Impact of High Speed of Vessels on Narrow and Shallow Waterways with Reference to the Adriatic Sea

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Utjecaj velikih brzina brodova na uske i plitke vodene putove s osvrtom na Jadransko more

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DOI 10.17818/NM/2022/2.2
UDK 629.5.02 : 551.466 (262.3)
Review / *Pregledni rad*
Paper received / *Rukopis primljen:* 13. 2. 2022.
Paper accepted / *Rukopis prihvaćen:* 4. 4. 2022.

Abstract

Sudden increase of demand of high speed craft, especially fast passenger-cargo ferries and catamarans in the last few decades, has made it necessary to respond in a timely manner to the set of negative impacts that such vessels cause with high speeds near coastal areas. All relevant literature was investigated in this paper, as well as the reports, scientific articles by different databases, and collected data was evaluated by analyzing the content and mitigation measures by specific categories in order to emphasise the importance of potential negative effects of wakes. In addition to the mechanism of wake generation and physical characteristics of waves generated by vessels in coastal areas, a critical overview of the investigated impacts is presented, which includes: impact on safety (lives, vessels, structures), and environmental impact (hydro-morphological impact, impact on flora, fauna and cultural heritage). Particular attention is paid to the analysis and review of applied methods of risk assessment and adoption of measures in various countries where such research has already been conducted to a certain extent, in order to compile a set of effective recommendations that can be applied to reduce negative impacts. Since the previous researches mostly cover some impacts individually, it is also pointed out, among other recommendations, the importance of conducting concrete comprehensive coordinated research on this topic with an emphasis on the Adriatic Sea area, which is unique in multiple locations in terms of safety and environmental aspect, as well as in terms of the aspect of preserving the cultural heritage.

KEY WORDS
Wake Impacts
High Speed Craft
Narrow Waterways
Environmental Risk
Wake Wash
Adriatic Sea

Sažetak

Nagli porast potražnje plovila velike brzine, posebno brzih trajekata za putnike i teret te katamarana u posljednja dva desetljeća učinio je potrebnim odgovoriti blagovremeno na zbir negativnih učinaka koje takvi brodovi uzrokuju u blizini obalnih prostora. Sva relevantna literatura ispitana je u ovome članku, kao i izvješća, znanstveni članci iz različitih baza podataka i prikupljeni podaci koji su se evaluirali analizirajući sadržaj i okolnosti na temelju specifičnih kategorija, da bi se naglasila važnost potencijalnih negativnih učinaka brazdanja. Uz mehanizme brazdanja i fizičke karakteristike valova generiranih brodovima u obalnim područjima, predstavlja se kritički pregled promatranih učinaka koji uključuje: utjecaj na sigurnost (živote, brodovi, strukture) i okoliš (hidro-morfološki utjecaj, utjecaj na floru, faunu i kulturno nasljeđe). Posebna pozornost pridaje se analizi i pregledu primijenjenih metoda procjene rizika i usvajanje mjera u različitim državama, gdje se takvo istraživanje provelo do određene mjere, da bi se sastavio zbir djelotvornih preporuka koje se mogu primijeniti kako bi se smanjili negativni učinci. Budući da su prethodna istraživanja većinom pokrivala neke individualne utjecaje, također je naglašena, među ostalima preporukama, važnost vođenja temeljite istrage o ovom pitanju, s naglaskom na prostor Jadranskoga mora koje je jedinstveno u višestrukim lokacijama glede sigurnosti i okolišnih aspekata, kao i očuvanja kulturnoga nasljeđa.

KLJUČNE RIJEČI
utjecaj brazdanja
plovilo velike brzine
uski plovni putovi
okolišni rizik
zapljuskivanje brazdanjem
Jadransko more

1. INTRODUCTION / *Uvod*

Vessels create waves that transfer their energy to other vessels and structures in the sea, creating a potentially large negative impact. Due to increased maritime traffic, especially in semi-enclosed and closed coastal areas, waves may be the factor most influencing coastal zone dynamics. The problem became more actual with the emergence of the first high-speed ferries and very fast craft (HSC, "High Speed Craft"), whose waves are significantly different from the waves of conventional craft in shallow areas. According to the International Code for High-Speed Craft, the International Maritime Organization defines a very fast craft as a vessel that meets the requirement to reach a

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speed greater than or equal to $3.7V^{0.1667}$ (m/s), where V (m^3) denotes the volume of displaced water on the structural waterline.

The first research on such waves was made in the 19th century by Sir William Thompson, better known as Lord Kelvin, after whom such a wave was named "Kelvin Wake". Building on Lord Kelvin's findings, the relationship between cruising speed and wave heights with respect to vessel design was presented by Franzius and Straub [1]. Detailed laboratory studies of the impact of the wavefront on the surrounding coast were made some twenty years later [2]. Negative impacts of wakes have been observed in various countries, such as Denmark [3], the USA [4], New Zealand [5], and in other countries that include impacts on rivers and lakes, or inland waterways.

The structure of this paper is divided in such a way that the initial part presents an overview of the characteristics of waves caused by vessels, and the impact of the coastal area on these characteristics. The analysis and existing models for predicting wave characteristics are presented in Chapter 3. In the main part of the paper (Chapter 4), all impacts that waves can have are analyzed, and they are grouped into two basic groups: safety impact and environmental impact. An overview of the problems in the Adriatic Sea is presented in Chapter 5, which describes the method of risk assessment for the purpose of adopting preventive measures. Conclusions and recommendations are made in Chapter 6 which also contains a proposal for further research.

