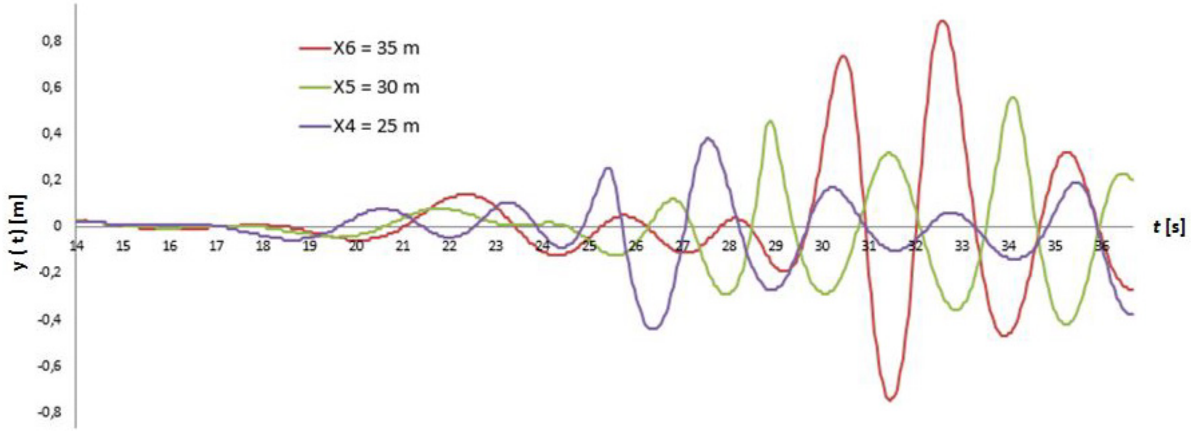


Figure 25: Water level elevation (y) as a function of time (t) in positions X_4, X_5 and X_6.

In positions X_5 and X_6 the water surface elevation range is greatest. It seems that the wall has influence on the water level elevation. In locations $X_1 - X_4$ the water surface elevation varies from -0.3 m to +0.45 m. The closer to the stop location the position is, the sooner the highest fluctuation of surface elevation occurs. From the locations $X_1 - X_4$, X_3 has the highest *wave crest* whereas location X_4 has the lowest *wave trough.* According to the water surface elevation as a function of time, five consecutive waves with *H* larger than 0.2 m propagate towards the shoreline after each *run*.

Table 5: Maximum wave height H_{max}, significant wave height H_{m0} and wave period T in positions X_1 - X_4 . (See section 3.1.2 for the explanations of the parameters)

	X_4	X_3	X_2	X_1	**Average**
Trough Y_{max} [m]	-0.44	-0.31	-0.29	-0.29	-
Crest Y_{max} [m]	0.38	0.46	0.38	0.36	-
H_{max} [m]	0.82	0.77	0.67	0.65	0.73
H_{m0} [m]	0.57	0.56	0.57	0.56	0.57
T_{min} [s]	26.28	25.04	21.4	20.2	-
T_{max} [s]	27.52	23.84	22.56	18.96	-
T [s]	2.48	2.4	2.32	2.48	2.35

Table 6: Significant wave height $H_{1/3}$ [m] in positions X_1-X_6

	X_1	X_2	X_3	X_4	X_5	X_6	**Average**
$H_{1/3}$ [m]	0.64	0.64	0.64	0.64	0.64	0.65	0.64

As shown in Table 5, the maximum wave height H_{max} ranges from 0.65 to 0.82 m and it increases as the distance from the stop location increases. The significant wave height H_{m0} varies only from 0.56 to 0.57 m. As shown in Table 6 significant wave height $H_{1/3}$ varies in between 0.64 and 0.65 and thus considerable alteration between the positions does not occur. T varies but the variation is not correlated with the position. The significant wave height, H_s, of the swell caused by the Artwave prototype is 30-40% lower than the produced surfable wave that has wave height of 1 m.

The significant wave height, H_s, of the swell caused by the Artwave prototype is 30-40% lower than the produced surfable wave that has wave height of 1 m. It would be interesting to study whether H_s would scale similarly as the produced surfable wave.

Appendix 4a shows calculated wave heights, wave periods and wave lengts with different fetch length F and wind speed U_{10} in deep water and Appendix 4b shows significant wave heights and wave periods with different fetch lengths and wind speeds in deep water according to formula by Vilmundardóttir et al. (2010). According to the calculations, with F less than 1000 m wind speed U_{10} of 20 m/s is required in order to reach wave heights more than $H = 0.5$ m. Maximum wave induced artificially by the Artwave prototype, H_{max}, corresponds to natural conditions where $F > 1000$ m and $U_{10} < 20$ m/s.

Wave height H as a function of time in positions X_1 - X_4 is shown in Figure 26. Wave diminishing does not occur in the studied distance of 30 m but instead wave height increases as the distance to the opposing wall decreases. With the results of this study, it is not possible to determine the distance, when the wave starts to diminish.

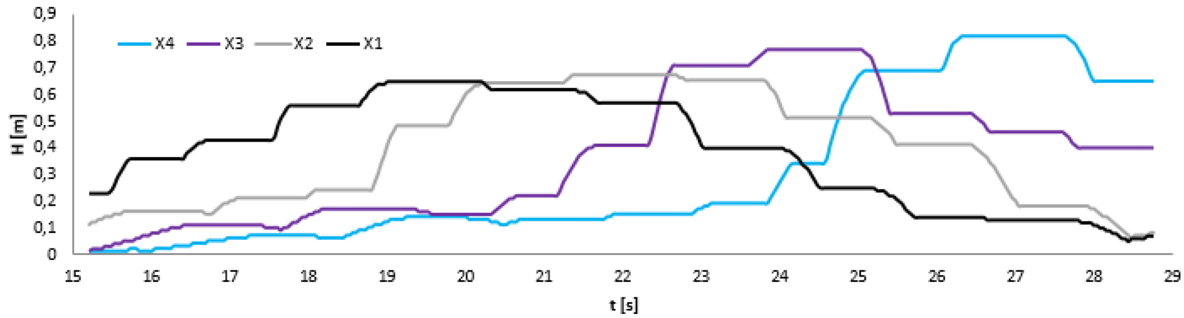


Figure 26: Wave height (H) as a function of time (t) in positions X_1 - X_4

The wave diminishing gives framework for the length of the spare area. In the studied conditions the length of the spare area must be longer than 30 m, since the wave does not diminish in that distance.

5.1.3 *Wave power and cumulative wave power*

The wave power *P* as a function of time in positions X_1-X_4 are shown in Figure 27. Wave power alteration follows same pattern as *H* (Figure 26). Hence wave power increases as the distance to the opposing wall decreases. The cumulative wave power P_c for each run, day and season are shown in Figure 28.

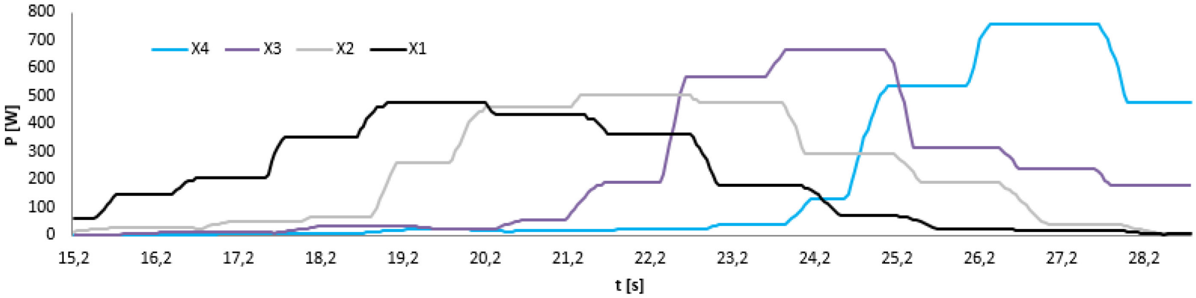


Figure 27: Wave power (P) as a function of time (t) in positions X_1-X_4

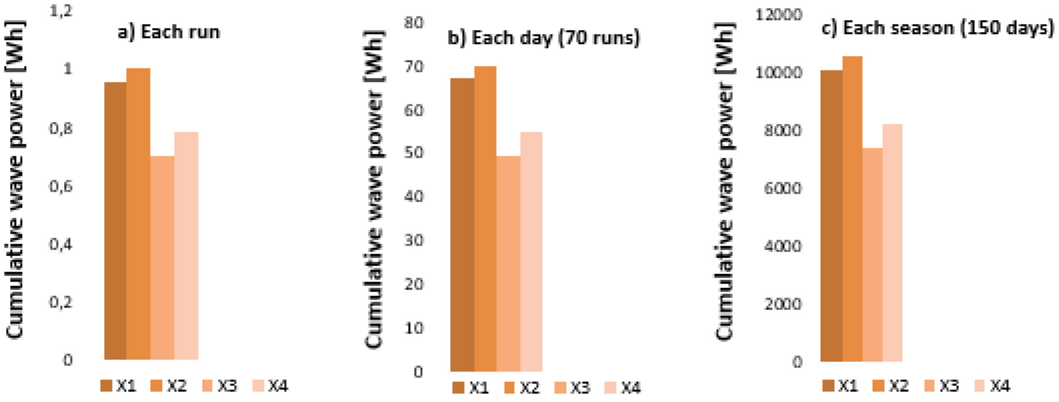


Figure 28: Cumulative wave power (P_c) *for each run (a), day (b) and season (c)*

Wave exposure of the Artwave waves varies depending on the location. Maximum *P* varies from 500 to 700 W (see Figure 27). The cumulative wave power P_c per run varies from 0.8 to

1 Wh (Figure 28a), P_c per day (70 runs) varies from 50 to 70 Wh (Figure 28b) and P_c per season (150 days) varies from 7500 to 1050 Wh (Figure 28c). The significance of these results depends on the reference values of wave power of the natural waves.

Three reference values for wave power were chosen. First, wave power levels of wind induced waves in the biggest oceans are typically from 10 to 50 kW per one meter of wave crest length in the oceans where fetch lengths and wind durations are unlimited (Brooke 2003). Second, Tolvanen and Suominen (2005) studied wave effects in Finnish archipelago environments. They studied temporal variation of wave power and cumulative wave power in two areas. The average wave power (W) for each 3-h period and the cumulative work (kWh) for each year from May 1 to November 30 in areas 1 and 2 is shown in Appendix 5a. Third, Vilmundardóttir et al. (2010) studied shoreline erosion along a lake reservoir in Iceland. 16 locations were studied. Transects R0-R12 were located in glacial till and R13-R15 in fluvioglacial sediments. Wave power events and cumulative wave power P_c for each location for the years 1997-2007 is shown in Appendix 5b. According to the study, wave power events varied from few kW to approximately 10 kW. Wave power values from the literature are shown in Table 7 and comparison of the cases 2-9 is shown in Figure 29. Maximum value of P in case 1 was extreme in comparison to other cases, so it was excluded from the comparison.

Table 7: Wave power values from the literature, cases 1-9

Case number	Case description	Wave power value type	F [km]	P [W]	Source
1	Wind waves in oceans	Max	Unlimited	50 000	Brooke (2003)
2	Finnish archipelago environments	Average	21.6	239	Tolvanen and Suominen (2005)
3	Finnish archipelago environments	Average	1.1	4.3	Tolvanen and Suominen (2005)
4	Finnish archipelago environments	Max	21.6	1909	Tolvanen and Suominen (2005)
5	Finnish archipelago environments	Max	1.1	31.8	Tolvanen and Suominen (2005)
6	Lake reservoir in Iceland	Max	0.6 - 1.9 (average)	3000	Vilmundardóttir et al. (2010)
7	Lake reservoir in Iceland	Max	2.2 - 2.8 (average)	10 000	Vilmundardóttir et al. (2010)
8	Artificial waves by Artwave prototype	Calculated, max	-	700	
9	Artificial waves by Artwave prototype	Calculated, average	-	226	

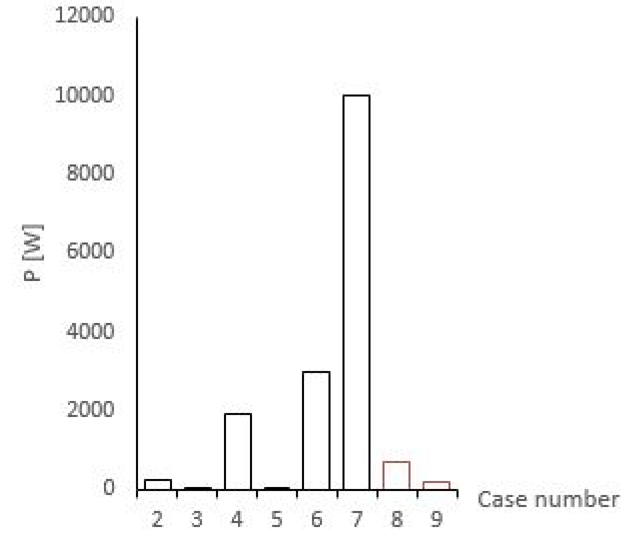


Figure 29: Wave power (P) of cases 2-9. Wave power of the hydrofoil method (prototype) in red and wind induced wave power values in black. See Table 7 for the description of cases.

