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Article

Review of UK inland waterways transportation from the hydrodynamics point of view

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Abstract

There are approximately 7,000 miles of inland waterways in the UK, many of them built during the 18th and 19th centuries principally to transport bulk materials. These waterways provide numerous benefits to society and the economy. However, they have untapped potential for freight transport which could be released to provide more efficient solutions compared to other modes of transport. In addition to providing solutions to reduce emissions from land or air transportation, inland waterways also bring environmental and public health benefits to local communities. Therefore, these blue-green spaces should play a central role in government and local authority planning. This paper explores some of the issues which prevent full use of the inland waterways transportation from being achieved from the hydrodynamics point of view. Specifically, the concepts and ideas underpinning vessel operation are reviewed and discussed in detail in this paper. It is shown how hydrodynamic concepts can inform public policy to maximise the efficiency of transportation from inland waterways.

Keywords: *inland waterways*, *inland navigation, shallow water hydrodynamics, vessel performance.*

Issue

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1. Introduction

Inland waterways navigation in the UK dates back to the 18th and 19th centuries when a significant number of canals were built, predominantly to facilitate movement of bulk cargos. Following a peak in activity during the 19th century, activity on and around inland waterways declined due to intense competition first from rail and then from road transport. Today, the UK has some 5,000 miles of inland waterways, 2,700 miles of which form an interconnected network. A further 2,000 miles are in a non-navigable state but have potential for navigation. Responsibility for the UK's waterways is split between many authorities, the largest of which include Canal and River Trust, Environment Agency, Broads Authority, and Scottish Canals.

Urban inland waterways are seeing a revival as a result of the recognition of their value to society, primarily through the lens of blue-green spaces. Such spaces are known to enhance local people's and visitors' mental and physical health with tangible monetary contributions to public health. Although further research is necessary to establish the exact link between exposure to blue spaces and health (McDougall et al., 2020), Tieges et al. (2020) found that following the restoration of a canal in North Glasgow, mortality rates fell by 3% in the community residing within 1 km of the canal. Shorter term exposure to blue spaces was studied by Vert et al. (2020) who found that walking in the vicinity of a blue space for 20 min enhanced people's mood.

Since over 50% of the world population lives within 3 km of a freshwater body (Kummu et al., 2011), the potential for enhancing public health through urban waterways is significant. Inland waterways, particularly in the UK, were typically constructed or manipulated to allow for navigation. In that light, O'Gorman et al. (2008) monetised the social benefit of inland waterways to society, finding that navigable waterways typically score higher in this respect (Hazenberg and Bajwa-Patel, 2014). A recent report by Canal and River Trust (2022) estimated an annual social value of the waterways under their care at £4.6 billion. In addition, they reported a £1.1 billion annual saving to the National Health Service (NHS) budget, and a £1.5 billion in Gross Value Added (GVA) through tourism and leisure activities. While these figures are significant on their own, it should be kept in mind that the Canal and River Trust oversees only a part (approximately 2,000 miles) of the UK's waterways.

Some 8.5 million people in the UK live within 1km of a waterway; approximately 15% of the population (Parry, 2021). The Inland Waterways Association (IWA, 2022) estimates that of those, 3 million reside next to a derelict inland waterway; that is, a waterway that is not being maintained. Similarly, based on data reported by McLennan et al. (2019) IWA estimates that 75% of districts with the highest deprivation indices in England are located on or near an inland waterway. Even if only a small fraction of the aforementioned benefits were to be realised, the economic, societal, and public health benefits would be substantial.

In addition to public health, inland waterways are thought to provide added resilience to extreme climate events, for example, by mitigating the Urban Heat Island effect (UHI). That effect can be characterised by a significant increase in the temperature in cities compared to surrounding areas, compromising human comfort during heat waves. Research has questioned the effectiveness of inland waterways in reducing UHI effects (Jacobs et al., 2020). However, UK-specific case studies report a reduction in ambient temperature in the vicinity of canals of approximately 1.5°C (Hathway and Sharples, 2012; McDonald et al., 2019), most likely due to the vegetation surrounding many canals in the UK.

Inland waterways can also contribute to mitigating the impact of other extreme climate events. For example, the Glasgow Smart Canal system incorporates weather forecasts to control the water level. The implemented system can lower water levels by up to 10 cm in advance of heavy rainfall, creating 55,000 m^3 of capacity for run-off and unlocking 110 hectares of land for development (Glasgow City Council, 2018; Scott et al., 2023). Thus, significant potential for flood prevention could be created across the UK. While the Glasgow Smart Canal is designed improve resilience to heavy rainfall, the River Severn to River Thames Transfer project does the opposite, moving up to 500 megalitres of fresh water per day (Severn Trent, 2021). Namely, water is transferred from wet to dry parts of the country through inland waterways to combat the worse effects of prolonged draughts.

The above evidence shows that inland waterways in the UK can be regarded as working industrial heritage with contributions to the economy, public health, and climate change adaptation, but the benefits that inland waterways deliver to society do not stop here. Transport over water is significantly more energy efficient than other forms of transport. That is the reason inland waterways were built across the UK in the late 1800s. Per tonne of goods carried, transport over inland waterways requires only 17% and 50% of the energy needed for road and rail transport, respectively (Jacobs, 2022). A focus on energy efficiency can create a measurable reduction in greenhouse gas emissions, allowing additional time for other means of industrial decarbonisation to mature, such as increasing the share of renewables in the energy mix and vehicle electrification. Focusing on such energy efficiencies in the short term decreases greenhouse gas emissions and postpones what are known as tipping-points due to climate change (Lenton et al., 2019).