2. CHARACTERISTICS OF WAKES CAUSED BY VESSELS / *Obilježja brazdi uzrokovanih brodovima*

A vessel moving through water creates divergent and transverse waves whose wave front ("wake") significantly affects the environment. Waves on waterways are most often caused by wind and the navigation of craft. Sheltered locations, such as canals, ports, lakes and rivers, are dominated by waves generated by craft. Such waves cause coastal erosion, damage coastal structures and moored ships, pose a danger to small vessels and human safety, adversely affect flora and fauna, and pose a danger through a number of other impacts.

The Kelvin wake is a characteristic wedge shape that delimits the created divergent and transverse waves of the vessel in navigation. Such a wedge shape is symmetrically bounded by "cusp" lines which, with regard to the vessel's route, close an angle of 19.5° on both sides of the route. The created divergent waves have a direction of movement from θ = 90° to 35°, and transverse θ = 35° to 0° with respect to the course line of the vessel. The speed of the transverse waves in this case under continuous conditions is the same as the speed of the vessel. The amplitude of the wave depends on the shape of the hull and the currently displaced water, but the main parameter describing the Kelvin wake is the ratio of the speed and length of the vessel on the current waterline represented by the dimensionless Froude length number:

$$Fn_L = \frac{V}{\sqrt{gL}} \tag{1}$$

where V (m/s) represents the speed of the vessel, g (m/s^2) the acceleration of gravity and L (m) the length of the ship on the waterline. The waves generated by the ship in motion are the resultant of the dominant systems of bow and stern waves. When the Froude number of length is between 0.4 and 0.6, for most 'conventional' craft when sailing in deep water, the excess pressure on the bow and stern increases, creating increasing resistance to the movement of the craft, i.e. already at 0.4 the length of transverse waves is equal to the length of the vessel on waterline, and at that time the vessel develops the so-called hull speed. The Froude length number is suitable for defining the speed at which vessel propulsion requirements and the amount of waves developed are maximized at a given speed. By further increasing the speed at one point the vessel is practically located between the crest and the troughs of the same wave, so only vessels of a certain design that have a high ratio of propulsion power to displacement can overcome such resistance. From an economic point of view, sailing at this speed is unacceptable, and also because of the negative impact of the creation of large waves. At low vessel speeds, the transverse waves have a shorter wavelength, and there are several crests parallel to the vessel.

The Kelvin wake is specific to deep water, where the distance from the bottom does not affect the speed of the waves created. Therefore, the Froude depth number Fn_h [7] was introduced,

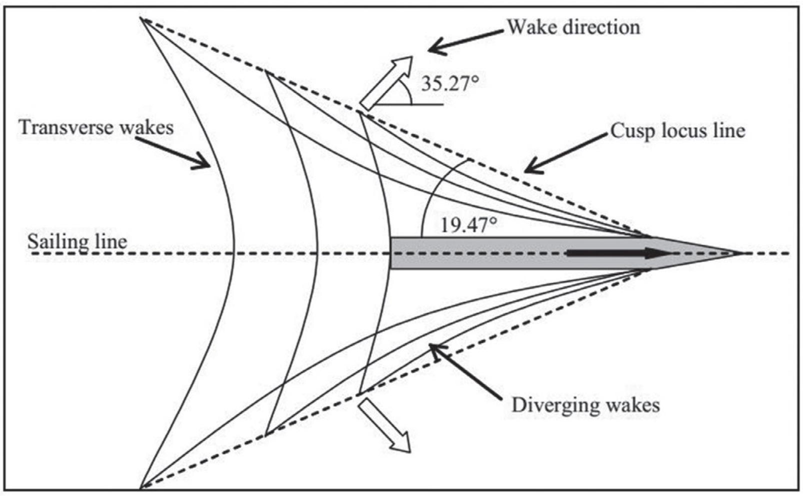

Figure 1 Kelvin wake
Slika 1. Kelvinova brazda

Source: [6]

which describes the wave pattern characteristic in shallow areas as a function of vessel speed and sea depth:

$$Fn_h = \frac{V}{\sqrt{gh}} \qquad (2)$$

where: V (m/s) represents the speed of the vessel, g (m/s^2) the acceleration of gravity, and h (m) the depth of the water. The Froude depth number has the greatest effect when the water depth is less than ¼ the length of the vessel on the waterline. The resulting waves generated by the vessel according to the speed it develops, i.e. depending on the Froude number of depth can be classified into 4 categories [8]:

- Subcritical ($Fn_h < 0.75$) – A Kelvin wake pattern in created,
- Transcritical ($0.75 < Fn_h < 1.0$) – By increasing the Froude number (due to increasing vessel speed or decreasing depth), the angle of propagation of divergent waves is also being increased, as well as the period of leading waves. Many larger vessels cannot develop a higher speed than subcritical (displacement), but smaller vessels that can achieve planing speed, operate at transcritical (transitional) speed for some time during acceleration and deceleration.
- Critical ($Fn_h = 1.0$) – By increasing the size of the Froude depth number to 1.0, the vessel speed becomes equal to the maximum value of the propagation speed of the wave. At this stage, the vessel moves away from the transverse waves behind the stern, and a significant portion of the propulsion force is concentrated to create a large leading wave perpendicular to the course line of the vessel.
- Supercritical ($Fn_h > 1.0$) – The transverse wave disappears because it merges with the divergent waves. At constant depth, the crest of the leading wave is flat, and its length depends on the time elapsed while sailing at a certain Froude number. The accompanying divergent waves have curved crests and troughs. As the vessel approaches Froude depth number 1.5, the planing has begun, and generated waves start to reduce its height, although they are still energetic. The propagation angle θ is determined by the equation $\cos\theta = 1 / Fn_h$.