As shown in Figure 29, artificial waves induced by the Artwave prototype solution are higher than average wave conditions in Finnish archipelago area. However, maximum values in Finnish archipelago environments, with a fetch length of approximately 20 km, are 3-4 times higher than the studied artificial waves.

Cumulative wave power of natural storms in Finnish archipelago (Tolvanen and Suominen 2005) are 1000-3500 kWh per year and in the lake Blöndulon, Iceland (Vilmundardóttir et al. 2010) 300-1700 kWh per 10 years, see Appendices 5a and 5b. These cases are described in Table 8 and the P_c comparison is shown in Figure 30.

Table 8: The cumulative wave power (P_c) per year in cases 10-12.

Case number	Case description	Value description	P_c [kWh]	Source
10	Finnish archipelago environments	Range, per year	1000-3500	Tolvanen and Suominen (2005)
11	Lake reservoir in Iceland	Range, per year	30-170	Vilmundardóttir et al. (2010)
12	Artificial waves by Artwave prototype	Computational, per season	8-10	-

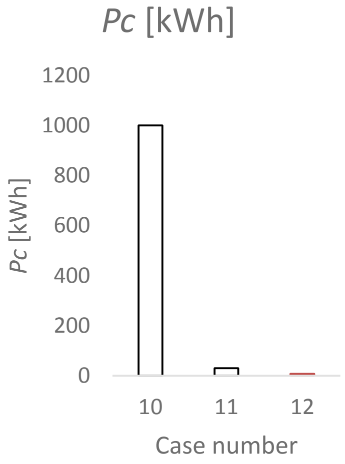


Figure 30: Cumulative wave power (P_c) of cases 10-12. Values of the hydrofoil method (prototype) in red and wind induced values in black. See Table 8 for the description of cases.

As shown in Figure 30, P_c of the Artwave prototype is significantly lower than the P_c per year caused by storms. It seems that the effects on the shoreline are potential but not significant. In the most vulnerable areas erosion could cause more damage, and therefore artificial wave production could cause a significant risk for the hydro-environment.

The duration of the wave influence is an important factor since wave influence together with P define cumulative wave power P_c. Wave influence of the hydrofoil method is dependent on duration of the apparatus use. Storms can last for days as the apparatus use can be limited for example to 8-12 hours per day.

5.1.4 *The velocities of the water flow and the risk of erosion*

U_{max} [m/s], in depths from 2.0 to 25.0 m below water surface are presented in Figure 31. U_{max} is 1.7 m/s in the depth of 3 m, and 0.05 m/s below the depth of 10 m. U_{max} decreases significantly in between 3.0 and 4.0 m (50%) and after 7.5 m depths seems to have no effect on maximum velocity. In the depth of 5 m U_{max} is 0.5 m/s and below the depth 7.5 m $U_{max} <$ 0.2 m/s. It seems that peat material can erode above the depth Y_6, fine sand can erode above the depth Y_5 and any soil material with particle size 0.005-3 mm can erode above the depth Y_3.

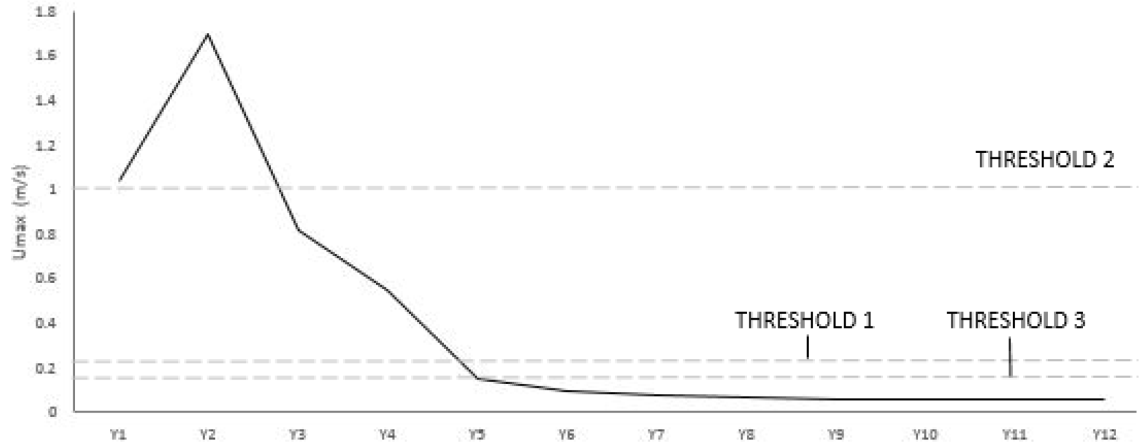


Figure 31: The highest velocity value during the time frame (U_{max}) in positions Y_1-$Y_{12.}$ Threshold velocities 1-3 marked with grey dash line.

The results given in Figure 31 give information about the maximum velocities in each depth. Along the maximum velocity, the distribution of the velocities is significant in terms of erosion and how likely it is to occur. The cumulative probability distributions in the different depths are shown in Figure 32 and Figure 33. The scale difference between the figures should be noted.

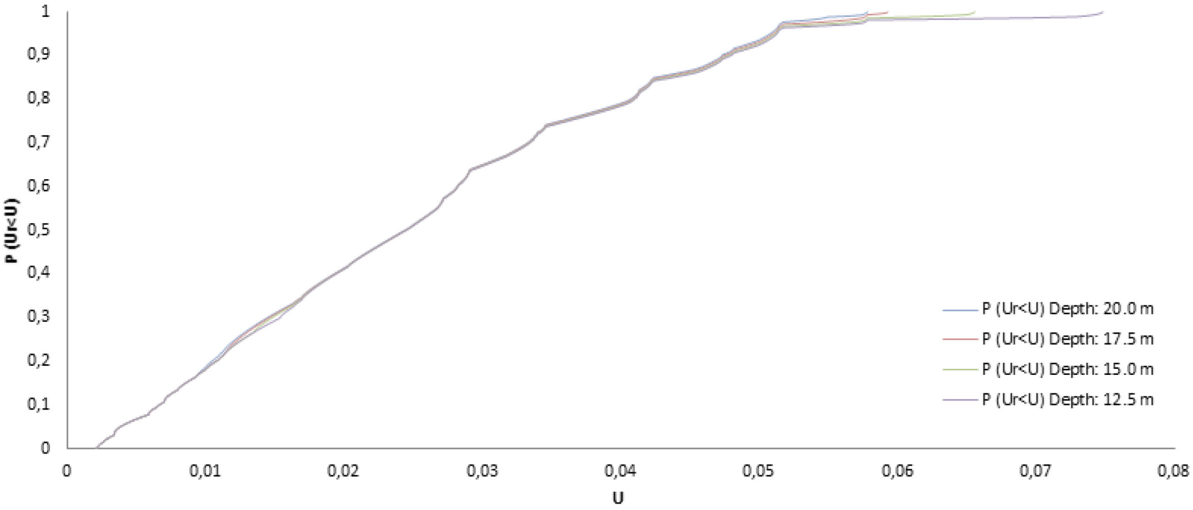


Figure 32: Cumulative probability distributions in the depths 12.5, ... , 20.0 m.

According to the Figure 31 the flow velocities decay significantly with increasing distance from the wave propagation source in terms of water depth. The threshold depth below which velocities do not diminish is the depth of 12.5 m. Water flow below the depth of 12.5 m has too low velocity to cause a risk of erosion. Above the depth of 12.5, erosion is likely to occur. Cumulative probability distributions for U_r in the depths 2.0, ... , 10.0 m and the thresholds 1-3 are shown in Figure 33. Table 9 shows threshold depths for peat, fine sand and fine silt or coarse gravel. The table includes a threshold depth below which erosion is unlikely to occur and a threshold depth below which erosion is minor. Erosion as assumed to be unlikely to occur if none of the velocities exceeded the threshold value for the soil material, and erosion was assumed minor if less than 90% of the velocities exceeded the threshold values for the soil material.

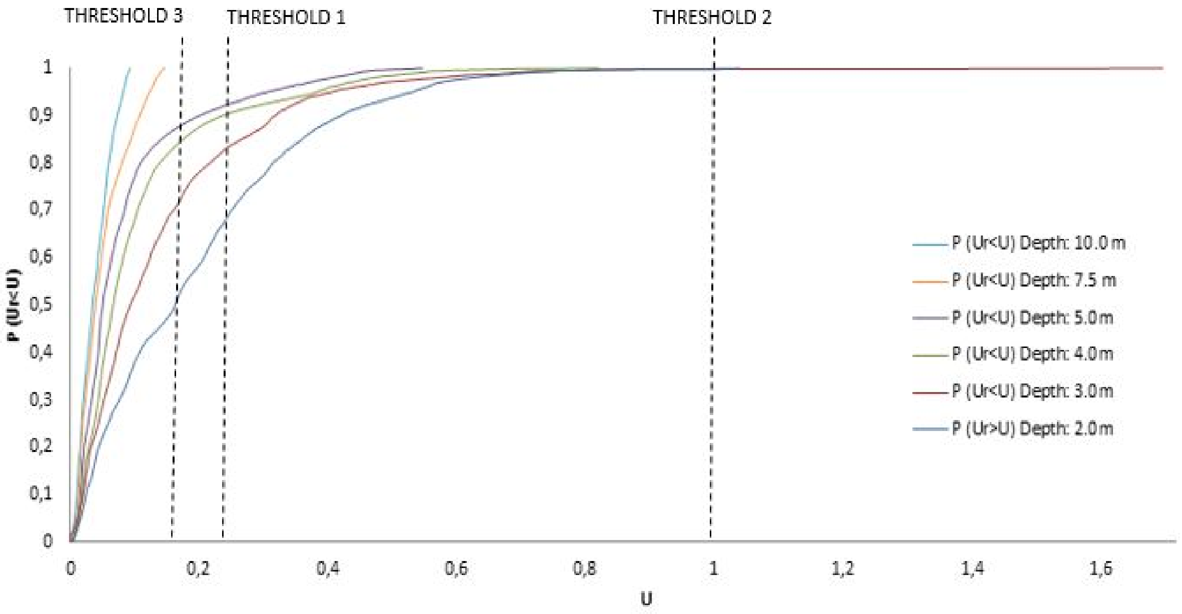


Figure 33: Cumulative probability distributions U_r in the depths 2.0 ... 10.0 m and the thresholds 1-3

Table 9: Threshold depths for peat, fine sand and fine silt or coarse gravel. The table includes a threshold depth below which erosion is unlikely to occur and a threshold depth below which erosion is minor

Soil type	Threshold velocity (see Figure 21)	Threshold depth: erosion unlikely to occur	Threshold depth: erosion is minor
Peat	Threshold 3: 15 cm/s (Marttila and Kløve 2008)	7.5	5
Fine sand	Threshold 1: 25 cm/s (Hjulström 1935)	7.5	4
Fine silt or coarse gravel	Threshold 2: 100 cm/s (Hjulström 1935)	4	2

The results given in the Table 9 give useful information about how to choose the proper site in the area. If the area has several potential sites, the site with the deepest water area should be selected. If the depth in the selected site is less than the given threshold depth, minimisation measures are recommended. These measures are described later in the section 4.4.3.

U_{max} in positions X_7-X_{11} (see Table 2) are presented in Figure 34. Also, probability integrals of velocity distributions in these positions are shown in Figure 35.

