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REVIEW OF PRACTICAL ASPECTS OF SHALLOW WATER AND BANK EFFECTS

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SUMMARY

The ship's behaviour and manoeuvrability change as depth of water decreases and/or when the ship is near a bank or shoal. This paper conducts a review on shallow water effects (SWE) and bank effects (BE). It summarizes the varying opinions from both experienced mariners and hydrodynamicists about SWE on factors such as resistance, trim, steering, manoeuvrability and stopping, as well as BE on elements such as bank suction and cushion and it is shown that there is not a common sense in the bibliography. This is strange because the successful navigation of a ship along the channel to the dock is an identifiable task whose outcome is the same in all cases. Yet surprisingly it is a subject upon which there are different opinions documented. This review refreshes mariner's memory and raises controversial topics that need clarification for the benefit of mariners, simulator modellers and the maritime industry they work.

NOMENCLATURE

BE	Bank Effects
C_b	Block coefficient
DGPS	Differential Global Positioning System
EAS	Portuguese acronym for South Atlantic Shipyard
F_D	depth of influence co-efficient
g	acceleration due to gravity (ft/sec²)
h	Water depth (m or ft)
L	Ship's length (ft)
MRD	Maximum Recommended Draft (m or ft)
PP	Pivot Point
r'	Dimensionless turning rate
SRW	Shallow and Restricted Waters
SWE	Shallow Water Effects
T	Ship's draft (m or ft)
UKC	Under Keel Clearance (m or ft)
V	Ship's velocity (knots)

Note: the large amount of contents in this review are clearly and precisely referred to other authors and punctually reported. Because we prefer to preserve the contents (including units) of the references exactly as they are, not all the physical dimensions are reported in SI units. Converting the units in the contents of other authors would cause unnecessary confusion to the readers of this work.

1. INTRODUCTION

The ability to handle large ships in shallow and restricted waters is one of the most demanding of a mariner's skills (Crenshaw [9], MacElrevey and MacElrevey [32], House [22], Inoue [24], Council [7], Hutchins [23], Inoue et al., [25]). Handling a ship in shallow and restricted waters can be very complex for many reasons, such as: (i) that is when ships are mostly exposed to hazards, e.g., fixed objects and other vessels passing close by; (ii) manoeuvring room is limited; (iii) the ship's speed is lower so she feels greater effect of wind, sea and current; (iv) there are several different types of current acting together, so the resulting current is heterogeneous and less predictable; and (vi) the ship's behaviour in general, and her manoeuvrability in particular, changes as depth of water decreases and/or when the ship is near a bank or shoal.

This paper is focused on the last topic. The aim is to give a summary about shallow water effects (SWE) and bank effects (BE) based on several documented references, in order to provide background information that can be useful for review and discussion. This will benefit mariners, simulator modellers and the maritime industry.

In fact, approximately 90% of all marine accidents occur in restricted water (MacElrevey and MacElrevey [32], Gould et al., [19]). Given the complexity, high risks to the environment and costs involved in shiphandling in ports, channels and inshore traffic zone, it is surprising that the maritime research literature contains few documented studies about the practical aspects of SWE and BE (e.g. (Millward [33], Ferreiro [14], Sadakane et al., [39], Vantorre [44], Barrass [1], Ch'ng et al., [5], Corllet, [6], Lo et al., [31], Barrass [2], Rowe [38], Institute, [27]).

Many variables influence shiphandling, particularly in Shallow and Restricted Waters (SRW). No publication can encompass all the elements involved and their interaction in all possible situations. Obviously, it is not the purpose of this paper to do so, but to give a brief summary of the practical conclusions about SWE and BE taken from experienced shiphandlers and hydrodynamicists, and particularly note when they are controversial.

The art and science of shiphandling in SRW can only be learned by practice. However, the theory is important firstly because shiphandlers can understand the changes in forces acting on a ship, base their actions on reasoning and be able to think ahead of the ship so that she reacts to orders rather than orders being given in reaction to ship's behaviour [22]. Thinking ahead and planning manoeuvers based on understanding the changes in resistance, trim, directional stability, turning diameter, rate of turn, stopping distance and twisting effect is essential if a ship is to be moved efficiently and safely. Secondly, training and certification of novice mariners becomes more efficient if they have a good theoretical background [32]. Finally, the mathematical model of ship's bridge simulators are based on trial manoeuvres in deep water (turning circles, stopping distance, zig-zag tests) of the original ship being modelled, so that the parameterization of the model for SRW is mostly based on theory for SWE and BE (Junior et al., [28], Silva et al. [40], Tannuri et al. [42], Konsberg, [29]).

The rest of this paper is organized as follows. Section 2 discusses the effects of depth restrictions on ship behaviour. It introduces the varying definitions of shallow water and the suggested minimum Under Keel Clearance (UKC) in different kinds of navigation areas. It then presents a review of SWE on isolated elements, i.e.: resistance, trim, steering, manoeuvrability and stopping. Section 3 describes BE while the last section concludes this paper, raises some controversial topics for discussion, and suggest future works.