The present paper aims to support the discussion around use of inland waterways for transport by providing additional context to the debate. Namely, we explore the reasons why transport over water is more energy efficient with the objective of enriching decision-making particularly as it relates to maintenance and repair of navigable waterways. This is done by reviewing the factors affecting the efficiency of a vessel sailing in a confined waterway, and by pointing out research gaps and opportunities for further research.

2. Activity on the UK's inland waterways

Goods-carrying inland vessels emit about 1% of the UK's greenhouse gas emissions (Walker et al., 2011) while carrying 5% of all goods (Department for Transport, 2021). More recent statistics include inland vessels' emissions in the 'Domestic Shipping' category contributing about 5% in 2020, but that includes coastal transport. The waterways where traffic primary takes place are depicted in Figure 1, which shows a significant reduction in activity in the period 1994-2020 from a total of 7.54 million tonnes to 2.69 million tonnes; a reduction of approximately 65%. The same figure also demonstrates that these reductions are primarily driven by a collapse in activity in the North of England. In relative terms, 14.5% of all goods transported through inland waterways took place on the Manchester ship canal in 1995; in 2021 that figure was 1.4% which represents a decrease of approximately two orders of magnitude in real terms (from 1.09 million tonnes to 0.04 million tonnes).

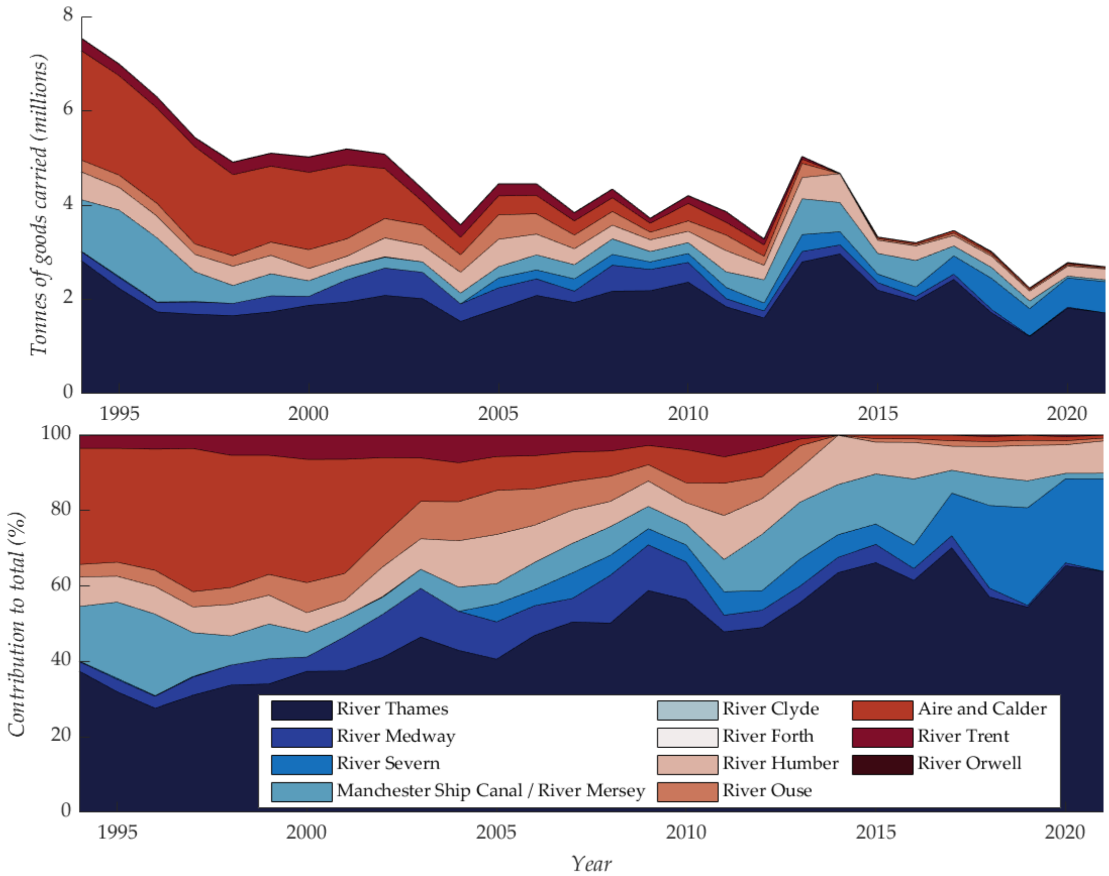

Figure 1. Freight statistics on the UK's inland waterways. This figure was produced using data from the Department for Transport (2021).

In addition to commercial activity, recreational boating takes place across the UK's navigable waterways. Although exact figures vary by source (Walker et al., 2011), there are an estimated 80,000 commercial and recreational hydrocarbon-powered craft (IWA (Inland Waterways Association), 2020), but statistics for their contribution to the country's greenhouse gas budget are not known at present. Many of these craft also have a residential function, contributing to their carbon footprint. To support the UK's net zero plans, all sectors must seek solutions aimed at rapid decarbonisation (Department for Business Energy and Industrial Strategy, 2021), while making full use of energy efficiency measures (Department for Transport, 2019). Inland waterways are an untapped resource in that sense due to the scale of potential savings of the UK's greenhouse gas budget. For example, inland waterways transport in accounts for 1% of London's emissions according to Port of London Authority (2020), but nationwide this value is significantly lower.