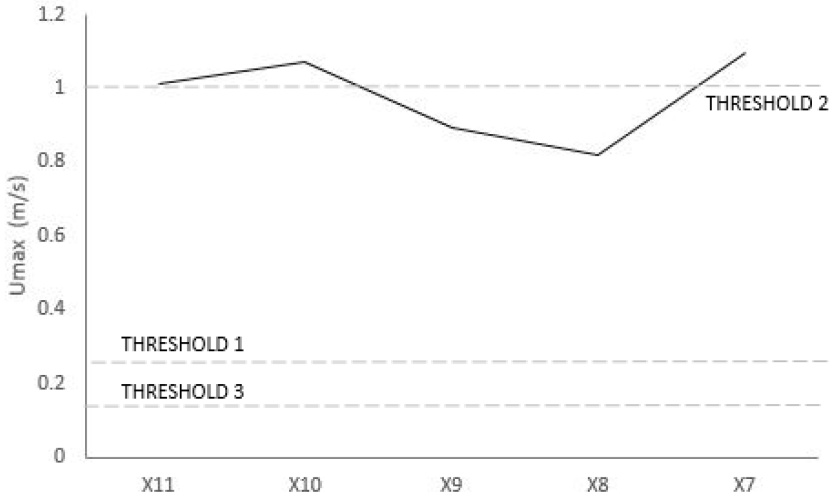


Figure 34: U_{max} *in positions* X_7-X_{11}. *Threshold velocities 1-3 marked with grey dash line.*

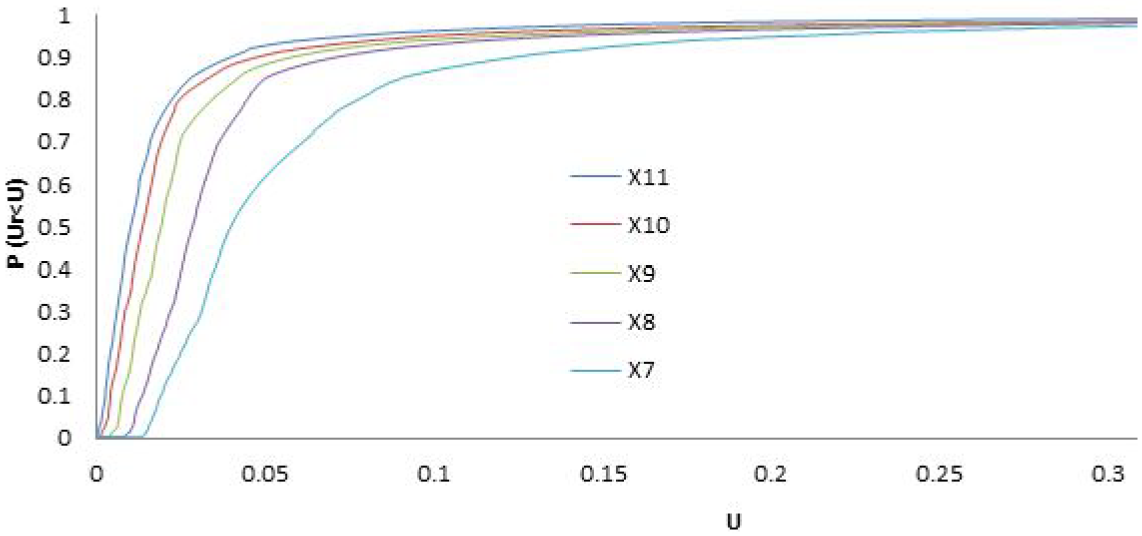


Figure 35: Cumulative probability distribution of velocities in positions X_7-X_{11}

As shown in Figure 34, the variation of the maximum velocity does not decrease as the distance from the stop location increases. This means, that the studied distance of 30 m is not enough for the water flow to diminish. This result is in line with the wave height analysis results (see Section 5.1.2). However, according to the Figure 35, flow velocities do decay with increasing distance from the wave propagation source in terms of x-directional distance. This means, that lengthening of the spare area can reduce erosion. However, with the results of this study, it is impossible to determine the required distance, since the length of 30 m is not enough. Erosion can occur in all positions X_7-X_{11}.

The hydro-environmental effects of the hydrofoil solution are not precisely predictable because of the uncertainties in the simulation or erosion analysis. While the prototype was tested in Kalasatama in summer 2014, hydrofoil collided with the induced wave as it surfaced thus decelerating the wave.

Two phenomena that are ought to reduce the risk of negative effects such as erosion, were exluded from the numerical data analysis. First, simulation corresponds to hydrofoil of infinite length in the 3rd dimension whereas in reality, wing length is approximately 8 m (Tossavainen 2014b). Same *P* is distributed to a wider area thus decreasing the exposure per meter of shoreline as illustrated in Figure 36.

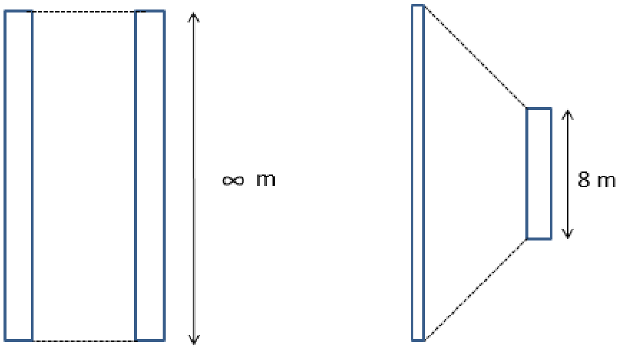


Figure 36: Hydrofoil with an infinite length on the left and the real prototype hydrofoil with a length of 8 m on the right from the aerial perspective. Wave power (P) distributes for a wider area thus reducing P per meter. The bar on the right represents the hydrofoil and the bar on the left represents the wave power on the shoreline.

The analysis has several limitations and thus the absolute list or magnitude of the hydro-environmental effects of the artificial wave production is impossible to predict. Due to limitations of this study and the complexicity of the hydro-environments, the use of the environmental indicators is recommended.

5.1.5 *The uncertainty factors in the numerical analysis*

Due to the scope of this study, the numerical analysis has uncertainties. Density of the grid, discretization of the equations, or selected turbulence model was not taken into account while analysing the results of the simulation model. The *k*-ω turbulence model applied by Tossavainen (2014a) is reported to represent measured values (Wilcox 2008). Hence, simulation model related uncertainty was assumed to be minor and examination of potential errors was outlined from the scope of the study. In this analysis the pool bottom topography was plain. Due to this, the simulation geometry is not realistic thus leading to uncertainty of flow behavior in natural hydro-environment. Alteration in the bottom topography affects the flow and makes bottom more vulnerable to the fluid forces.

The simulation was based on a wave produced by Artwave prototype and thus analysis is limited to production of a specific wave size. Also, shape of the produced wave can differ from the simulated scenario, which should be taken into account while adapting the results for further use. The simulation geometry was not sufficient to study the required distance of the spare area. Due to these limitations, further simulation is recommended.

5.2 Potential hydro-environmental effects of artificial waves in natural waters and the possibilities for minimising the hydro-environmental effects

5.2.1 *The hydro-environmental effects of waves*

Wave activity has impact on ecological and geomorphological processes in the littoral zone (e.g. Tolvanen and Suominen 2005). Sydänoja et al. (2012) analysed the state of marine areas in Finland. Ship wash was identified as significant cause of erosion in coastal and archipelago areas. Erosion causes geomorphological change in the littoral zone in a form of surface abrasion. Exposure, effect of waves on lakeshore vegetation, is also under concern and appears directly (e.g., by uprooting seedlings) or indirectly (e.g., by eroding fine sediments). (Sydänoja et al. 2012, UK Marine SAC 2001a.)

Risk of erosion can differ depending on the wave or water basin characteristics. Guenaydin and Kabdali (2003) performed an experimental investigation to study coastal erosion geometry under regular and irregular waves. Study concluded that whether the wave type was regular or irregular did not affect to the erosion geometry. (Guenaydin and Kabdali 2003). Wave power values studied in Finnish archipelago area (Tolvanen and Suominen 2005) and in a lake reservoir In Iceland (Vilmundardóttir et al. 2010) differ a lot from the typical value of wave power in wind waves in oceans (see Figure 29). This shows that in lakes and in archipelago areas wave power is less than in open ocean areas where fetch lengths are unlimited. Studies also show that the *wave exposure* has temporal variation within the year and regional variation within the water basin. Extreme events can cause erosion even ten times more than what occurs in average conditions. Shoreline material also has an influence on hydro-environmental effects. These results also show that in lakes, with similar fetch lengths than in archipelago areas, *the wave exposure* can be higher. This can be due to different wind speeds or wind periods. (e.g. Vilmundardóttir et al. 2010, Tolvanen and Suominen 2005.) Huntley and Coco (2009) studied how bedforms respond to changing conditions by using abstracted models. They analysed field, laboratory and modelling studies about the bedforms development in response to changing conditions. According to them, the development of the bedform is dependent on the pre-existing state of the bed. Still, they also found out that consensus about this dependence is lacking. To investigate the manner how field of ripples responds to a step change in forcing conditions they used a simple abstracted model. The study resulted that the influence of pre-existing bedforms is significant.

Erosion can cause further effects in the hydro-environment. Disturbance towards lake or sea bed and erosion of fine sediments appears mostly in the form of turbidity. Turbidity decreases water clarity in the water column affecting light transmission through the water column. This phenomenon causes problems for both aquatic flora, which require light for growth, and fauna which feed on the submerged vegetation (UK Marine SAC 2001b). Eroded material can also affect organisms directly. Waves along shipping channels can directly detach benthic organisms. This detachment occurs due to friction and pressure. Moreover, biomass, abundance and species number of plants decreases. Sediment resuspension and shoreline erosion occur mostly due to ship activity, but even boats can cause such effects in areas especially sensitive for erosion. UK Marine SAC (2001a) stated that sheltered archipelago areas and narrow straits are especially vulnerable for ship wash effects. Also, littoral zone and the shallows are under great impact. (Sydänoja et al. 2012). The form of the seabed is an important variable, since wave energy is dependent on the water depth. The deeper the water area, the less erosion occurs.

Erosion causes also indirect effects in the water system. These indirect effects include increasing of sludge (accumulation) and other changes in vegetation in such locations. These effects cause even further effects, since those areas are also typical breeding locations for animal species such as fish. According to Sydänoja et al. (2012) and UK Marine SAC (2001a.) areas under influence of *ships wash* differ in comparison to sheltered shorelines. The difference can be seen in decrease of number of species, density of individuals and in biomass. Sediment suspension can cause oxygen loss for spawns and block gills of fish (Sydänoja et al. 2012). Eroded sediment and increased turbidity in water can also smother and suffocate other benthic organisms (UK Marine SAC 2001b).

The aspects earlier in this section related to the adverse hydro-environmental effects. However, waves can also have effects that can be considered beneficial. Resuspension of sediments might have either adverse or beneficial effects, and aeration of the water column can be considered beneficial (UK Marine SAC 2001c). One beneficial effect is the “forced convection of dissolved substances across the sediment-water interface” (Peterson, 1999). Water quality and biodiversity can increase as the water masses are mixed and oxygen as well as nutrients are circulated.

Waves and water flow can cause erosion and erosion can cause further effects due to several reasons. Also water layering changes might occur. The adverse hydro-environmental effects of the artificial waves can be morphological and ecological. Figure 37 illustrates the summary of the potential hydro-environmental effects and their relations.

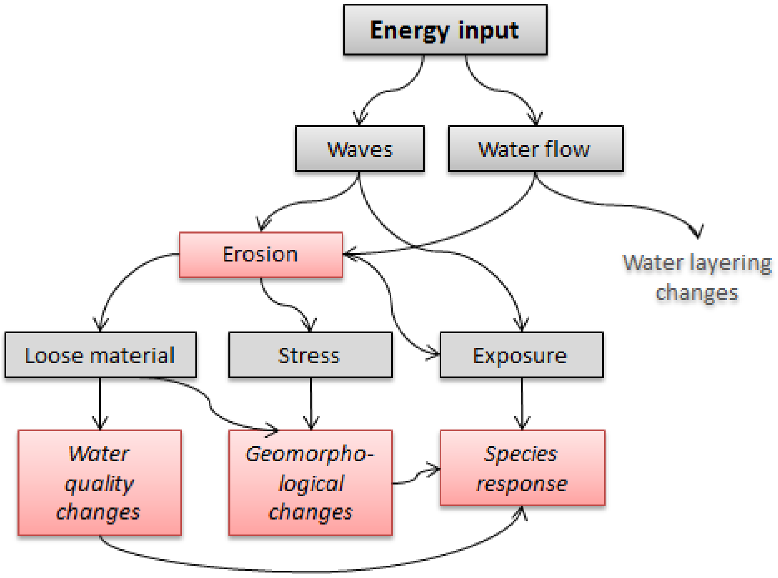


Figure 37: Adverse hydro-environmental effects of external energy input into waters; water quality changes induced by eroded sediment in the water fluid, loose material,, geomorphological changes induced by material loss in bed or shoreline, stress, and species response induced by either direct collision on species or trough water quality and geomorphological changes.

Hydro-environments are complex entities and coastal processes are difficult to predict. Processes such as flocculation, settling and scour lag make it difficult to predict the behavior of sediments in long-term. Expecially cohesive sediment behaviour prediction without extensive knowledge of the study area and field data is really difficult (Lumborg and Vested). Advantage of the curves such as the Hjulströn curve is the ease of their use (Paphitis 2001) which was important for this study. However, such curves are restricted to the conditions under which they have been originated (Paphitis 2001). Hjulström diagram is a crude simplification, and it has been critizised and expanded since its publication. In natural waters erosion phenomenon is more complex. Hjulström curve is based on experimental setting rather than natural environment, and it refers to uni-directional water flow in a channel in a certain water depth. Curve is not totally applicaple since in our case flow is turbulent (velocities vary in time and space) and water depth can vary. Even though the results given by the Hjulströn curve are crude approximations, in the scope of this study, the curve was assumed to have a sufficient accuracy. For cohesive sediments, it is not possible to predict the erosion solely on particle size (Marttila and Kløve 2008). Also the transport of cohesive sediments is different in comparison to coarser particles because they travel as aggregated groups of particles rather than separately (McAnally and Mehta 2000).

In easily erodable areas even small wakes cause massive effects whereas in other areas effects are less significant. Water basins as physical systems are complicated and diverse due to many aspects. Hydro-environments are complex entities and action-effect relation is particularly hard to predict. Each water body is a complicated and diverse system having certain characteristics and their interrelation. A connection between *ships wash* and potential impacts on the erosion of intertidal flats and saltmarsh is difficult to establish because of the natural variability of the marine systems (UK Marine SAC 2001).