The direction of propagation of the leading wave created by the craft sailing at supercritical speed is a function exclusively of the Froude depth number (Figure 2). The divergence between the leading and other waves also depends on the Froude number [10]. At a higher Froude number of supercritical velocities, the divergent waves are more parallel than at lower supercritical values of the Froude number. Divergence decreases with respect to the vertical distance from the craft. The divergence of waves created by supercritical velocities is also affected by the depth of the water. The change in the divergent wave pattern is smaller in deep water than in shallow water.

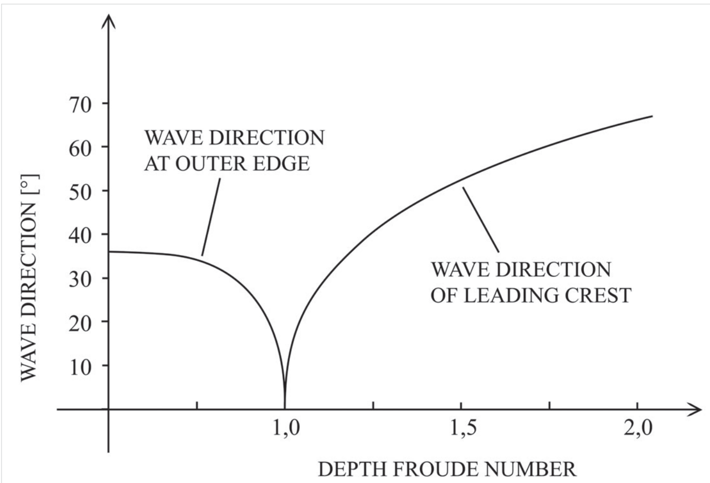

Figure 2 Relationship between the direction of wave motion and the Froude depth number
Slika 2. Odnos između smjera kretanja vala i Froude broja za dubinu

Source: [9]

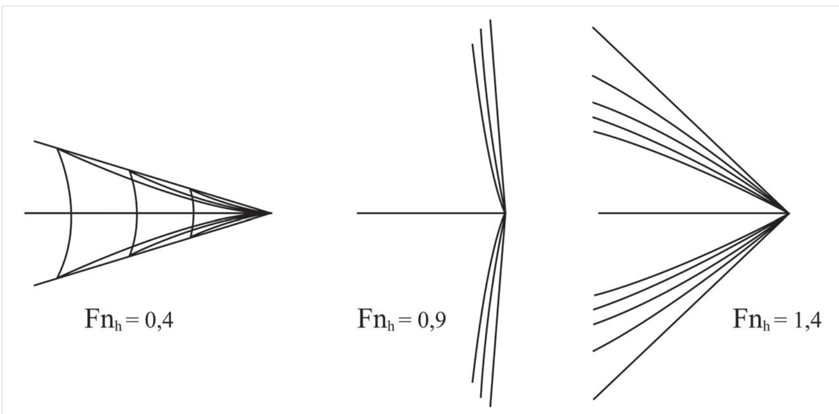

Figure 3 Sample of generated waves with respect to the Froude number
Slika 3. Uzorak generiranoga vala s obzirom na Froude broj

Source: [9]

The height of the created wake is a function of the hull design. It is generally true for vessels of different lengths and similar hull shapes, that a longer craft will create waves of greater height than a craft of shorter length. Furthermore, the period of the created waves is not a function of the hull design, but of the speed of the vessel, the depth and the distance that the created wave has traveled from the position of creation. From the moment of creation, the amplitude of the wave decays by moving away from the position of creation. The decay of transverse and divergent waves created by a vessel sailing at a subcritical speed is proportional to ω^n, where ω represents the distance from the craft, and *n* the constant value, which is n = -1/2 for waves inside the Kelvin wedge, and n = -1/3 for waves on the outside wedge [7]. Based on multiple extensive measurements of catamaran navigation parameters at supercritical speeds, the value n = - 0.55 was proposed. A value of n = -1/3 has also been proposed for waves at a distance of 3 vessel lengths to determine the decay rate of the generated wave [11].

2.1. Influence of the coastal area on wave characteristics / *Utjecaj obalnoga područja na karakteristike vala*

The propagation of waves generated by the vessel's navigation is defined primarily by the vessel's speed, i.e. it depends on the Froude number of depth, and on the transformation of the waves during the change in bathymetry due to the approach to the coastal area. Accurate prediction of wave transformation via irregular bathymetry is complex. The processes that have the greatest impact on the transformation and propagation of waves approaching the coastal area include [12]:

- Refraction – deflection of the wavefront and reduction of the wave height due to approaching a smaller depth,
- „Shoaling" effect – deformation of the wave due to the impact on the shoal, which changes its height,
- Diffraction – wave diffraction due to an obstacle (e.g. breakwater),
- Dissipation – loss of wave energy due to friction with the bottom or due to percolation through the porous material,
- Breaking – energy dissipation due to increasing steepness of waves, and occurs in the form of surging, spilling, collapsing, and plunging,
- Wave/sea current interaction – influence on the change of wave height and speed due to sea currents
- Reflection – change in wave height and direction due to complete or incomplete reflection from an obstacle