Inland waterways are melting pots where the interests of a multitude of stakeholders can collide. A good example of the problem can be illustrated by Canal and River Trust's (2022b) investigation on the Aire and Calder where navigation was temporarily suspended to determine whether fish deaths were related to barge traffic. Similar conflicts can arise due to inland waterways users' diversity which include towpath use, recreational sports and water-based leisure activity, angling, and freight transport. Due to the frequently incompatible goals of waterways users, prioritising the interests of one group inevitably creates the conditions where another group perceives an interference or threat to their goals or activities (Church et al., 2007). Such conflicts can be easily resolved when they occur between groups whose ultimate goals align. For example, boat-generated waves can erode canal banks, which left unchecked can progressively damage towpaths and prevent others from using the towpath, but this a situation is easily remedied through bank protection and maintenance. By contrast, the aforementioned report by Canal and River Trust (2022b) shows that stakeholders with fundamentally opposing goals and uses cannot resolve easily resolve conflicts. In such cases, knowledge of the hydrodynamic aspects governing the observed phenomena can inform how to best resolve a dispute.

The UK's inland waterways system is unique in its extensive reliance on a complex network of locks, without which transport is not possible. Historically, these locks were manned, which is increasingly rare in the recent past. The reliance on what are in many cases old, manually operated locks, creates an added layer of complexity which is not explored in the present paper.

3. Hydrodynamics

The fundamental reason why a vehicle requires energy to move is a consequence of Newton's third law: every action has an equal and opposite reaction. To sustain a constant speed, a vehicle, whether terrestrial, aerial, or aquatic, must produce a force in the direction of motion such that a given resistance is overcome. In terrestrial transport, that reaction consists of, for example, friction between a vehicle's tires and the road, and the aerodynamic force acting on the external surface of a car. The former does not exist in floating craft, instead, only fluid forces affect the performance of a vehicle operating at the air-water interface because no contact exists between the vehicle and seabed.

The discipline of hydrodynamics is concerned with estimating the aforementioned forces with the aim of understanding their source and magnitude. Unfortunately, the hydrodynamic forces acting on a steadily translating body at the water surface are highly complex and consist of several subcomponents. These forces and their subcomponents have been subject to intense research for more than two centuries (Gotman, 2007). Yet there are many unresolved questions, a sample of which are explored in the following sections. Although the following discussion focuses on energy efficiency of floating craft, the same arguments apply to minimising the environmental footprint of a vessel in terms of local disturbance. That is, a more energy efficient craft will create a lesser disturbance in terms of waves, current, and pollution, meaning that actions beneficial for energy efficiency are analogous to measures to minimise detrimental interactions such as bank erosion.

3.1 Dimensionless groups

When a boat advances at a steady velocity it produces waves, meaning that some amount of energy is radiated into the environment from the vessel. One way to estimate that energy is to measure the deformation of the water surface. Similarly, the vessel produces turbulence and accelerates a mass of water in its direction of motion, which also requires energy. The challenge for hydrodynamicists is to use the physical mechanisms driving these phenomena and devise strategies to maximise cargo/carrying potential and speed while reducing the fuel consumed.

A set of dimensionless parameters govern the performance of a steadily advancing floating vessel. These include the Reynolds number ($Re = VL\rho/\mu$, where V is the velocity, L is the vessel length, ρ is the density of water, and μ is the dynamic viscosity), the ratio of inertial and viscous forces. The Reynolds number is useful in quantifying the flow regime; that is, whether the water surrounding a vessel is turbulent or laminar. For example, Reynolds numbers above 10^5 indicate the flow is mostly turbulent. Even at very high Reynolds numbers, in the range 10^9, some of the flow near the bow of the vessel will remain laminar.

The friction a vessel experiences as a result of viscosity can be characterised through the Reynolds number through correlation lines such as the International Towing Tank Conference (ITTC) line, or other friction lines (Grigson, 1992; Katsui et al., 2005). Recent research by Zeng et al. (2019a, 2019b, 2018) showed that the submerged geometry of a vessel is critically important in determining how friction changes with Reynolds number in shallow water, hinting that no universally valid expressions can be derived. The formulations that Zeng et al. (2019a) arrived at depend on the Reynolds number and water depth, reflecting the fact that proximity to the seabed is important in determining the resistance due to friction. To the best of the authors' knowledge, no similar work exists for cases when a lateral confinement due to a canal bank is introduced. Friction dominates the viscous component of the force experienced by the vessel; therefore, its estimation is critically important in deriving power requirements. The unavailability of fast, robust expressions to estimate that component injects a level of epistemic uncertainty in predicting and optimising performance. It also prevents reliable estimates of fuel consumption.

A second dimensionless parameter is the Froude number ($F_n = V/\sqrt{gL}$, where g is the acceleration due to gravity), the ratio of inertial and gravitational forces. In shallow water, the Froude number is replaced with the depth Froude number ($F_h = V/\sqrt{gh}$, where h is the water depth). Unlike in deep water, where the length of a wave determines its speed, in shallow water, a single wave speed exists $c = \sqrt{gh}$. Due to this fact, the depth Froude number is analogous to the Mach number in aerodynamics where the wave speed is the speed of sound. F_h then represents the vehicle speed as a fraction of the speed of the fundamental wave in a given medium and controls wavemaking, i.e. deformations of the water surface. This has far reaching consequences, for example, the frictional component formulations produced by Zeng et al. (2019a) are valid for low speeds only because they did not take into account depth Froude number effects, and therefore, deformations in the water surface.