Hydro-environmental effects depend on water systems natural conditions which vary a lot depending on several variables. Location of the lake, soil and vegetation of the area, size of the watershed, retention time of the water, structure of the biotic community formed by the plants and animals, climatic conditions, and the variations caused by human activities, for example nutrient load, water level regulation and fishing, are all important factors that effect on the lakes properties. (Sarvilinna and Sammalkorpi 2010.) Features representing great variety of water system properties relate to morphological, physical and chemical characteristics of water systems. Each individual change in nature should be examined in relation to the entirety of alteration patterns (Haila 1992).

5.2.2 *Potential measures to minimise the hydro-environmental effects*

In this section the factors behind the hydro-environmental effects and thus potential measures to minimise the effects are reviewed. Most examples have been taken from the ships wash studies, since the wavelike motion is similar to the artificial waves produced by the hydrofoil system.

According to the literature analysis, measures are required not only during but also before and after the artificial wave production. The proposed framework for minimising the hydro-environmental effects is presented in Figure 38.

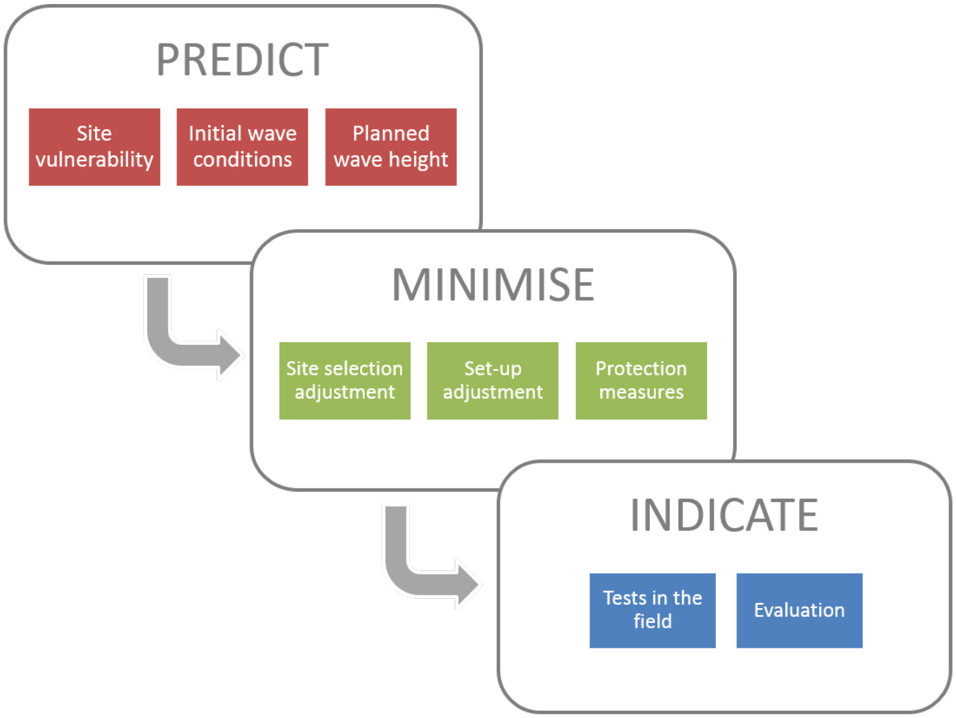


Figure 38: The proposed framework for minimising the hydro-environmental effects

Predict

Environmental vulnerability is one aspect that needs to be taken into account when analysing the hydro-environmental effects. Some areas are more vulnerable to erosion than others and how vulnerable selected area is, depends on several characteristics at the area. One way to identify a vulnerable area is to check whether the area is under conservation programme. Furthermore, when assessing effects of artificial waves, it is in great interest to study initial flow conditions and wave climate in the area. Lakes are lentic water systems meaning that they are still-water bodies (Dodson 2005). Wave climate is naturally more stable than in lotic environments. In estuaries the water system is under influence of both flow and waves. Estuarine species are tolerant to alteration of temperature, salinity, sediment concentrations and to a certain degree current velocities (Lumborg and Vested). Even though Baltic Sea or Gulf of Finland is not categorized as an estuary, it is under influence of flow and waves more than lakes. Also, due to this, shoreline areas are commonly somehow protected against wave activity. So, in this case, lakes are in more concern than seas. However, even in Finnish coastal waters large waves occur only during storms. Also, shoreline areas in the Gulf of Finland are rather shallow. Due to these two reasons, caution is required also in marine sites.

Studies report that the background wave climate has influence in how detrimental erosion is. For example, the wave energy generated by moving vessels must be compared to the background wave climate in an area (UK Marine SAC 2001c). Biota tolerance for flow alteration depends on background wave and water flow climate and the strength of the environmental effect depends on how considerably artificial wave production causes alteration compared to natural conditions. If information about wave heights is lacking, natural wave and flow conditions can be assessed trough fetch length, wind speed and length of windy period.

Wave heights in the area can be checked from the diagram (see Figure 6). Also, the calculated values in Appendices 4a and 4b can be used.

Sediment properties have great influence on erosion. As suggested by the Hjulström curve (see Figure 9) theoretically sediment with particle size 0.01-0.1 mm in diameter erodes at the lowest velocities. Sydänoja et al. (2012) report that steep moraine shores are the most erosion sensitive.

Minimise

Table 10 shows the factors or variables that influence the magnitude of effect that wash, or artificial waves, can have on shoreline erosion. There is a possibility of morphological variation along the shoreline at the area. In some cases, adjustment in the site selection might minimise the hydro-environmental effects. In some cases adjustment of the set-up might be required. *Ships wash* effects are mostly minimised by speed restrictions (UK Marine SAC 2001a). In context of the current study, this can be applied by restricting the size of the hydrofoil and thus restricting the size of the produced wave. Another *ships wash* effects minimisation possibility is associated with the distance between navigation channel and shoreline. This is reported to be in important consideration, as wash dissipates relatively quickly (UK Marine SAC 2001a). In data analysis of this study, it was shown that in distance of 30 m neither surface elevation nor flow velocities dissipated significantly. Hence, the required distance between the spare area (see Figure 11) and shoreline is more than 30 m.

Table 10: Variables or factors and proposed actions to minimise the influence of the variable or factor

Variable or factor	Proposed action	Why relevant?
The speed of the vessel; the faster the speed, the bigger the waves (UK Marine SAC 2001c)	Restricting the speed of the hydrofoil	Relate to magnitude of the waves
The size and displacement of the vessel; the bigger the vessel, the bigger the waves (UK Marine SAC 2001c)	Restricting the size of the wave machinery and thus the scale of the produced wave.	Relate to magnitude of the waves
The distance between the vessel and the shoreline; the longer the distance, the smaller the effects (UK Marine SAC 2001c)	Lengthening of the spare area. Displacement of the selected site Re-adjustment of the positioning of the hydrofoil system	Relate to magnitude of the shoreline erosion
Type of sediment (UK Marine SAC 2001d).	Selecting a site with non-easily-erodable sediment	Relate to magnitude of the shoreline erosion
The orientation of the shoreline (UK Marine SAC 2001d)	Re-adjustment of the positioning of the hydrofoil system	Relate to magnitude of the shoreline erosion
The profile of the shore (UK Marine SAC 2001d)	Displacement of the selected site; Depth must be more than the threshold depth	Relate to magnitude of the shoreline erosion
Bounce back from estuarine shores and hard flood protection schemes (UK Marine SAC 2001d)		Relate to magnitude of the shoreline erosion

If the measures shown in the Table 10 are considered insufficient or impossible to implement, *shoreline protection measures* are recommended. The shoreline protection measures are structure or actions that protect the shoreline against eriosion. These measures can be divided to *“soft engineering”* and *“hard engineering”* related measures. The hard engineering approach relies on construction of physical structures whereas the soft engineering approach relies on planning, management, non-structural measures and ecological principles and practices to achieve stabilization of shorelines and safety (e.g. Caulk et al. 2000).

The soft engineering measures can enhance habitat and improve aesthetics. Also, the soft engineering measures are inexpensive in comparison to hard engineering measures. (Caulk et al. 2000.) Vegetation is an important factor in erosion. Plant communities work as a protective shield for the soil as the network of plant roots hold soil particles and stabilize the slopes. Leaving the vegetation in place is easy and cheap protection measure. (UMESF 2006). The hard engineering measures are considered as a further management option that is relevant after other appropriate measures have been considered and applied. Protection structures can be breakwaters, bunds or mounds of sediments on the intertidal. (UK Marine SAC 2001.)

Storm effect minimization, for example in harbours, commonly relies on protection structures. Many studies report about harbour wave damage during storm events. For example, Atkins and Mocke (2009) studied safe boating harbour construction and energy transmission rates into the harbor structures in Port Philip Bay, Victoria, Australia. Wave screen was designed to protect the harbor structures from unacceptable wave conditions during storm events. Study concluded that the partial depth wave screens offer less protection than the offshore reefs. This limits the salient growth in the lee of the structure. To minimize erosion problems, caused by wave action, in Maria Farinha Beach, Pernambuco, Brazil, the following protection structures were recommended by Mallmann and Pereira (2014): 1) The construction of a submerged breakwater; and 2) the use of a sand bypassing system. The hydrofoil itself can function as a breakwall by diminishing the wave while floating in the water surface at stop location before the reverse phase.

With a proper site selection, set-up adjustment and protection measures the potential hydro-environmental effects are ought to be minimised. However, environmental effects and thus hydro-environmental effects are impossible to predict. Hence, use of environmental indicators is recommended.

Indicate

In the previous section site characterisation aspects were described. Some shores in sea environments are naturally more protected from wind and wave action and in some lakes the wind climate and pool size cause larger variety in flow conditions. Each water system is a specific entity and therefore species response and effect on biota is impossible to predict.

Environmental indicators are simple measures of changes in the complex environment providing a practical way to track the state of the environment or appeared change. In order to analyse changes in environment, it is impossible to record each variable or to assess absolute variable relations. However, several environmental indicators can be used to indicate environmental response to produced actions. Some of the indicators can be measured visually, some need special equipment. Not all environmental indicators fit to this case. Still, literature analysis resulted in many useful indicators. These indicators can include: 1) Turbidity; indicator of water quality changes (e.g. UK Marine SAC 2001b, Kahiluoto 2015), 2) Chemical composition of sediment; indicator of potential water quality changes and 3) Macrozoobenthos and Benthic Brackish water index (index of water state qualification, change or species response) (e.g. Laaksonlaita 2012). Tracking of these or other environmental indicators can help to assess changes in the hydro-environment and to react before long-term effects occur. Further literature review and practical examination of the listed indicators is recommended. Especially turbidity can be measured in the field with reliable results (Kahiluoto 2015).

6 Conclusions

This study aimed to identify the hydro-environmental effects of implementing the hydrofoil technology in natural waters and to identify approaches to minimise any potential adverse hydro-environmental effects. It seems that the artificial wave production does not require environmental or water permit. However, it is important to minimise any adverse effects that could modify the hydro-environment.

Artificial wave production in natural waters can cause erosion and indirect effects such as water quality changes induced by eroded sediment in the water fluid, geomorphological changes induced by material loss in the bed or shoreline and species response induced by either direct coillision on species or trough water quality and geomorphological changes.

According to the study flow velocities do decay significantly towards the lake or sea bed but do not decay towards the shoreline in the distance of 30 m. As flow decelerates towards the sea or lake bed relatively quickly, water depth at the site has a significant influence on erosion and hydro-environmental effects. For fine sand, depth of 4 m seems to be a threshold depth below which the erosion is minor and depth of 7.5 m seems to be a threshold depth below which erosion does not occur. For fine silt and gravel, depth of 4 m seems to be a threshold depth below which the erosion is minor and depth of 2 m seems to be a threshold depth below which erosion does not occur.

The wave power values of the artificial waves induced by the particular Artwave prototype solution are higher than average wave conditions in the Finnish archipelago area. However, maximum values in Finnish archipelago environments, with a fetch length of approximately 20 km, are 3-4 times higher than the studied artificial waves. Cumulative wave power P_c is 0.8-1 Wh for each run, 50-70 Wh for each day, and 7500-10500 Wh for each season which is minor in comparison to natural storms where P_c can be 30-3500 kWh per year.