As the vessel approaches areas with less depth, a vessel that maintains a constant speed at all times may, in order to reduce the depth, switch to navigation mode in which a pattern of waves characteristic of critical speed begins to develop, resulting in a higher energy wave. Sudden and larger course changes at higher speeds further increase the energy of the side waves on the turning side. In general, acceleration and deceleration are critical operations for very fast craft. When starting, the vessel must accelerate from subcritical to supercritical speed, and at some point sail at critical speed. The same applies to deceleration from supercritical to subcritical speed, where the cruising speed at critical speed should be reduced to a minimum. An interesting feature of the coastal area involves the navigation of larger vessels moving through a narrow navigable area at a subcritical speed, such as canals or narrow passages, and creating a large Bernoulli wave on the bow. Conventional craft and very fast craft when sailing in such areas close to the critical speed can create a solitary wave that can have a higher speed than the vessel itself. Waves of this type have a very large period and can move at a distance of several lengths in front of the craft.

3. ANALYSIS AND MODELS FOR PREDICTING WAKE CHARACTERISTICS / *Analiza i modeli predviđanja karakteristika brazde*

In order to predict the impact of the created waves of a certain vessel on a certain route, it is necessary to have a model that predicts the characteristics of the wave field near the vessel, as well as transformation and propagation at a greater distance where the wave approaches the shore. There is no hybrid model that predicts all the characteristics of the wave field, so only some methods will be mentioned in this chapter. According to Maritime Navigation Comission's guidelines [9] there are certain models that offer significant wave characteristics prediction, which, among others, include: CFD (Computational Fluid Mechanics), DHI (Danish Hydraulic Institute model), LSV (Lagrangian Super-Critical Vessel model) and SGH (Ship Generated Hydrodynamics model).

CFD (Computational Fluid Mechanics) – encompasses various models of computational fluid mechanics that focus on waves moving away from a ship. Models give good predictions of wave size if the hull shape is precisely determined, but is limited to constant conditions, vessel speed, and constant depth.

DHI model (Danish Hydraulic Institute) – The Danish Institute is proposing its modified MIKE21 NSW (Nearshore Spectral Wave) software package for practical large-scale wave modeling. The limitation of the model is expressed in the fact that the model does not reproduce the dispersion, due to which the created waves actually lose in height by moving away from the vessel. Also, the model simulates the occurrence of waves with constant conditions of the direction of movement of the vessel, so it is not suitable for vessels that change course more often.

LSV model (Lagrangian Super-Critical Vessel) – is a kinematic-dynamic model that uses Lagrange formulations to simulate waves, thus achieving: creation and prediction of waves created by subcritical and supercritical velocities of vessels; the possibility of variable course sizes and vessel speeds; predicting wave transformation characteristics (wave refraction due to sea current or depth, wave refraction and dispersion); efficiency for larger areas.

SGH model (Ship Generated Hydrodynamics) – This model makes it possible to determine wave characteristics and reliably predict sea currents caused by craft, but its use is limited to large displacement craft sailing at subcritical speeds.

Havelock's theory [7] makes it possible to determine relatively accurate estimates of the wave propagation angle, wavelength, wave period, and propagation velocity of the leading wave, but not the wave height. Precisely due to the height of the waves, the speed of vessels is limited in sensitive areas, which seeks to reduce their negative impact. Balanin and Bykov [13] derived an equation to estimate the wave height on the canal shore. Later, different models were developed to predict the height of the waves at certain distances from vessels sailing at different speeds [14]. Extensive research on the impact of waves caused by high-speed craft was conducted in Denmark [3], on the basis of which new criteria were adopted which were later implemented in local legislation. In their paper, the authors also proposed mathematical relationships between vessel speed, wave period, and maximum wave height. The data on the basis of which the authors of the research draw conclusions are based on the results of experiments in test pools for models, computer simulations and measurements in nature. Measurements in nature provide specific data for a specific area and type of vessel. In doing so, it is desirable that the vessel moves at a constant speed, over a constant depth and contour of the bottom, in places without external influences of wind, sea current and waves from other sources. Measurements are made in several attempts, provided that navigation in the opposite direction can also be measured, assuming that the vessel is symmetrical. Measurements should be started long enough before the vessel approaches due to possible waves in front of the bow passing before the vessel. The measurement continues as the vessel recedes until there are no more significant waves in a given period. Measurements in nature often last for days due to differences in tides, i.e. water levels. In general, to assess the risk of generated waves, it is convenient to use data on the highest measured wave heights in relation to their maximum values of wave periods, and data on the distribution of wave heights and periods throughout the observed area. The most common instruments for measuring the characteristics of ship waves are ondograph, measuring platform, accelerometer, acoustic doppler, laser, current meter, stereo photogrammetry, RADAR, LIDAR, etc.

4. CONSEQUENCES OF THE IMPACT OF WAKES / *Posljedice utjecaja brazdi*

In general, waves generated by vessels have a negative impact on safety and the environment. The impacts listed here are based on reported accidents and reports. All impacts are not necessarily the result of exclusively very fast craft, but can also be caused by other types of craft.

4.1. Impact of waves on safety / *Utjecaj valova na sigurnost*

The possibility that the wave front has a negative impact on safety is directly related to the physical characteristics of a particular waterway and the associated shore, as well as the characteristics of the waves themselves. Also the magnitude of the negative impact depends on what kind of created wave interacts with the specific current activity of people on waterways and the coast.