Changes in the depth Froude number have a profound effect on the geometry of the boat-generated wave system. Increases in the depth Froude number are linked to a greater transfer of energy from a craft onto the wave system. Unlike frictional effects which grow following an approximately quadratic curve with increasing speed, wave resistance can oscillate due to interference between the wave systems generated at the bow and stern. In general, waves are only shed from locations where the cross-sectional area (or beam) of a vessel changes. Thus, no waves will be emitted from the parallel midbody of a vessel.

At depth Froude numbers below approximately 0.5, the wave pattern in shallow or confined waters will closely resemble a deep water equivalent shown in Figure 2 with the exception that waves will typically be higher. This shows that more energy is radiated as waves when the water depth is shallow. Further increases in the depth Froude number cause the wave system to undergo a dramatic change, best expressed through the Kelvin half-angle (illustrated in Figure 2) as shown in Figure 3. Namely, the divergent wave system broadens to become near-perpendicular to the vessel track while the transverse wave system can no longer keep up with the vessel.

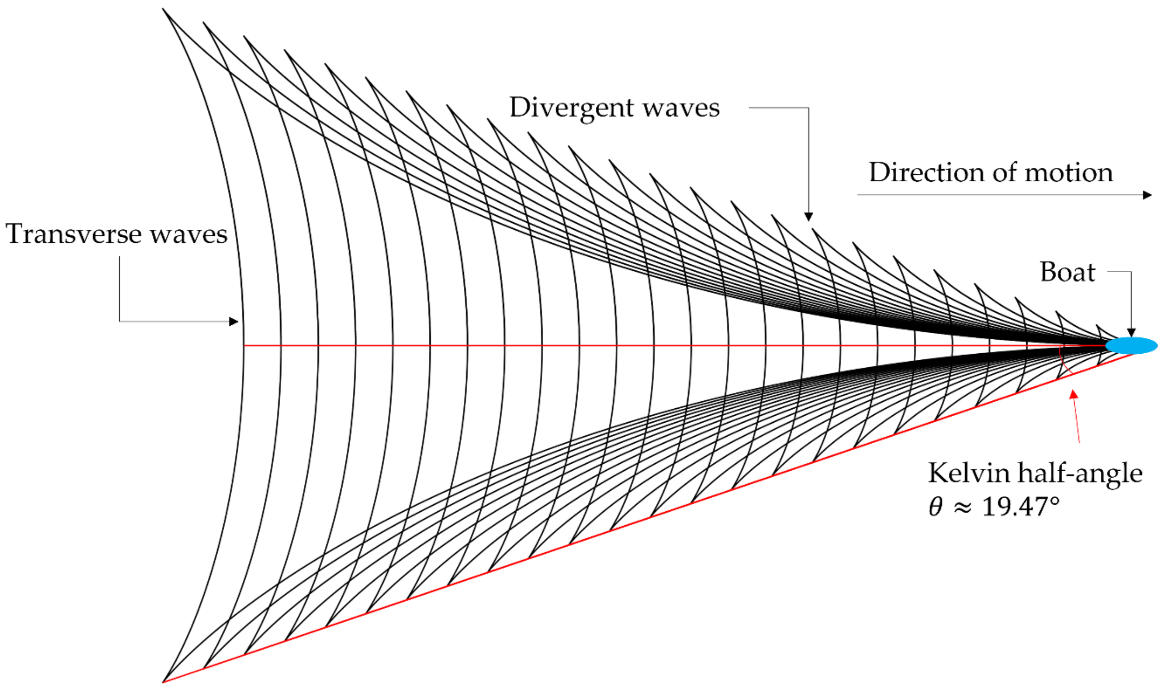

Figure 2. Wave system generated by a steadily advancing craft in deep waters.

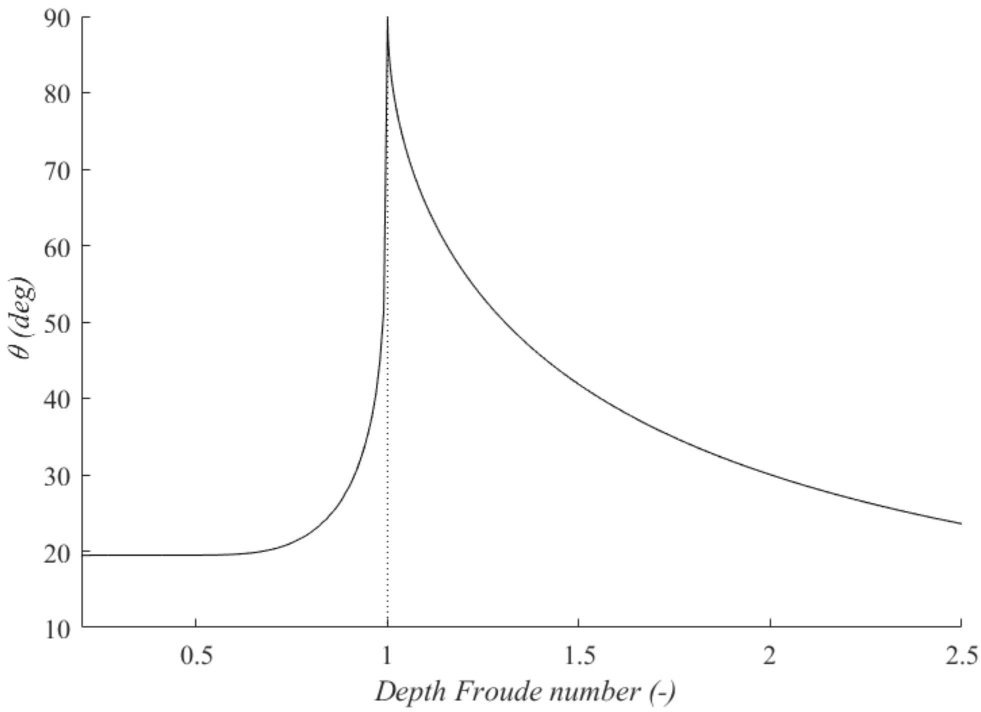

Figure 3. Kelvin half angle as a function of the depth Froude number. The relationships used to construct this figure are given in Havelock (1908).