The proposed framework for minimising the hydro-environmental effects of implementing the hydrofoil technology in natural waters include measures before, during and after the wave production in order to predict, minimise and indicate the hydro-environmental effects. When a particular area is considered as a potential location for the application of the hydrofoil method, vulnerability of the area and potential sites in the area should be examined. The characteristics that should be examined are water depth, sediment properties and shoreline properties. Furthermore, background or initial wave conditions must be examined. Erosion can be adverse in areas with less than 5 m deep water, in areas with vulnerable ecosystem or in areas where natural wind induced waves have smaller H than the waves will be produced in the site. If the area is considered vulnerable, artificial wave production is not recommended. If the site has no special vulnerability, it seems that artificial wave production is possible without water or environmental permit but still all hydro-environmental effects must be minimised. The more vulnerable the site is, the smaller waves should be produced. The produced wave height is dependent on the size of the hydrofoil system thus the size of the hydrofoil must be selected suitable for the area. Potential minimisation measures relate to site selection adjustment, set-up adjustment and shoreline protection measures. If the potential area has variation along the shoreline, the site with the deepest water must be selected. Furthermore, the set-up can be adjusted. The produced wave should dissipate before it reaches the shoreline. For instance, the run can be aligned towards or away from the shoreline depending on the required precaution. If the run is aligned towards the shoreline, lengthening of the spare area is recommended. According to this study the length of the spare area could not be identified, but it should not be less than 30 m. Investigating the required length of the spare area is recommended. According to the velocity analysis, if water depth is more than 5 m it should not require any protection as the risk of erosion is minor. However, if the area has limitations and lengthening of the spare area or aligning the run away from the shoreline is not possible, shoreline protection measures are recommended. These measures can be soft engineering measures, such as leaving the original vegetation untouched, or hard engineering measures, such as breakwaters or other structures. In the semi-permanent set-ups hard engineering measures might come into question, but especially in event set-ups soft engineering measures are recommended. Closer investigation of the soft engineering measures is recommended.

Due to the innovative character of the artificial wave production method and complexity of the hydro-environments, potential effects are not completely predictable. Erosion causes many of the detrimental effects and therefore minimising the erosion is in great significance. The risk of erosion is possible to define, whereas other hydro-environmental effects are much more complex to assess. However, indirect effect such as water quality changes and biota response can be traced trough environmental indicators. Hence, use of environmental indicators is recommended. The environmental indicators help to evaluate the occurred hydro-environmental effects and whether additional minimisation measures are required. If changes in water quality are indicated, the minimisation measures must be re-evaluated.

The artificial wave production causes potential hydro-environmenta effects but potential measures to minimise the effects were identified. As the proposed minimisation measures are conducted, hydro-environmental effects are ought to decrease. In fact, circulation of water might have positive effect on water quality as oxygen and nutrients are put into movement.

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Appendix 1. The hydrofoil method

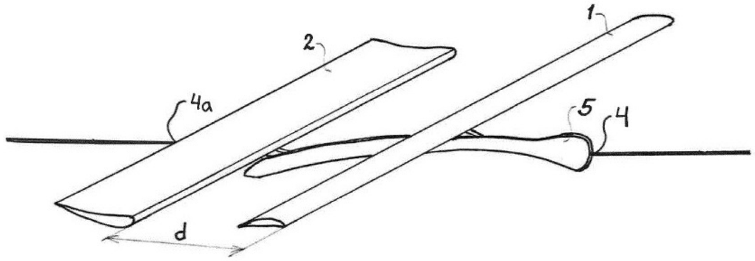


Figure 1: The hydrofoil system consist of two or more wings (1 and 2) attached to a trunk (5) drawn with a rope (4a and 4).

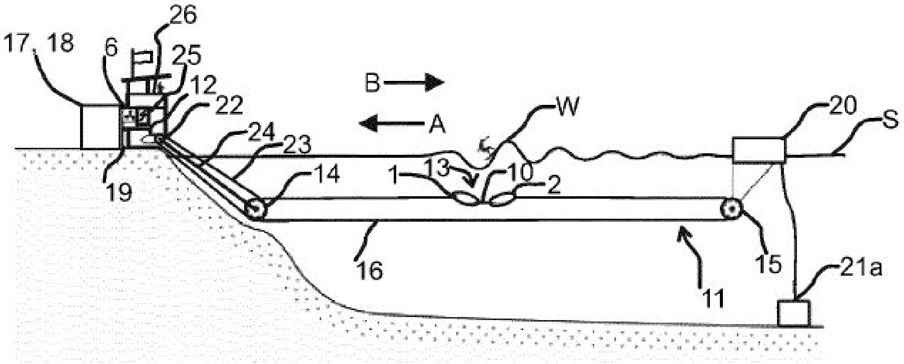


Figure 2: The surfable wave (W) is formed by two or more wings (1 and 2) propagating underneath the water surface (S).

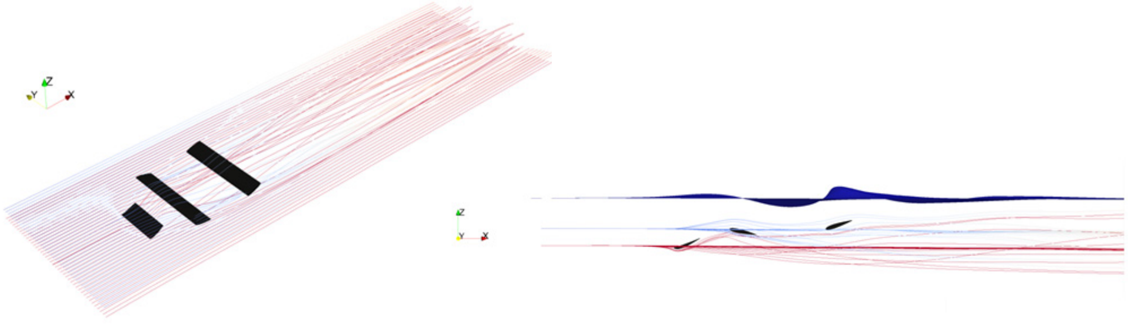


Figure 3: Wave formation principle and stream lines from the 3D-simulation visulalisation by ParaView (Tossavainen 2014a). Isometric view on the left and sideview on the right.

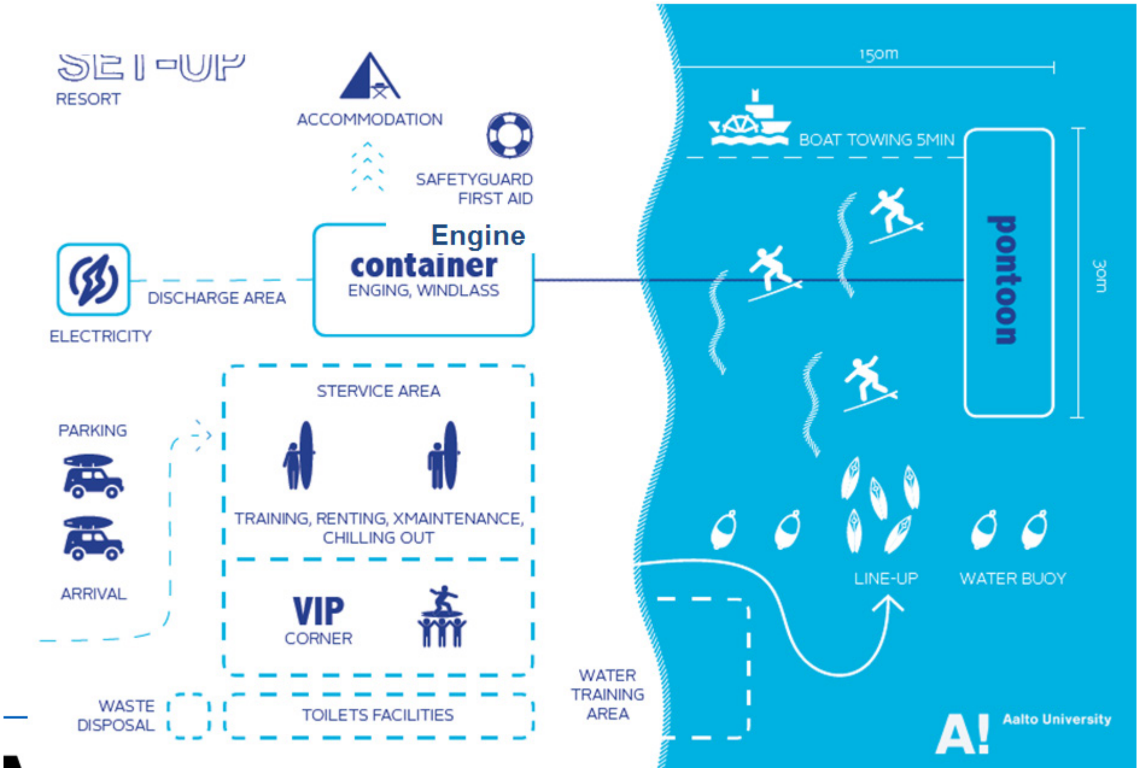


Figure 4: Planned set-up for the solution.

Appendix 1. (2/2)

Appendix 2. The hydrofoil method and the Artwave prototype in images

Figure 1: Prototype installation in Kalasatama, 2014. (Tossavainen 2014c, Sellgren 2014b)

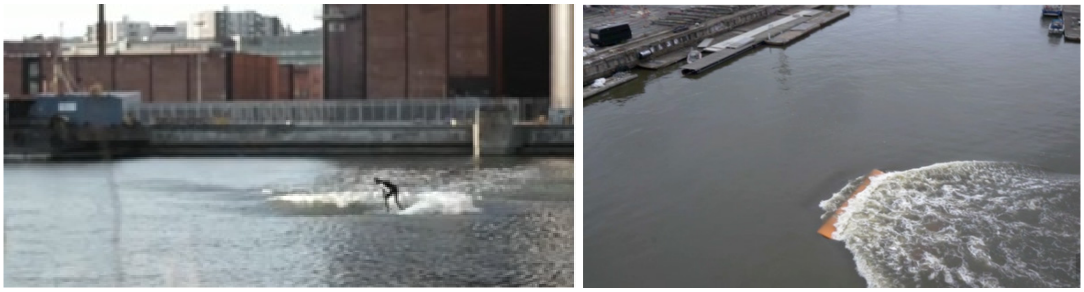
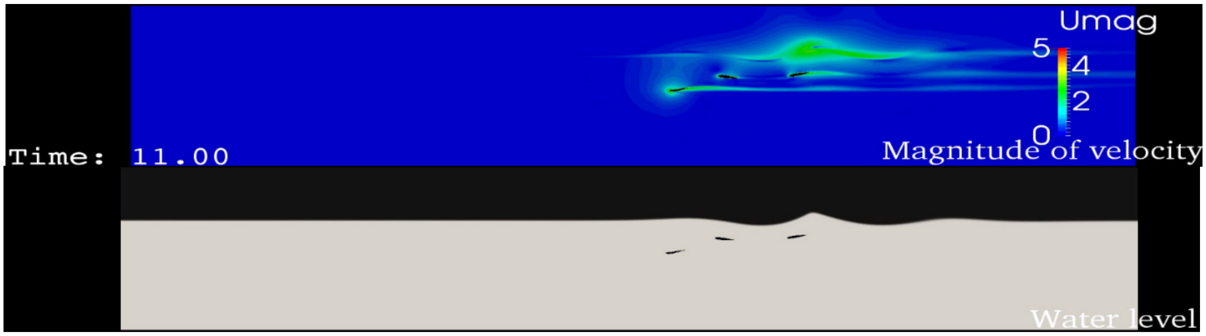


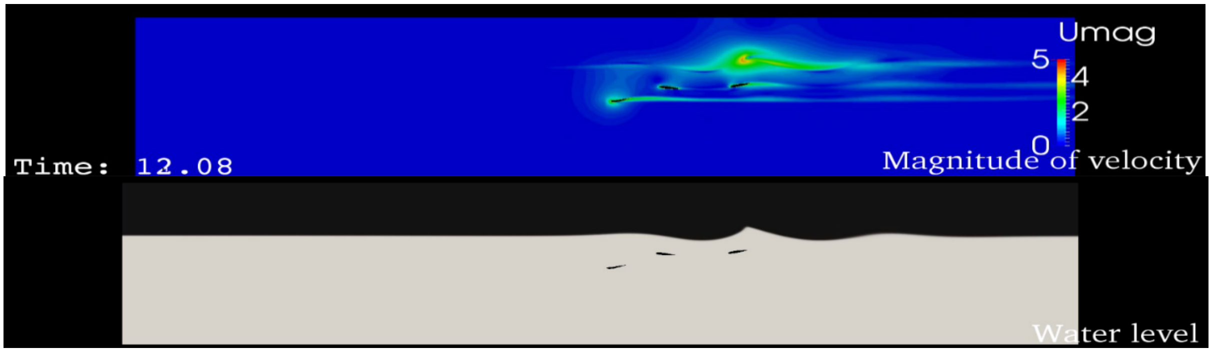
Figure 2: Image on the left shows the wave in the surfing phase (Artwave Surf 2014b) and image on the right shows the wave after the hydrofoil is stopped (Sellgren 2014b)