Impact on human safety – In general, the safety of people on other vessels, and on the craft itself that creates the waves (due to sudden turning and/or stopping), as well as swimmers and people close to the shore affected by transverse waves of the vessel that move at almost critical speed, and the first group of long-period waves caused by vessels at supercritical speeds. Depending on the shape of the coast and the seabed, sudden waves that break are a great potential danger, which is especially dangerous for swimmers and people in smaller vessels, especially during the summer months, when large waves are unexpected due to favorable weather conditions.

Impact on vessel safety and structures – The impact of waves on other vessels depends on the characteristics of those vessels, and the behavior of vessels on waves also depends on the skills of the person operating the other vessel. Waves generated by a vessel that has a slightly lower speed than the critical one are a great danger for smaller vessels that may suddenly load large amounts of water and/or capsize due to steep waves that are about to break. The impact on large cargo ships is caused by long-period waves that cause a larger vessel to yaw, so due to the instability of the course there is an increased risk of running aground or causing collisions when sailing in narrow areas. In the shallow area orbital motion of water particles are more elliptical than circular, which causes horizontal movement of certain sizes of vessels more often in horizontal than in the vertical direction. Also, due to the small depth below the keel, in larger ships there is a greater possibility of damage due to rolling caused by the wakes of another ship. The impact on moored ships (to a fixed structure or other vessels) can be dangerous, and is most commonly caused by transverse waves generated by ships sailing at transitional speeds and long-period waves caused by supercritical speeds. Due to the caused translational-rotational movements of moored ships, there is a risk of damage to vessels, docks, moorings, breaking of mooring ropes, stranding, and indirectly environmental pollution during loading/unloading operations of cargo or fuel, and damage to the hull. The negative impact on the structures is manifested in the potential possibility of weakening the foundation and construction of the structure. The impact on an individual floating structure depends on its characteristics, while a particularly dangerous situation presents a potential floating structure that gets too much free movement due to the influence of waves.

4.2. Environmental impact / *Utjecaj na okoliš*

Waves generated by vessels act physically on the environment at the same time as waves caused by winds, so it is difficult to prove a direct correlation between the specific cause and effect of the waves' impact on the environment. Among the current impacts of waves on the environment are: hydro-morphological impact, impact on flora and fauna, and impact on cultural heritage.

Hydro-morphological impact - Shores with softer sediments that are naturally sheltered are generally exposed to greater wave effects than rocky shores. Sensitivity is higher in shores where certain human activities have already been performed (buildings, excavations), which is why less wave energy is needed, which will affect the shore, depending on the composition and particle size of the material. The consequences of waves caused by vessels are coastal erosion, and the mobilization and deposition of sediments. Short steep waves often apply material to the beach, while long-period waves can disrupt sediments that are further away from the shore. Depending on the angle of propagation to the shore, waves can cause transverse or longitudinal deposits of sand and other materials. A more accurate assessment of the hydro-morphological impact must be carried out by observation over a longer period, in order to determine the individual contribution of the waves generated by the vessels.

Impact on flora and fauna – Sediment mobilization also affects changes in biological communities affected by hydrodynamic wave forces. If there are no external influences, the habitats can survive in the long term in natural balance. As traffic increases, impacts are greater especially in shallower areas where vessels can cause direct damage to the ecosystem with propellers. Sedentary and mobile organisms can be displaced or stranded, plant species can suffer damage due to higher energy of incoming waves, which also increases water turbidity due to fine sediment that is slowly deposited, and also reduces the amount of light reaching the habitat. Breaking waves and long-period waves often flood coastal bird habitats, reducing the likelihood of winter survival. The negative impact on ichthyofauna can also be direct, but also indirect, through the impact on vegetation, which disrupts the food chain. One of the indirect impacts on flora and fauna is unnatural noise caused by high-speed vessels.

Impact on cultural heritage – Due to the significant energy of the waves, and erosion and sediment transfer, there is a possibility of negative consequences for sites that represent cultural heritage, historical monuments, underwater archaeological sites, and historic buildings on the shores. The impact of wakes has been identified as a threatening factor of coastal cultural heritage, and only a small percentage of research work deals with this area.

5. PREVENTION OF NEGATIVE CONSEQUENCES WITH REFERENCE TO THE ADRIATIC SEA / *Sprečavanje negativnih posljedica s osvrtom na Jadransko more*

The Adriatic Sea is a predominantly closed sea with an indented Dalmatian type of coast that includes many islands. Due to its traffic-geographical position and the fact that the Adriatic is an attractive tourist location, due to the growing number of vessels there is a danger of increasing the negative impact. Research in this direction mainly includes the hydro-morphological impact of wakes and wind waves, and there are no consolidated and coordinated studies that include all aspects of the negative impacts of wakes. In the early 1990s, UNESCO launched an extensive study to assess the impact of wakes on buildings on the interior of the canal in Venice, which later created the Moto Ondoso Index, which describes the level of canal load on wakes. Recent research includes estimates of the impact of maritime traffic in the navigation lanes of the Venetian Lagoon using the AIS system, identifying that the biggest hydrodynamic factor is the Bernoulli wave depression, which is up to 2.45 m at certain canal margins [15]. Given the fact that in 2016 alone, more than 3,000 passages of commercial ships were recorded in this area, the negative impact of ship waves is not negligible.