2. SHALLOW WATER EFFECTS

2.1 SHALLOW WATER CONDITIONS

According to the ratio of the water depth, h, to the ship's draft, T, the marked changes in ship behaviour that occur in shallow water will become apparent when $h/T < 1.5$ and full shallow water effect is felt when $h/T = 1.2$ (p7-8, [32]). They recommend that characterization of ship manoeuvrability and controllability is best done by putting the vessel through a series of standard manoeuvres, and "preferably, these tests will be done in water depth less than 1.5 the ship's draft" (p7).

Data from tests in shallow water are scarce. The known SWEs are mostly based on simulations, and rarely on full scale observations. These are so uncommon that relatively old trials (e.g. Crane, [8], Nizerry and Page, [34]) are still used as theoretical knowledge and to compare results obtained in simulations [30]. In fact, the Esso Osaka trials have become legendary because they were carried out in water depths down to 1.2 times ship draft, which is very difficult to test, although not very shallow - ships often operate with depths about 1.1 times draft in low water and only 1.05 at a pier or wharf (p281, [30]).

The World Association for Waterborne Transport Infrastructure [37] makes a rather arbitrary distinction:

- deep water: $h/T > 3.0$;
- medium deep water: $1.5 < h/T < 3.0$;
- shallow water: $1.2 < h/T < 1.5$;
- very shallow water: $h/T < 1.2$.

Using this definition, Vantorre [44] states that "roughly spoken, the effect of depth restrictions can be noticed in medium deep water, is very significant in shallow water, and dominates the ship's behaviour in very shallow water".

Lewis uses another definition: "In regard to manoeuvring performance, shallow water may be defined as water in which the ratio of water depth to ship draft is three or less. At greater ratios, shallow-water effects on manoeuvring become rapidly less significant as the water deepens" (p279, [30]).

Other references use much higher values for h/T than the aforementioned. For example, OCIMF [35] [36] apud Hensen (p71-72 [21]), in regard to current forces acting on a ship, define deep water as $h/T > 6$ and provide formulae for values of h/T ranging from 6 to 1.1. The most practical aspect observed here is when h/T is reduced from 6 to 1.1, current force is nearly 5 times higher (more exactly 4.86).

Barrass uses a depth of influence co-efficient, F_D, to know when a ship has entered shallow waters making distinction for each ship type (p22-23, [2]):

$$F_D = k \times T \tag{1}$$

where k is a constant for each ship type, respectively, 5.68, 7.07, 8.25, 9.20 and 12.04 for a supertanker, general cargo ship, passenger vessel, ro-ro vessel and "Leander" frigate; and T is the static mean draught. h/T is then compared with F_D: "If h/T is above the respective F_D value, the vessel's resistance will not alter, her speed will remain constant, her propeller revolutions will remain steady and her squat will remain unchanged. She is in fact operating in deep water conditions" (p23, [2]).

Fonseca [15] writes that, in general, the effect of shallow waters is to increase resistance to propulsion. For ships with ordinary forms operating at a ratio $V/\sqrt{L} < 0.9$, he defines the minimum depth to avoid SWE is:

$$h_{min} = 10 \times T \times \frac{V}{\sqrt{L}} \tag{2}$$

where T the ship's draft in feet, V the ship's velocity in knots and L the ship's length in feet (p650-651, [15]). For example, a ship with 400 feet of length and 8 feet of draft, proceeding at 6 knots, is considered to be in shallow water when depth is smaller 24 feet (7.2 meters).

As a rough guide, Rowe assumes that a ship may experience SWE when $h/T < 2$. However, serious cases of shallow water problems have been experienced with larger ratios, especially at high speeds (p33, [38]).

Finally, Crenshaw does not objectively defines shallow water, although he provides important conclusions with regard to SWE [9].

2.2 MINIMUM UNDER KEEL CLEARANCE (UKC)

UKC is equal to depth of water minus ship's draft, thus:

$$\frac{UKC}{T}=\frac{h}{T}-1 \tag{3}$$

The International Commission on the Reception of Large Ships (ICORELS) suggests the following values for UKC in different kinds of navigation areas (PIANC, [37], Brunn, [4], Vantorre, [44]):

- Open sea areas: for those exposed to strong and long stern or quarter swell, where speed may be high, UKC/T should be about 0.2.
- Waiting areas: for those exposed to strong and long swell, UKC/T about 0.15.
- Channel: for sections exposed to strong and long swell, UKC/T about 0.15.
- Channel: less exposed to swell, UKC/T about 0.10.
- Manoeuvring and berthing areas: for those exposed to swell, UKC/T about 0.10 to 0.15.
- Manoeuvring and berthing areas: protected, UKC/T about 0.07.