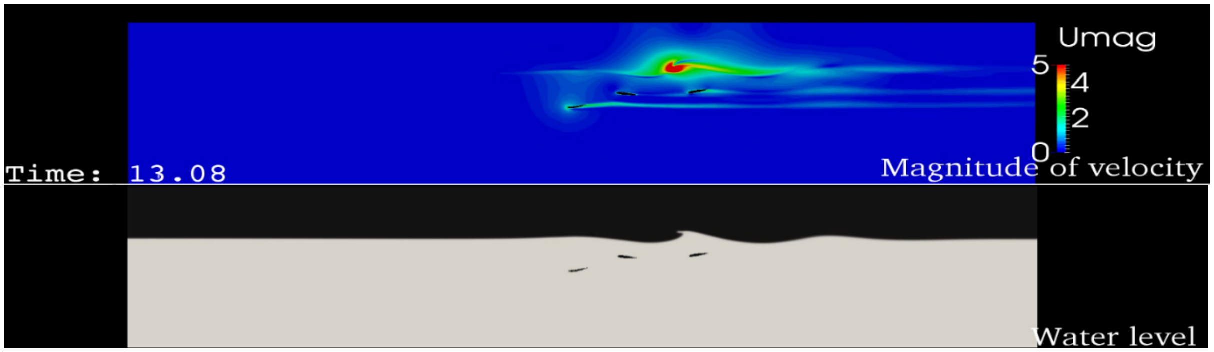
Appendix 3. Flow field and the shape of the wave from the simulation visualization by Tossavainen (2014a)

The constant speed phase (until $t = 12$ s):



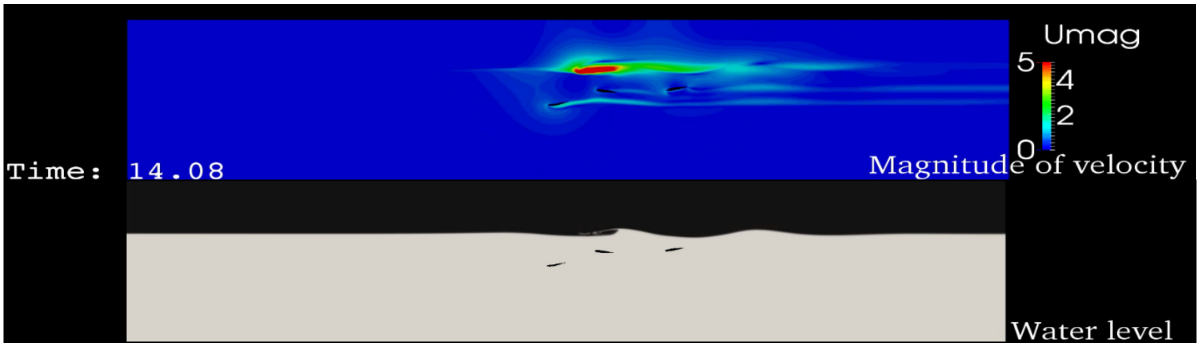
The decay phase ($t = 12.08 - 14.00$ s):

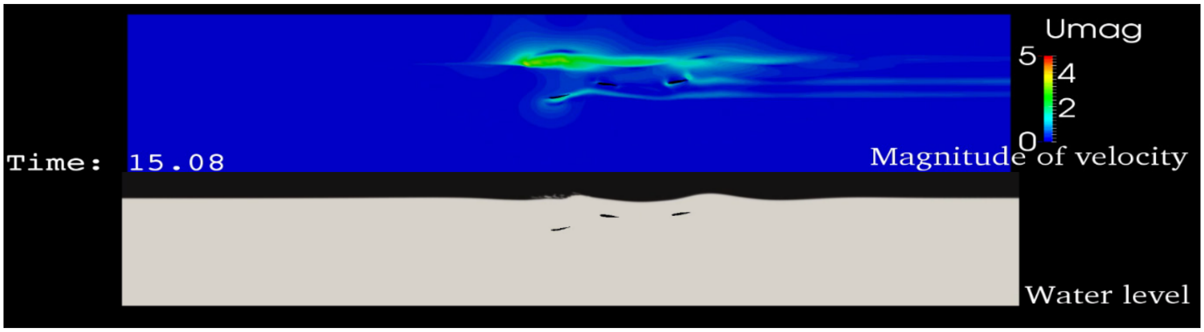


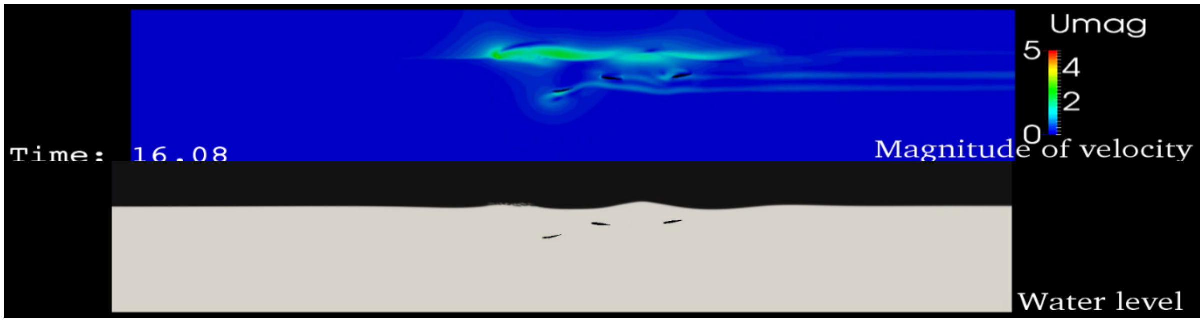


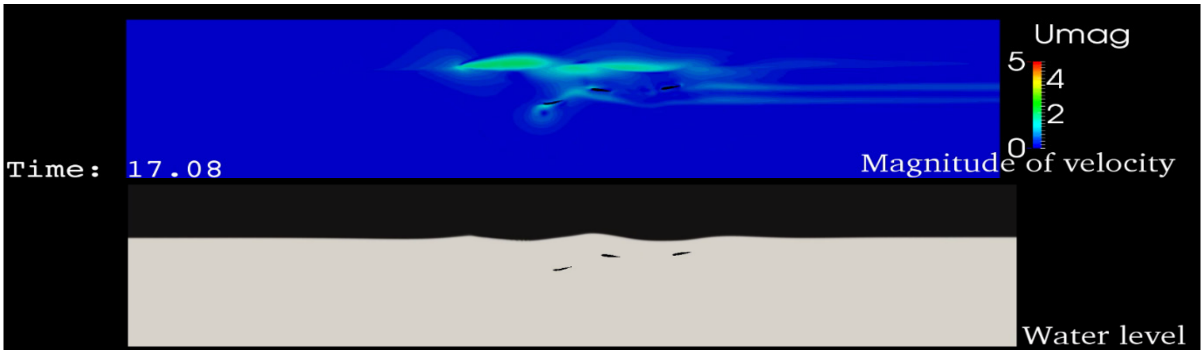
Appendix 3. (2/6)

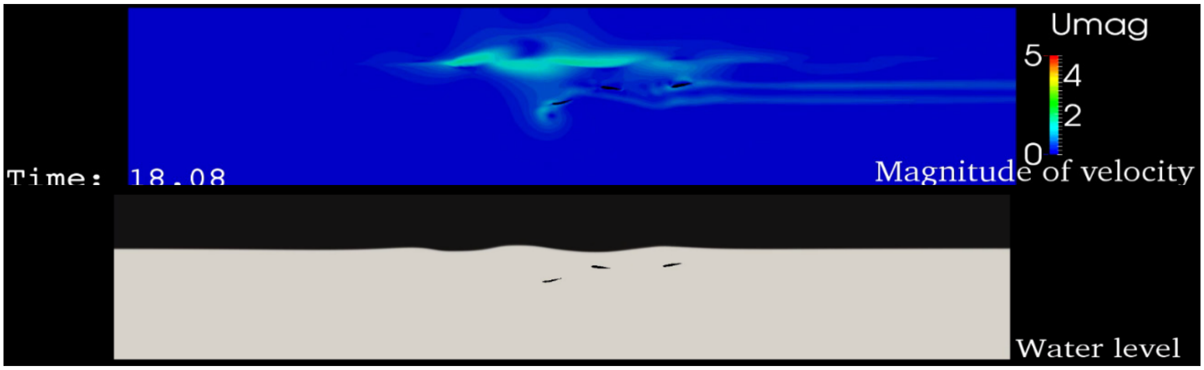
After the run (*t* = 14.08- s):