Although geometrical properties of a craft and its draft play a role in determining the underlying forces, it should be noted that such properties do not play a role in the relations used to construct Figure 3. In other words, the waves emitted from a point disturbance will undergo the same transformation as the waves shed from a barge. Since the angle at which waves propagate from a vessel depends on the speed in shallow waters, adequate speed limits must be observed. A consequence of the fact that water depth is involved in the definition of the depth Froude number is that high F_h values can be produced even at relatively low speeds (in m/s). Thus, sedimentation of a waterway can cause a shift in F_h even if the speed (in m/s) is kept constant by varying the depth Froude number through the water depth. As mentioned previously, the energy radiated in the form of waves grows rapidly at high depth Froude numbers (Jiang, 1999; Terziev et al., 2018), meaning that maintaining adequate depth levels can reduce power requirements and erosion.

3.2 Confined water effects

The depth Froude number and Reynolds number cannot account for canal bank effects since the width of a waterway does not play a role in either of these dimensionless groups. Researchers have therefore introduced a third parameter, the blockage ratio, $m = A_S/A_C$, where A_S is the cross-sectional area of the hull (usually the maximum is taken), and A_C is the canal cross sectional area. A value of m =1 indicates that a vessel occupies the entire canal, while a value of m =0 can be attained in infinitely wide or deep waters.

Similar to flow in a pipe of varying cross-section, conservation of mass and energy can be applied to predict the change in pressure and velocity of water around the vessel. Unlike pipe flow, the presence of the water surface exposed to atmospheric pressure imposes certain limits to the interplay between pressure and velocity, since a reduction in pressure lowers the water surface. That can only occur up to a point, causing violations in the steady form of the law of conservation of mass (Lataire et al., 2012). In other words, under certain conditions, illustrated in Figure 4 as the trans-critical region, water cannot pass through the space between a boat and the canal banks in a steady manner, producing hydrodynamic instabilities. It is highly unlikely that a typical vessel will have sufficient power to traverse the boundary between the sub- and trans-critical regions, because of the exponential rise in resistance associated with the latter region (Terziev et al., 2018). Thus, the attainable speed of a vessel is limited by the available cross-sectional area.

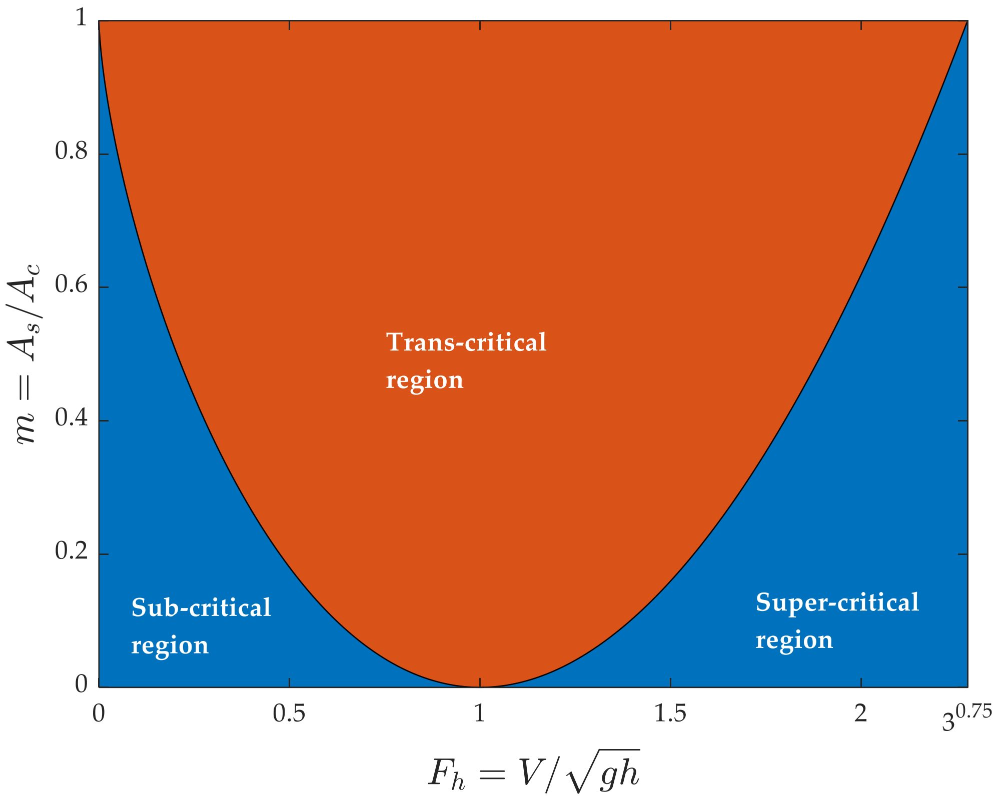

Figure 4. Speed-blockage relation, constructed using equations given in Lataire et al. (2012).