The area of the Adriatic Sea on the territory of the Republic of Croatia contains most of the islands, cliffs, canals, shoals, beaches, and as such may be subject to the negative effects of wakes. Meteorological and oceanographic conditions in the navigable area of the Croatian part of the Adriatic Sea do not significantly affect the navigation of larger craft, but the safety of navigation of yachts, boats and smaller craft can be endangered, especially during the winter months. The most frequent surface waves caused by meteorological conditions are caused by the bora and the sirocco in winter, and the mistral in summer. Steep storm waves are especially dangerous for smaller craft on the Adriatic. Due to its orientation, the largest wind waves on the Adriatic Sea are caused by the sirocco, and can reach a height of more than 10 m [16]. Waterways are generally categorized into two parts, namely waterways for the traffic of merchant ships, and for the traffic of other ships, boats, yachts, or recreational craft.

According to the data of the Central Bureau of Statistics of the Republic of Croatia, it is evident that the Croatian part of the Adriatic Sea is the destination of a large number of vessels. Namely, the number of vessels in transit in nautical tourism ports in 2019 amounted to 204858, which is an increase in the number of vessels by 5.5% compared to 2018 [17] . Total number of motor yachts in 2020 reached 49092 (permanent and in transit) [18]. A total of 672 cruises of foreign passenger ships were realized by 72 cruise ships in 2019 (January to October) with more than 1 million transported passengers, while in 2020 during the same period, only 10 foreign cruisers entered the Croatian part of the Adriatic Sea and realized 26 cruises due to the world pandemic crisis [19]. Shipping company "Jadrolinija" owned by the Republic of Croatia, which performs permanent and a small number of seasonal lines, held a total of 61085 trips in 2019 with a fleet of 51 vessels, which, among others, include high-speed lines[20].

The biological diversity of the ichthyofauna of the Adriatic Sea includes about 450 fish species, including 6 endemic fish species [21], and it has been confirmed that a total of 123 fish species are endangered in the Adriatic Sea [22]. In addition to other endangered species, the Adriatic is inhabited by 3 species of protected turtles and 4 species of mammals that are constantly present, while some protected species appear periodically, such as the Mediterranean seal and some species of whales. 2597 species of algae have been recorded in the Adriatic Sea, of which 152 are endemic [23].

The coastal states of the Adriatic Sea have a large number of underwater archaeological sites dating from all historical periods, as well as a large number of historic coastal buildings that represent cultural monuments. The Venetian lagoon, as the largest in the Mediterranean, has hundreds of underwater archeological sites in its area. About 400 underwater archeological sites have been recorded in the Croatian part of the Adriatic Sea, and about a hundred of them have been entered in the Register of Cultural Heritage of the Republic of Croatia.

The general management of decreasing measures will depend on the design of the vessel, as well as the method of management and the location of the vessel. The design of the vessel enables the achievement of certain sailing speeds, on which the characteristics of the created waves will depend. Since it is difficult to subsequently change the shape of the ship during exploitation, in order to take measures to reduce the negative impact, during the design, as well as when buying a used ship, the purpose of the ship for certain geographical locations should be taken into account. At the location itself, it is possible to change or set the route of the vessel in such a way that navigation causes the least negative consequences. The Maritime Navigation Commission [9] proposes a procedure for assessing the negative impacts of wakes. The procedure begins with the characterization of the route into individual segments, where each segment corresponds to a specific craft speed based on the Freud depth number. Already this first step can indicate the potential impact of waves along the segment and identify locations where changes in the route can eliminate or reduce the negative impact. After route characterization, potential impacts along segments are defined. In order to do this, it is necessary to have expert knowledge of the waterway from various already mentioned aspects of negative impacts, which is achieved by agreeing the expert opinions of experts from different fields based on the conducted research of waterway locations. It is necessary to determine what the characteristics of the generated waves must be (height/energy, period/ length, direction) that will cause a certain negative impact in order to adopt the most precise measures that will reduce such impacts.

Table 1 Categories of probability and consequence
Tablica 1. Kategorije vjerojatnosti i posljedice

Probability		
Score (L_S)	Description	Example
5	Very likely	Every passage
4	Likely	Most passages
3	Quite possible	High tide during passage
2	Possible	During storms
1	Unlikely	Only during unusual and unpredictable circumstances
Consequence		
Score (C_S)	Description	Example
5	Very high	Unacceptable impact, causes serious injury or death, unsafe navigation for smaller vessels
4	High	
3	Moderate	Noticeable impact, people may be injured, moored vessels and environment may be damaged
2	Slight	
1	Minimal	No visible impact

Source: [6]

The calculated value of the I_N index is added to the identified potential individual impacts, thus creating a list of priority impacts:

$$I_N = \frac{L_S \times C_S}{CF_S} \tag{3}$$

where L_S is the probability score, C_S is the consequence score obtained according to Table 1, and CF_S is the value of the causal factor which may have a value of 1, 2 and 3, depending on whether the generated ship wave is the primary, secondary or tertiary cause of the potential negative impact. The value of CF_S often depends on the subjectivity of the estimator, which is why it is important to have knowledge and understanding of the physical differences between the effects of wakes and those waves created by natural processes.

Table 2 The value of I_N and the corresponding recommended actions
Tablica 2 Vrijednost I_N i pripadajućih preporučenih aktivnosti

Index value (I_N)		Recommended action
1-5	Minimal	Preventive measures are not necessary
6-10	Acceptable	Preventive measures are not necessary. Condition monitoring is required.
11-15	Moderate	Preventive measures and monitoring are needed. If moderate risk is associated with high or very high consequences, further analysis and assessment is required.
16-20	Significant	The vessel must not perform operations on the given route until the risk has been reduced.
21-25	Unacceptable	The vessel must not perform operations on the given route until the risk has been reduced. If it is impossible to reduce the risk, the vessel is prohibited from operating on the given route.