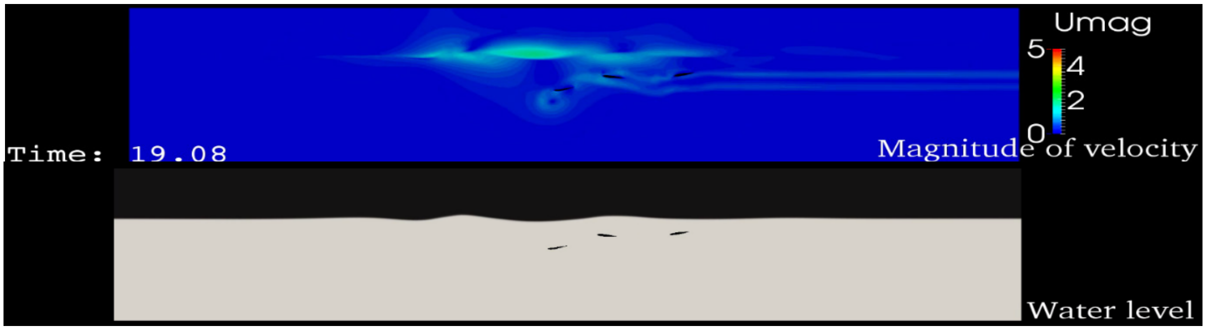


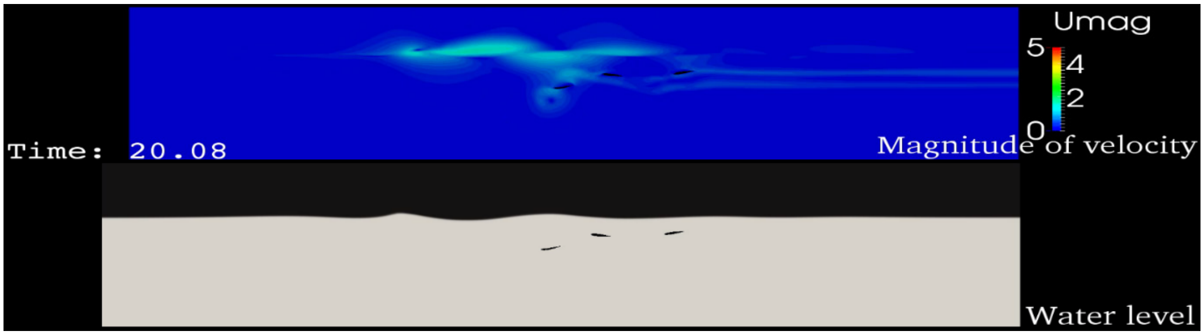


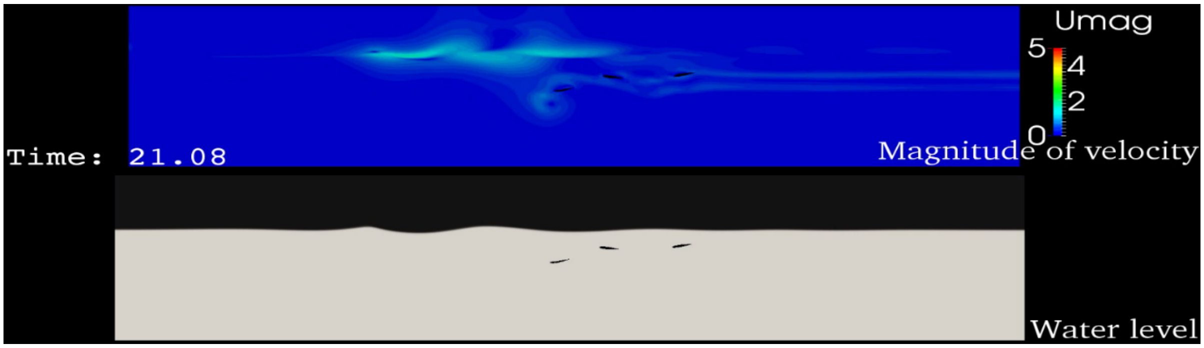




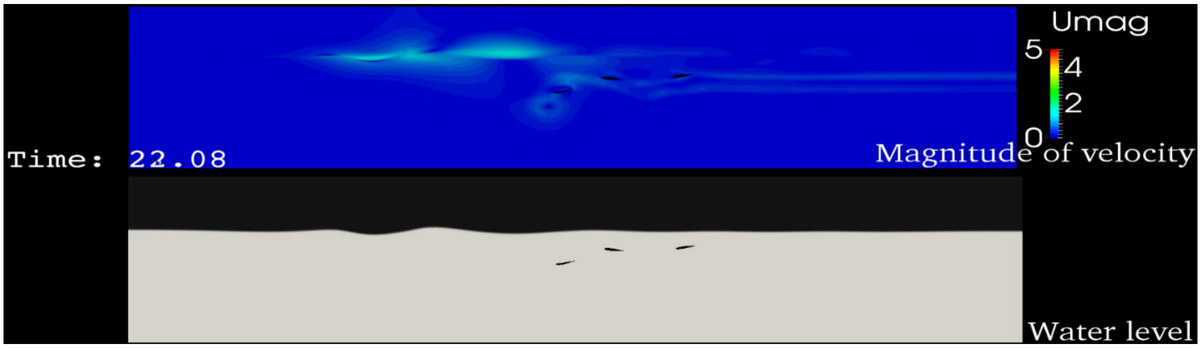

Umag
5
4
2
0
Magnitude of velocity
Time: 18.08
Water level

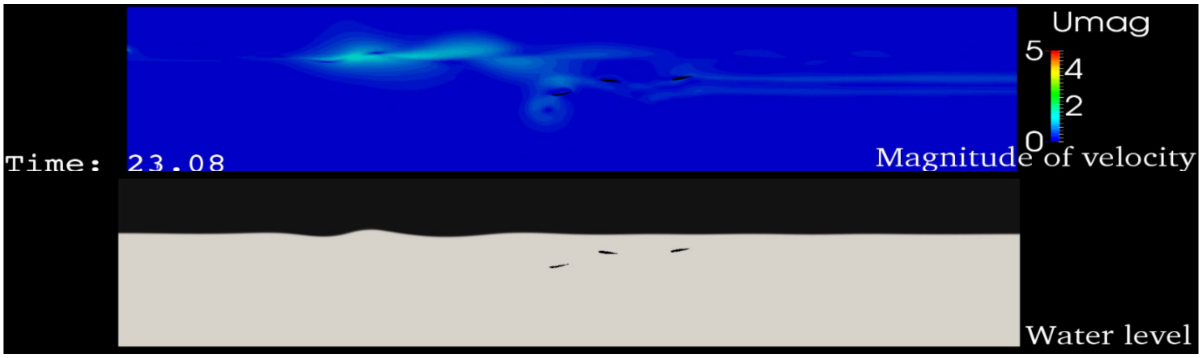

Umag
5
4
2
0
Magnitude of velocity
Time: 19.08
Water level

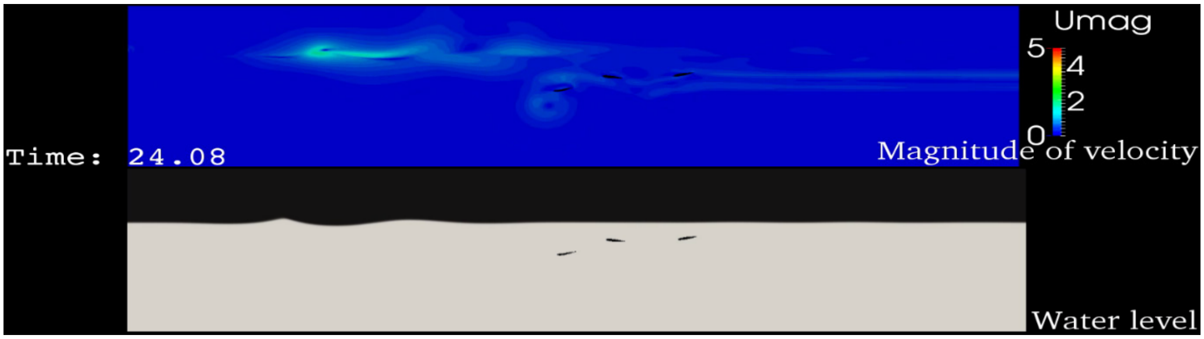

Umag
5
4
2
0
Magnitude of velocity
Time: 20.08
Water level

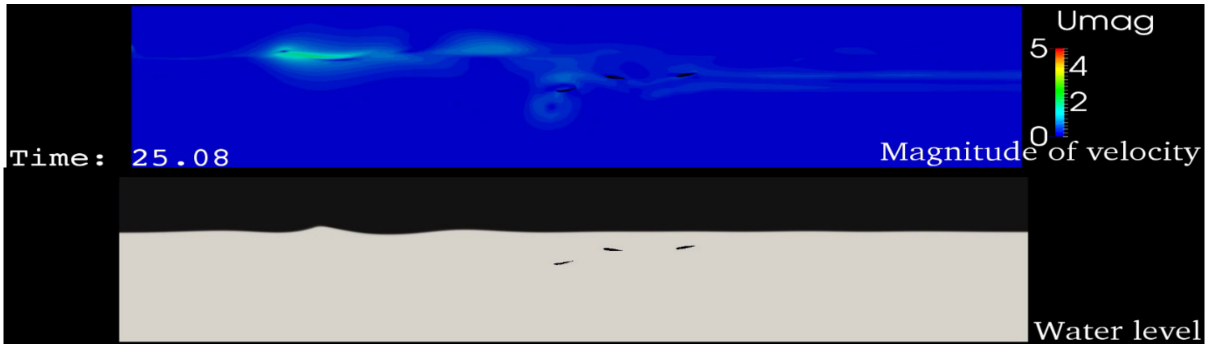

Umag
5
4
2
0
Magnitude of velocity
Time: 21.08
Water level

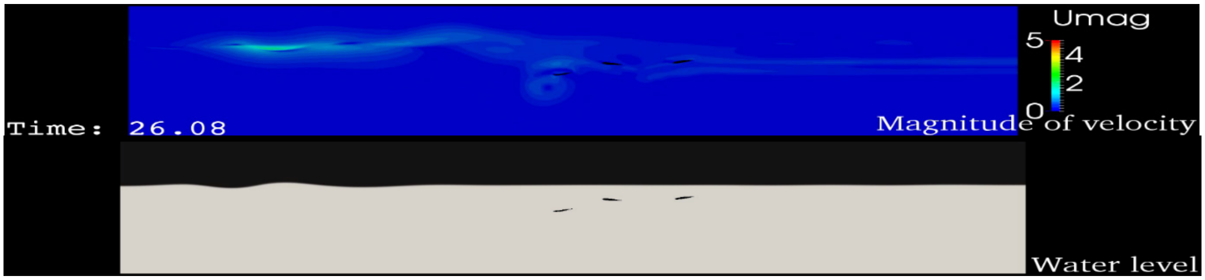
Appendix 3. (4/6)

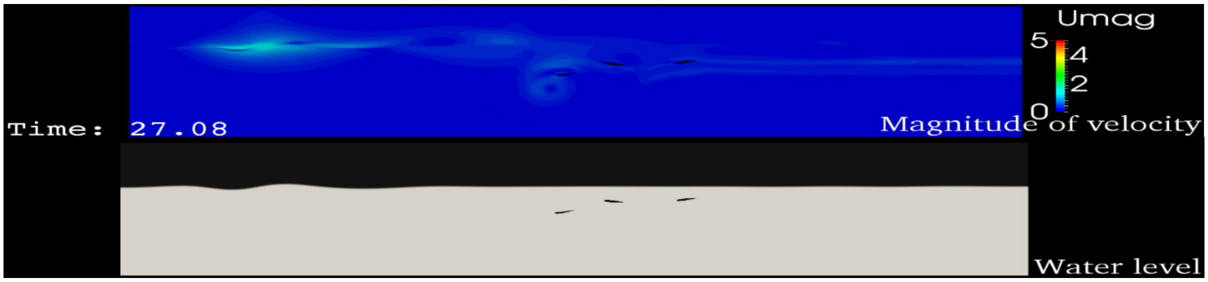


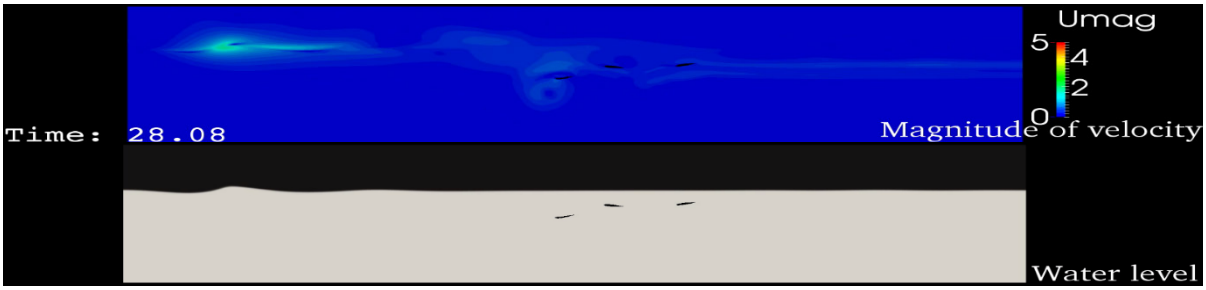


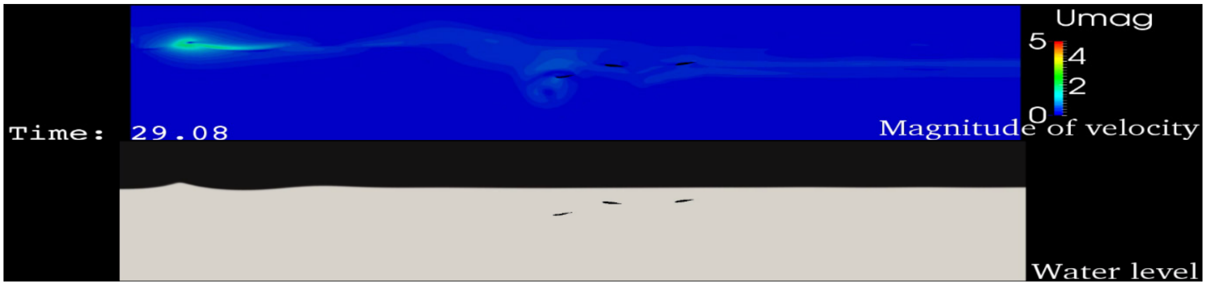


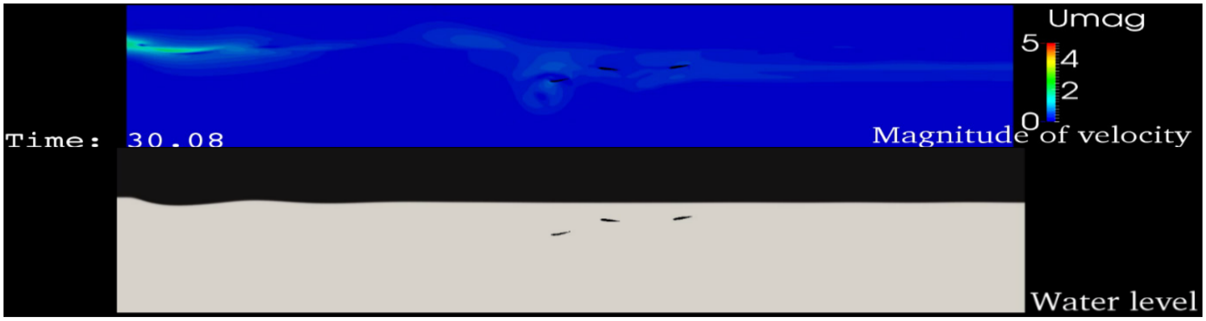



Time: 26.08
Umag
5
4
2
0
Magnitude of velocity
Water level

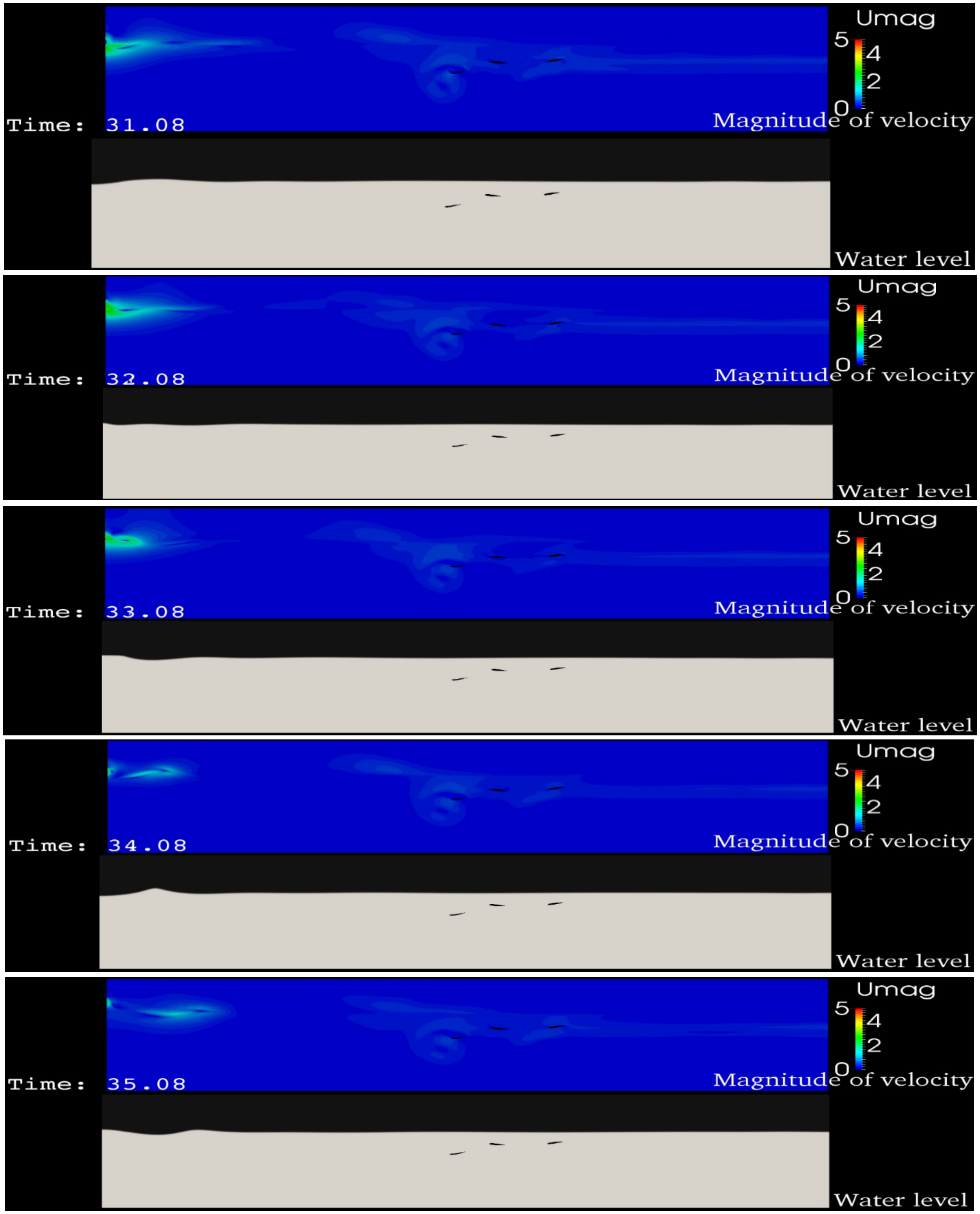

Time: 27.08
Umag
5
4
2
0
Magnitude of velocity
Water level


Time: 28.08
Umag
5
4
2
0
Magnitude of velocity
Water level


Time: 29.08
Umag
5
4
2
0
Magnitude of velocity
Water level


Time: 30.08
Umag
5
4
2
0
Magnitude of velocity
Water level

Appendix 3. (6/6)