As mentioned previously, the trans-critical region is characterised by an inability to achieve a steady flow in the vicinity of a craft. That creates a hydrodynamic instability which is expressed as a build-up of energy ahead of the vessel in the form of a wave elevation. Once the wave elevation reaches a critical threshold, it has modified the local water depth sufficiently to bypass the restriction imposed by the wave speed ($c = \sqrt{gh}$) and is able to escape upstream; that is, a wave which can move at speeds faster than the limiting wave speed is formed. This is known as a solitary wave (Darrigol and Turner, 2006; Katsis and Akylas, 1987), first discovered by John Scott

Russel in the late 1800s (Darrigol, 2003). Soon after this discovery, engineers realised that exceeding the trans-critical region and operating in the super-critical region through an increase in speed can lower power requirements. In essence, a vessel will experience less resistance to motion if it advances at depth Froude numbers to the right of the trans-critical region in Figure 4 than it would at lower speeds within or near the trans-critical region (Du et al., 2020).

The dominant physics within the trans-critical region are highly non-linear. Such conditions are difficult to replicate experimentally, and theoretical methods to analyse such conditions have matured only relatively recently. Little is therefore known about the exact behaviour one may encounter in that region. The high blockage ratio values that craft experience in the UK can also be used as a full-scale laboratory to predict phenomena in international waterways, such as the Suez Canal and Panama Canal. If ship dimensions continue their historical trend of growth, the levels of restriction typical for the UK will find applications internationally in many rivers, canals, and ports.

In 2018 and 2022 extreme droughts across Europe and China caused water levels of rivers used for navigation to drop to dangerously low levels (Vinke et al., 2022). This prevented carriage of goods, compromising supply chains and creating shortages of materials. If such climate events are to become more frequent (Christodoulou et al., 2020), industries dependent on bulk materials which are principally transported through large rivers will suffer. Since reductions in water depth cause an increase in the blockage ratio and depth Froude number, everyday hydrodynamics of UK canals must be studied to obtain further information on how a vessel performs under extreme conditions. Such knowledge could facilitate safe operations of ships and barges internationally even in low water level conditions.

3.2.1 Effects of fluid mud

As sediment accumulates at the canal bed, it is not immediately compacted to a rigid boundary. Water can permeate a layer of the canal bed creating fluid mud. The density of this layer is typically significantly higher than that of the fluid above it. Nevertheless, a vessel can move through such a layer without being in contact with a rigid surface, creating ambiguity in defining the water depth. McAnally et al. (2016) define the nautical depth as "*a safe and effective channel bottom criterion in areas where fluid mud confounds conventional acoustic (echo sounder) surveying methods.*" Alternatively, "*the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability*" (Delefortrie et al., 2005).

For many ports, it makes sense to use echo sounder measurements and define the water depth as the location where the fluid density reaches a certain value. For example, Welp and Tubman (2017) compiled international nautical depth criteria, showing that 1,200 kg/m^3 is the most frequently used value. Most ports are frequented by sea-going vessels which enter ports for brief periods of time. They spend the majority of their time, and therefore, greenhouse gas budgets, offshore. Transferring practice from ports onto inland waterways in that respect would not be beneficial due to the fundamentally different modes of operation.

The effects of fluid mud do not necessarily end if a clearance is present between the hull and the mud-water interface. Although a fluid, this type of mud behaves in a non-Newtonian manner (McAnally et al., 2007). The complex behaviour of fluid mud allows for a second wave system to be generated within the mud layer in addition to the one at the air-water interface. Since producing waves requires energy, the overall energy expended by the vessel to maintain the forward speed must increase (Delefortrie et al., 2010; Kaidi et al., 2020).

4. Slope stability and erosion

The likelihood of the banks and slopes of inland waterways to erode depends on the balance of forces acting on the sediment.

On the bed, the applied energy in the form of an applied shear stress is balanced by stabilising/resistive forces including gravity and cohesion. As the fluid transmitted forces exceed the stabilising forces, the erosion threshold is breached and sediment is transported as bed or suspended load. Several stages of erosion of cohesive sediments have been identified in the marine environment, ranging from erosion of loose surficial bed material or aggregates (Type I), to mass failure of the bed (Type II) (Amos et al., 1992; Parchure and Mehta, 1985; Winterwerp and Van Kesteren, 2004), which are transferable to freshwater environments.

On banks, both erosion of the bank face due to the hydrodynamic forces and gravity driven bank failure processes occur, often cyclically. When applied shear stresses exceed the erosion threshold of the sediment the bank face erodes, and as these processes create overhangs, cantilevers, or bank steepening, geotechnical failure occurs as a result of gravity-induced mass movement (Fischenich, 1989), enhancing bank retreat and depositing sediment into the waterway.

Erosion is therefore dependant on both the hydrodynamic forces, and the nature and history of the sediment which makes up the bed or bank (i.e. grain size; proportion of sand to clay/mud (Mitchener et al., 1995) clay mineralogy (Torfs, 1995)) and consolidation processes (i.e. bulk density/bed strength) which are related to sediment supply, and cycles of deposition and resuspension (Thompson et al., 2011). These sediment properties are related to the underlying and catchment geology, which vary at both local and national scales.