Source: [6]

This proposed procedure is the basis on which specific mitigation measures are adopted with regard to the geographical location and the envisaged types of vessels. Mitigation measures refer to reducing the magnitude of the wave components that have the greatest negative impact. By adopting a single standard of mitigation measures for a larger area, it may happen that certain areas are overprotected, while others are insufficiently protected, so the adoption of different segmental standards may be a more acceptable solution.

6. Recommendations and conclusion / *Preporuke i zaključci*

Advances in shipbuilding in recent decades have made it possible to use stronger propulsion systems to be installed on higs-speed craft. Such vessels, sailing at large Froud numbers, generate waves according to complex physical laws, like linear and nonlinear components of disturbances, from Korteweg-de Vries solitons to undular solitons. Very fast craft in navigation often generate waves with a dozen components that all have different physical properties [24], and are fundamentally different from the waves of conventional craft. Wave fronts generated by fast vessels can have a significant negative impact on coastal systems. The negative impact spread around the world with the introduction of high-speed ferry lines. Recent researches have contributed to a better understanding of the impact of waves by developing physical and numerical models. The main consequences of the negative impacts of waves generated by vessels in this paper are: impact on safety (people, buildings, vessels), and environmental impact (hydro-morphological impact, impact on flora and fauna, and impact on cultural heritage).

Given the before mentioned general situation in the Adriatic Sea, it is recommended to conduct coordinated research that will include a detailed coverage of all these impacts for waterways that are of priority importance, and continuous monitoring of the situation. This would require the identification of priority coastal sensitive areas over which the action of wakes has a greater negative impact, and the development of the most appropriate mathematical models that will predict the characteristics and magnitude of the resulting waves for a particular area. The negative impact that needs to be further investigated is the effect of the interaction, i.e. the simultaneous interaction of constant and seasonal wind waves with the waves caused by vessels, since such research is less represented. Many states introduce speed limits to reduce the negative impact of waves, which is often not a necessary measure for a larger area, but is a first step in taking precautions. Sometimes such a measure can have a negative effect, in case such a speed is still sufficient for a vessel of a certain shape to sail close to the value of the critical speed. In general, reducing the speed of craft also has a positive effect in environmental terms, as it enables up to 75% reduction of harmful gas emissions from craft [25]. According to HSC Code 2000, the Route Operational Manual must contain information on the maximum permitted speeds with respect to the size of the generated wave. This is especially important on constant lines on which the same high-speed craft operates, so the impact of the created waves is constant. It is recommended to determine the critical point during acceleration and deceleration which represents the geographical position at which the vessel will develop a maximum wave at the stern. Such a point must be set in accordance with predetermined sensitive coastal areas. If possible, it is advisable to set the vessel's route in areas where changes in depth do not cause the vessel to exceed from transitional to critical speed. In order to increase general awareness of the importance of the negative effects of waves, it is recommended to continuously educate the public about the significant consequences of wakes, especially to those who operate recreational vessels. Identification and evaluation of coastal cultural heritage is necessary in order to adopt specific conservation measures for individual sites. The installation of physical barriers can have a positive effect on the stabilization of coastal buildings, i.e. cultural monuments. With the coordinated participation of experts from different disciplines, it is possible to compile more comprehensive detailed guidelines for the assessment and development of specific mitigation measures for certain priority geographical areas.

REFERENCES / *Literatura*

[1] Franzius, O. (1936). *Waterway Engineering: a Text and Handbook, Treating of the Design, Construction, and Maintenance of Navigable Waterways*. MIT, Cambridge.

[2] Johnson, J. W. (1957). Ship waves in navigation channels. *Coastal Engineering Proceedings*, *1*(6), 666-690. https://doi.org/10.9753/icce.v6.40

[3] Kirkegaard, J., Kofoed-Hansen, H., & Elfrink, B. (1998). Wake wash of high-speed craft in coastal areas. *Coastal Engineering Proceedings*, *1*(26), 325-337. https://doi.org/10.1061/9780784404119.023

[4] Stumbo, S., Fox, K., Dvorak, F., & Elliot, L. (1999). Prediction, Measurement, and Analysis of Wake Wash from Marine Vessels. *Marine Technology and SNAME News*, *36*(04), 248-260. https://doi.org/10.5957/mt1.1999.36.4.248

[5] Croad, R. & Parnell, K. (2002). *Proposed controls on shipping activity in the Marlborough Sounds: A review under S. 32 of the Resource Management Act.* Opus International Consultants Ltd and Auckland UniServices Ltd. https://www.marlborough.govt.nz/repository/libraries/id:1w1mps0ir17q9sgxanf9/hierarchy/Documents/Your%20Council/Environmental%20Policy%20and%20Plans/MSRMP%20Changes%20Variation%203%20List/D_Notified_Plan_Change.pdf

[6] Osborne, P. D. & MacDonald, N. J. (2005). *Wave energy evaluation of passenger only ferries in Rich Passage*. (Report No. FTA-WA-26-7007-2005). Pacific International Engineering. https://www.wsdot.wa.gov/research/reports/fullreports/641-1.pdf

[7] Havelock, T.H. (1908). The propagation of groups of waves in dispersive media, with application to waves on water produced by a travelling disturbance. *Proceedings of The Royal Society A: Mathematical, Physical and Engineering Sciences, 81*, 398-430. https://doi.org/10.1098/rspa.1908.0097