Appendix 4a: Significant wave heights H_s, wave periods T_s and wave lengths with different fetch lengths and wind speeds

Values that correspond to Artwave induced H_{max} and H_{m0} are **bolded**.

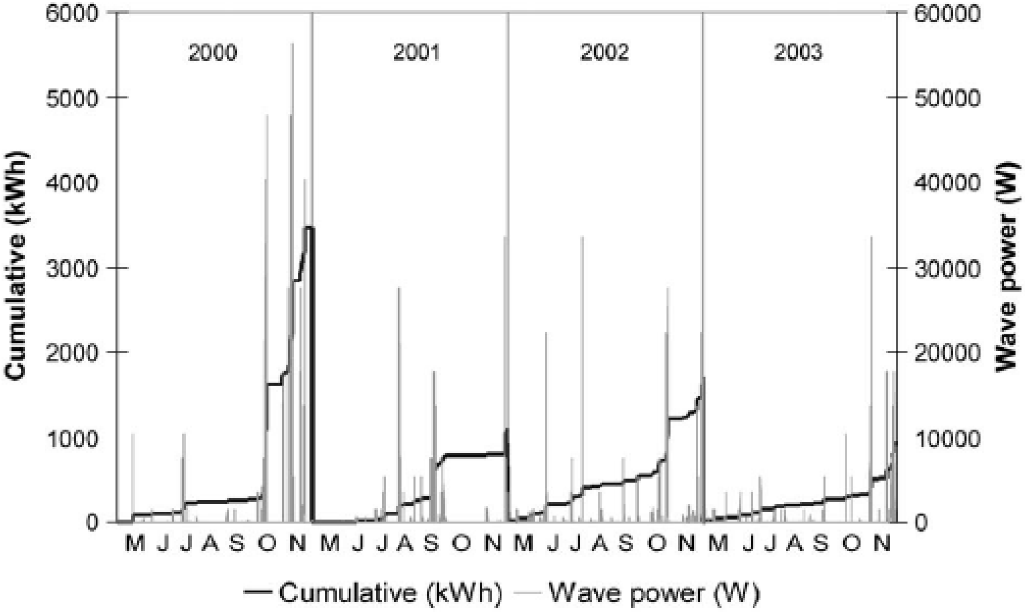
H_s [m]										
U_{10} [m/s]; F[km]	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
5	0.06	0.08	0.09	0.10	0.11	0.12	0.13	0.13	0.14	0.15
10	0.13	0.17	0.20	0.22	0.25	0.27	0.28	0.30	0.32	0.33
15	0.20	0.27	0.32	0.36	0.40	0.43	0.46	0.48	0.51	0.53
20	0.28	0.38	0.45	0.50	0.55	0.60	0.64	0.67	0.71	**0.74**
T_s [s]										
5	0.87	1.02	1.13	1.20	1.27	1.32	1.37	1.41	1.45	1.48
10	1.23	1.46	1.61	1.73	1.83	1.91	1.98	2.04	2.10	2.16
15	1.52	1.80	1.99	2.13	2.25	2.35	2.44	2.52	2.60	2.66
20	1.75	2.08	2.30	2.47	2.61	2.73	2.83	2.93	3.01	3.09
L [m]										
5	1.17	1.63	1.98	2.26	2.51	2.73	2.93	3.11	3.28	3.44
10	2.38	3.34	4.07	4.68	5.21	5.69	6.12	6.53	6.90	7.25
15	3.59	5.05	6.17	7.10	7.92	8.65	9.32	9.95	10.53	11.08
20	4.80	6.77	8.27	9.52	10.62	11.62	12.53	13.37	14.16	14.91

Appendix 4b: Significant wave heights H_m and wave periods T_m with different fetch lengths F and wind speeds calculated by using the Equation 6 by Vilmundardóttir et al. (2010).

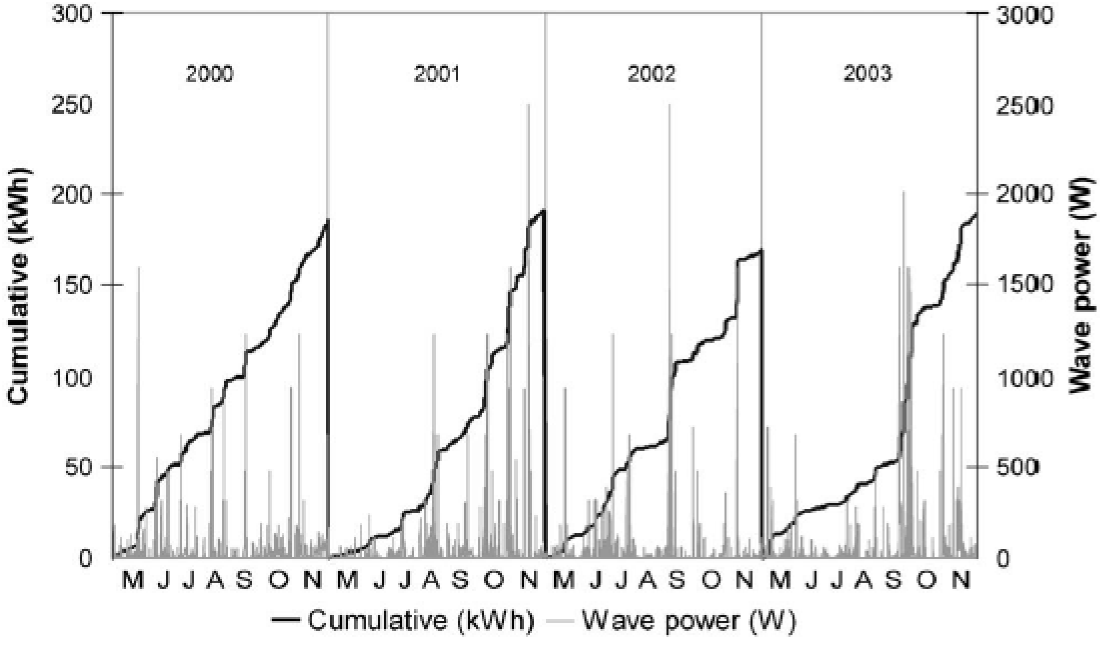
Values that correspond to Artwave induced H_{max} and H_{m0} are **bolded**.

H_m [m]										
U_{10} [m/s]; F[km]	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
5	0.05	0.07	0.09	0.10	0.11	0.12	0.13	0.13	0.14	0.15
10	0.11	0.15	0.18	0.21	0.23	0.25	0.27	0.29	0.30	0.32
15	0.18	0.24	0.29	0.33	0.36	0.39	0.42	0.45	0.47	0.49
20	0.24	0.33	0.39	0.45	0.50	0.54	0.58	0.61	0.65	**0.68**
T_m [s]										
U_{10} [m/s]; F[km]	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
5	0.76	0.92	1.02	1.10	1.17	1.23	1.28	1.33	1.37	1.41
10	1.04	1.26	1.40	1.52	1.61	1.69	1.77	1.83	1.89	1.94
15	1.26	1.52	1.69	1.83	1.94	2.04	2.13	2.21	2.28	2.34
20	1.44	1.73	1.93	2.09	2.22	2.33	2.43	2.52	2.60	2.67

Appendix 5a: Average wave power *P* [W] and cumulative wave power P_c [kWh] in the study by Tolvanen and Suominen (2005)

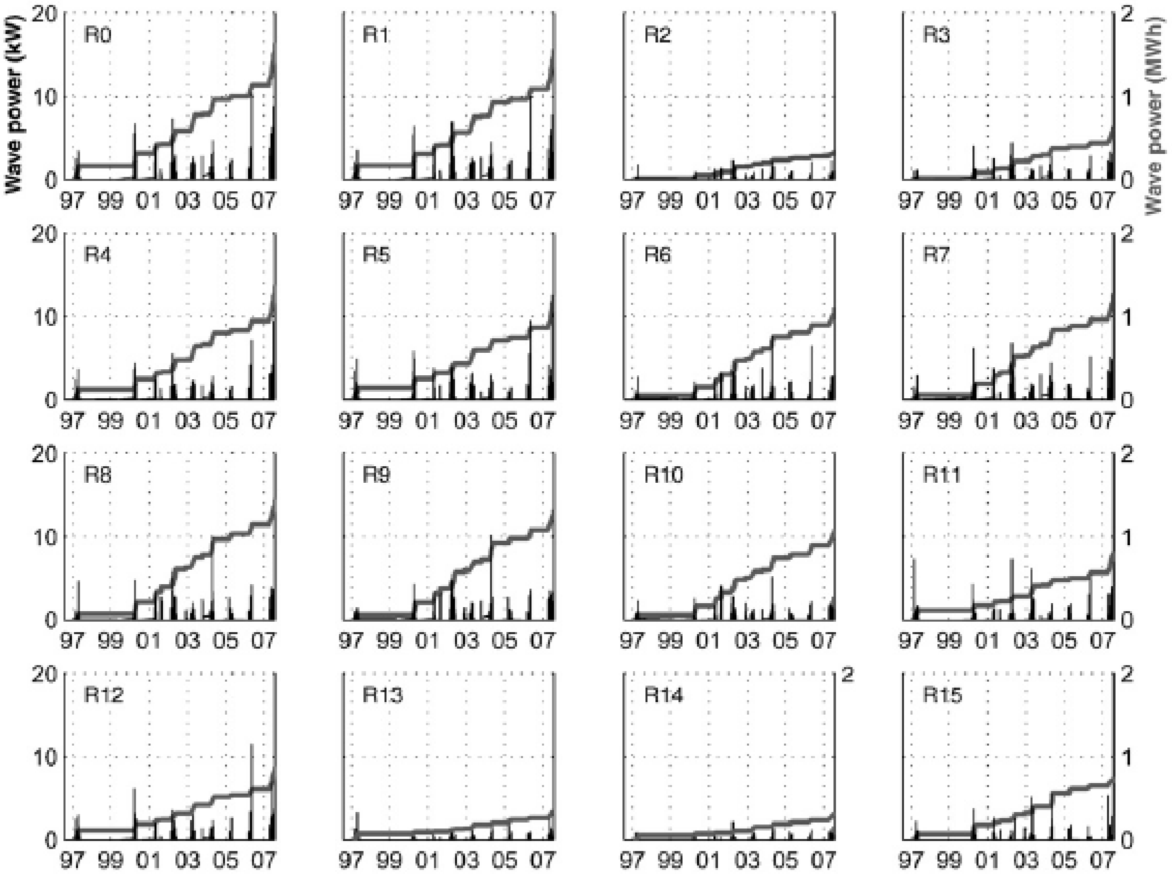


Average wave power *P* [W] and cumulative wave power P_c [kWh] in area 1.



Average wave power *P* [W] and cumulative wave power P_c [kWh] in area 2.

Appendix 5b: Wave power events and cumulative wave power in the study by Vilmundardóttir et al. (2010)



Wave power events [kW] (left axis) and cumulative wave power [MWh] (right axis) in each location. Average fetch lengths were following: R0 2.7 km, R1 2.8 km, R2 1.1 km, R3 0.6 km, R4 2.3 km, R5 2.2 km, R6 2.6 km, R7 2.6 km, R8 2.8 km, R9 2.8 km, R10 2.6 km, R11 2.3 km, R12 1.9 km, R13 1.9 km, R14 1.5 km and R15 2.6 km.