Where waterways are tidal, beds and banks are subject to bidirectional flows which vary in intensity over the tidal cycle. This can result in cycles of deposition and resuspension across the tidal cycle, influencing consolidation processes (Mehta, 1989) and ultimately bed and bank stability. Variations in water level also influence the area of bank over which the hydrodynamic forces act. In addition, frequent cycles of wetting and drying can destabilise bonds between sediment particles, enabling erosion under low-energy conditions over medium timescales (1-10 years), as often seen in intertidal creeks (Chen et al., 2012).

Additionally, vegetation influences bed stability in a number of ways, which may enhance or decrease the likelihood of erosion. At small scales, microbial influences can stabilise sediments through the formation of biofilms which bind sediments and protect them from the flow, or destabilise them through modification of their density, reducing stabilising forces, depending on their developmental stage (Zhang and Thompson, 2023, in press). At larger scales, vegetation can reduce applied shear stress through flow modification (reducing fluid transmitted forces), as well as binding sediment (increasing stabilising forces) through the influence of roots (Chen et al., 2012).

5. Relevance for decision making

The information discussed above has several practical implications. Firstly, it is important to acknowledge limitations in current understanding and therefore, ability to provide precise advice. Some gaps in understanding have been known for a considerable length of time (Tuck, 1978), while others are emerging with new research. For example, Raven (2022) was motivated by discrepancies in observations and calculations to provide an extensive list of corrections one may apply to simpler cases (e.g. infinitely wide shallow water) to obtain a confined water result. The aim of these factors is to correct for confined water effects. Raven (2022) also developed a correction aiming to reduce these discrepancies. Although these corrections may be useful for moderate water depths and low blockage ratios, they show too much disagreement in the cases that would be relevant for UK inland waterways. Inland waterways in the UK are for the most part considerably narrower and shallower than waterways in Europe, China and the US. It should be kept in mind that historically, UK inland waterways were dug by manual labour only to the point thought sufficient to allow for a barge to pass. In a sense, that makes the challenges around inland waterways faced in the UK unique. The increased use of canals to absorb excess run-off also has consequences for sedimentation with knock-on effects on other users' ability to use the waterways. Since vessel-induced disturbances such as waves and current are responsible for a significant portion, if not the majority, of the energy budget in inland waterways. The accurate estimation of hydrodynamic forces is therefore critically important not only for vessel efficiency but also to ensure banks are protected as discussed previously.

A useful piece of information one may extract is concerned with speed with consequences for erosion. The energy within a vessel-generated wave can be released through, for example, wave breaking, causing erosion which widens a canal. Under a fixed quantity of water or controlled water level within a canal the blockage ratio is maintained constant while the depth is reduced. This increases the depth Froude number, causing more energy to be expended as waves, creating a positive feedback loop.

Canal and River Trust recommend a speed of no more than 4 mph on their waterways. However, it is the authors' understanding that such speeds are unattainable in many cases due to blockage effects. A speed of 4 mph maps onto a depth Froude number of 0.807 and critical blockage of $m = 0.025$ if a water depth of 0.5 m is used. Assuming the critical speed and blockage point cannot be exceeded due to unavailability of power, the vessel can occupy no more than 2.5% of the canal's cross-sectional area in order to sustain a speed of 4 mph. If the speed were halved to 2 mph, the equivalent critical blockage becomes 0.262, i.e. the vessel can occupy up to approximately 26% of the cross-sectional area. These effects are depicted in Figure 5.