[8] Saha, G.K., Abdullah, M.S., & Ashrafuzzaman, M. (2017). Wave Wash and Its Effects in Ship Design and Ship Operation: A Hydrodynamic Approach to Determine Maximum Permissible Speed in a Particular Shallow and Narrow Waterway. *Procedia Engineering, 194*, 152-159. https://doi.org/10.1016/j.proeng.2017.08.129

[9] Aage, C., Bell, A. K., Bergdahl, L., Blume, A., Bolt, E., Eusterbarkey, H., Tetsuya, H., Kofoed-Hansen, H., Maly, D., Single, M., Rytkönen, J., Whittaker, T., & Elsaesser, B. (2003). *Guidelines for managing wake wash from high-speed vessels*. PIANC. http://pianc.us/workinggroups/docs_wg/marcom-wg41.pdf

[10] Whittaker, T.J.T., Doyle, R., & Elsaesser, B. (2000). A study of the leading long period waves in fast ferry wash. *Proceedings of 2nd International Conference Hydrodynamics of High-Speed Craft - Wake Wash and Motions Control, paper 7.* https://www.researchgate.net/publication/260944423_An_Experimental_Investigation_of_the_Physical_Characteristics_of_Fast_Ferry_Wash https://doi.org/10.3940/rina.hs.2000.06

[11] Kirkegaard, J., Kofoed-Hansen, H., Jensen, T. & Fuchs, J. (1998). Prediction of wake wash from high-speed craft in coastal areas. *Proceedings of International Conference Hydrodynamics of High Speed Craft 1999, 1-11*. http://resolver.tudelft.nl/uuid:f8bec16b-e509-4519-aa78-3d72101d52a8

[12] U.S. Army Corps of Engineers (2002). *Coastal Engineering Manual Part II: Coastal Hydrodynamics.* Books Express Publishing, Berkshire.

[13] Balanin, V.V., & Bykov, L.S. (1965). Selection of leading dimensions of navigation channel sections and modern methods of bank protection. *Proceedings of the 21st International Navigation Congres, 151-170.*

[14] Sorensen, R. M., & Weggel, J. R. (1984). Development of ship wave design information. *Proceedings of the 19th Coastal Engineering Conference*, *3227-3243*. https://doi.org/10.1061/9780872624382.217

[15] Scarpa, G.M., Zaggia, L., Manfé, G., Lorenzetti, G., Parnell, K., Soomere, T., Rapaglia, J.P., & Molinaroli, E. (2019). The Effects of Ship Wakes in the Venice Lagoon and Implications for the Sustainability of Shipping in Coastal Waters. *Scientific Reports, 9*(1), 1-14. https://doi.org/10.1038/s41598-019-55238-z

[16] Pomorski fakultet u Rijeci. (2015). *Prometno-plovidbena plovidbena studija - plovna područja Primorsko-goranske, Ličko-senjske, Zadarske i Šibensko-kninske županije.* Ministarstvo pomorstva, prometa i infrastrukture. https://mmpi.gov.hr/UserDocsImages/arhiva/MMPI%20-%20PROM-PLOV%20STUD%20PFRI%20v.3.2%2029-1_16.pdf

[17] Državni zavod za statistiku Republike Hrvatske. (2020). *Kapaciteti i poslovanje luka nautičkog turizma u 2019*. https://www.dzs.hr/Hrv_Eng/publication/2019/04-03-04_01_2019.htm

[18] Državni zavod za statistiku Republike Hrvatske. (2021). *Kapaciteti i poslovanje luka nautičkog turizma u 2020*. https://www.dzs.hr/Hrv_Eng/publication/2020/04-03-04_01_2020.htm

[19] Državni zavod za statistiku Republike Hrvatske. (2021). *Kružna putovanja stranih brodova u Republici Hrvatskoj u razdoblju od siječnja do studenoga 2020.* https://www.dzs.hr/Hrv_Eng/publication/2020/04-03-05_06_2020.htm

[20] Uprava društva Jadrolinije. (2020). *Izvješće poslovodstva za 2019. godinu.* https://www.jadrolinija.hr/docs/default-source/financijska-izvije%C5%A1%C4%87a/izvjesce_poslovodstva_2019.pdf?sfvrsn=2

[21] Dulčić, J., & Kovačić, M. (2020). *Ihtiofauna Jadranskog mora*. Golden Marketing - Tehnička knjiga, Zagreb and Institut za oceanografiju i ribarstvo, Split.

[22] Jardas, I., Pallaoro, A., Vrgoč, N., & Jukić-Peladić, S. (2008). *Crvena knjiga morskih riba Hrvatske*. Ministarstvo kulture, Zagreb.

[23] Mosor, P., Berković, B., Jakl, Z., Žuljević, A., Bitunjac, I., Plepel, I., Dragičević, B., Pleslić, G. & Holcer, D. (2016). *Priručnik za zaštitu mora i prepoznavanje živog svijeta Jadrana*. Udruga za prirodu, okoliš i održivi razvoj Sunce, Split.

[24] Soomere, T. (2007). Nonlinear Components of Ship Wake Waves. *Applied Mechanics Reviews, 60*(3), 120-138. https://doi.org/10.1115/1.2730847

[25] International Maritime Organization. (2009). *Second IMO GHG study 2009.* https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/SecondIMOGHGStudy2009.pdf