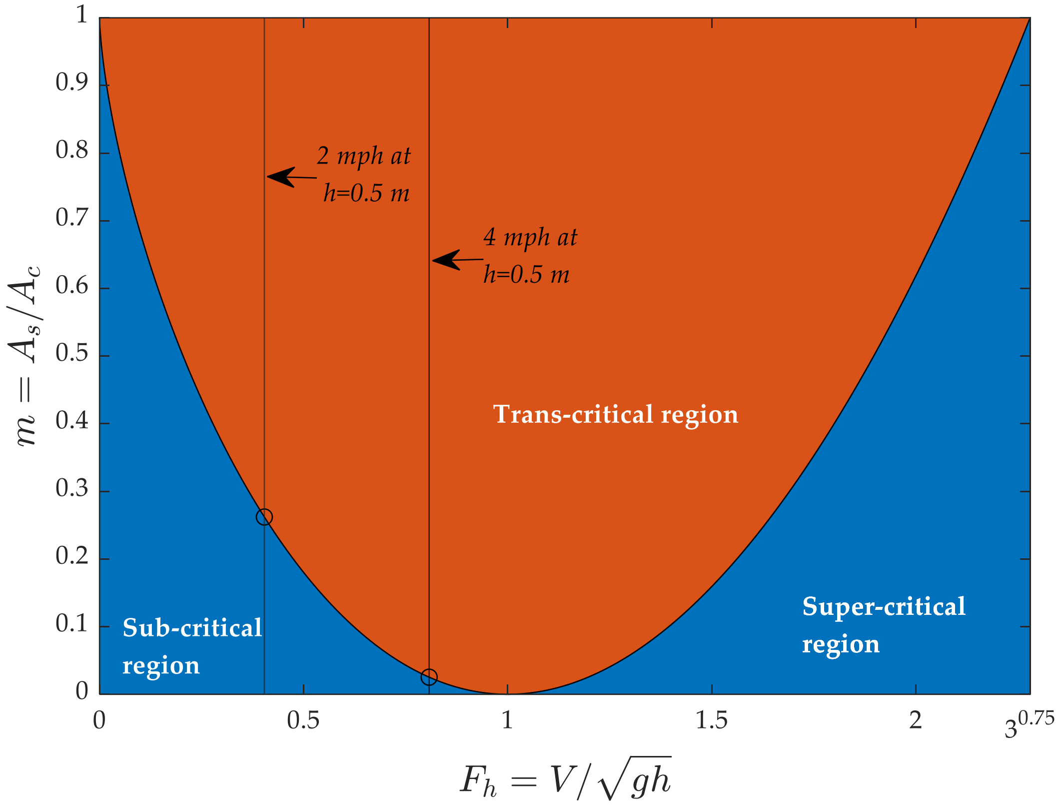

Figure 5. Speed-blockage relation, constructed using equations given in Lataire et al. (2012). Vertical lines show the depth Froude numbers achieved for 4 mph (as recommended by the Canal and River Trust) and 2 mph if the water depth is assumed to be h =0.5 m. The intersections of those lines with the trans-critical boundary are depicted by circles.

At speeds near or above the critical boundary, large volumes of water are mobilised causing friction on the canal bed resulting in erosion, sediment resuspension and poor water quality. This means that erosion and other adverse environmental effects can occur even at very low depth Froude numbers provided the blockage is sufficiently high. Canal and River Trust have extensive online resources explaining, in practical terms, wash and its contribution to bank erosion. However, as discussed above, wave-related phenomena are not dependent on the speed in dimensional values (e.g. mph), they depend on the depth Froude number. A speed of 4mph may result in a low depth Froude number and minimal wavemaking if the water depth is sufficient. In other cases, 4 mph may cause extreme disturbances in the canal and promote erosion by transferring energy into the wave system and through the return flow. As illustrated by Figure 5, the depth and blockage determine the attainable speeds for a vessel and show the useful domain of operation (to the left of each circled point).

The specific case of the Aire and Calder investigation by Canal and River Trust mentioned previously can be used as an example to illustrate the effects discussed above. Using the method used to construct Figure 5 and taking as an example a vessel that occupies 1/3 (m =0.333) of the available cross sectional area of a canal moving at a speed of 4mph at a depth that is 1.5 times the vessel's draft (F_h ≈0.14) results in a local disturbance characterised by flow speeds of approximately 50% of vessel speed. In other words, a current of strength 2mph in the direction opposite to that of the vessel is created, which may pose a danger to recreational users and aquatic life. Such a current is likely to create sufficient turbulent friction on the canal to suspend sediment causing erosion and disturbing aquatic life which creates a multitude of conflicts from a number of perspectives including but not limited to water sports users and anglers. Halving the speed also halves the produced current strength, but doubling the depth (m = 0.166) creates a current that is only 20% of the vessel speed, that is, approximately 0.36m/s or 0.81mph. The relationship between the cost and the delivered benefit must be understood to allow informed decision making. It is unlikely that a navigation authority would be able to double the depth during a dredging campaign, but as demonstrated here, simple calculations can give an estimate of the associated trade-offs.

As evidenced by Canal and River Trust (2015) strategic priorities, tourism, the well-being economy, and heritage are the primary focus in waterway management and restoration, while freight is promoted as a secondary item. Many of the benefits to society, the economy, and public health cited in the introduction are based on leisure activities rather than on commercial activities. It is therefore important to recognise the need for synergy between freight transport and all other stakeholders, that is, conflicting goals of different users must be reconciled through informed decision making.

Finally, although the effects of blockage have been discussed, the effect of shape has not. It is known that varying the submerged geometry of a canal, for a constant depth Froude number (near the vessel) and blockage, affects power requirements. However, to the best of the authors' knowledge, no set of geometrical optima have been produced. This is an area where hydrodynamics research can inform dredging practice. It is plausible that simple alterations in the shape of a canal, created during maintenance dredging, can influence the overall fuel consumption and disturbance created by a vessel and minimise the energy and burden of dredging.

6. Conclusion

Inland waterways in the UK have significant untapped cargo carrying potential which may be used to affect a reduction in greenhouse gas emissions from the transportation sector. However, commercial activity in the UK has reduced by approximately 65%, driven primarily by changes in practice in the North of England. Transport over inland waterways requires only 17% of the energy consumed by road transport per tonne-mile. With the series of tipping-point events facing humanity, all energy efficiency measures should be adopted to postpone irreversible climate change. Such energy efficiencies can contribute to greenhouse gas budgets, allowing additional time for other decarbonisation strategies to be implemented at scale.

Increasing recognition of inland waterways, ranging from public health, through climate change adaptation and prevention, calls for better and smarter use of inland waterways. This paper examined some factors affecting the operation of inland craft from a hydrodynamic point of view. Emphasis was placed on conditions affecting craft in the UK. Specifically, UK waterways, particularly those constructed during the 18th and 19th centuries are significantly narrower and shallower than many navigable rivers internationally. This creates a set of unique challenges, for example, restricted space particularly in urban settings is likely to cause conflicts between different users of the waterways. Knowledge of the hydrodynamics governing flow behaviour can be used to devise effective measures to minimise disruption through cost-effective decision making. In this context, it is particularly important to understand the trade-offs between vessel speed and depth or blockage.

The present paper reviewed the parameters governing the resistance of a craft advancing steadily in confined water. Examples of several outstanding research questions were discussed. In addition, some limitations of current advise issued by navigation authorities were discussed. It was demonstrated that more targeted advice, taking into account local conditions is necessary if decarbonisation of inland waterway transportation in the UK is to be optimised.

Conflict of Interests

The authors declare no conflict of interests.

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