Obviously, the aforementioned values are only recommendations and helpful as a rule of thumb. Local conditions, allowable speed, availability of pilots and tugs will determine accurate rules concerning minimum UKC. As an example, according to the rules and procedures of the captaincy of Pernambuco ports, distinct values for minimum UKC in the port of Suape were established for winters (Apr 16th to Sep 31st) and summers (Oct 1st to Apr 15th). These rules are being followed in everyday operations since their establishment in the 28th of November 2014 [3], regardless of wind and sea at that day. The rationale to categorize minimum UKC into two classes (winter and summer) is because wind and sea vary in a predictable manner according to the season of the year, whereas these conditions keep almost the same during all winters and all summers. Conditions are more favourable during summers, when Maximum Recommended Draft (MRD) to give access to ships is greater, so minimum UKC is smaller. MRD follows the rule: MRD = h + A – min (UKC), where A is the lowest tide height (m) in the period along the channel to the dock plus 48 hours.

In summers, the minimum UKC in the waiting area (open sea; h = 14.8 m; min (UKC) = 2 m) to the port of Suape is about 16% of MRD. In more sheltered areas, these values are reduced to about 14%, as is the case in the external basin (less exposed to swell; h = 14.8 m; min (UKC) = 1.8 m). In protected manoeuvring areas, this value is gradually reduced down to a minimum of 10%, as is the case in the dock evolution basin (confided access channel; h = 9.5; min (UKC) = 0.9 m) to the local shipyard EAS. In protected berthing areas, even lower values are practiced: the internal berth EAS 1 gives access to ships with a draft up to 10.2 m + A, whereas h = 10.5, so that UKC/T is only 0.03 of draft. Obviously, pilot and tug services are available in this port, what makes it possible to practice such low values for UKC, without affecting a safe passage.

Finally, MacElrevey and MacElrevey do not suggest a minimum UKC but a maximum safe speed given UKC in almost all conditions: "*In any case, absent specific knowledge to the contrary, the 6-knot speed limit for 5 feet of UKC is a useful rule of thumb … that is suitable for safe navigation in almost all conditions*" (p96 [32]).

2.3 RESISTANCE

In general, shallow water conditions increase resistance, so a ship makes a lower velocity at the same power. With sufficient power, some ships can reach a critical velocity V_c at which the resistance is very much greater than in deep water. Above V_c, the resistance does not increase, and at sufficiently high speeds, the resistance becomes less than in deep water. The definition of V_c varies among authors as follows:

Lewis explains that changes in resistance occur due to two effects: (i) "*the water passing below it [the hull] must speed up more than in deep water, with a consequent greater reduction in pressure and increased sinkage, trim and resistance*"; and (ii) "*the changes in the wave pattern which occur in passing from deep to shallow water*" ([30] p42). Based on the research of Havelock [20] for a point pressure impulse travelling over a free water surface, Lewis provides a more detailed explanation about the changes in wave pattern.

The velocity of surface waves (in knots) is given by the expression:

$$V_c=\left(\frac{gL_w}{2\pi}\right)\tan(\frac{2\pi h}{L_w}) \tag{4}$$

where L_w is the length of wave from crest to crest (in feet), g is the gravitational acceleration (≈ 32.174 feet/sec²) and h the water depth (in feet). T

As h decreases, and the ratio h/L_w becomes small, $\tan(2\pi h/L_w)$ approaches the value $2\pi h/L_w$, and for shallow water, the wave velocity is approximately given by the equation:

$$(V_c)^2=gh \tag{5}$$

Since the wave pattern as a whole moves with the ship, the transverse waves are moving in the same direction as the ship at the same speed, V. The wave pattern goes through a critical change when the ship's speed reaches the critical speed for a particular depth, i.e.: $V = \sqrt{gh} = 5.672 \times \sqrt{h}$. For example, a ship moving in water of 6 feet depth will only reach the critical speed at about 14 knots. The effect upon resistance due to these changes in wave pattern in shallow water are summarized as follows ([30] p42-44):

- For $V < V_c$ (subcritical zone), wave-making resistance in shallow water increases more rapidly as speed increases. Nearly all displacement ships operate in this subcritical zone. Thus, in practice, a ship moving in shallow water will travel at a lower speed than in deep water.
- As V approaches V_c, wave-making resistance becomes very much greater in shallow water.
- As V increases above V_c (supercritical zone), wave-making resistance in shallow water decreases more rapidly, and ultimately at very high speeds the resistance in shallow water will become less than in deep water. Ships that operate in this supercritical zone are exceptions, such as destroyers, cross-channel ships and similar types.

Crenshaw writes that wave resistance in deep water would be in the form indicated in Figure 1 (Crenshaw, 1975, p30-31). It can be seen that in deep water there is a general decrease in resistance at very high speeds (speed-length ratio $V/\sqrt{L}$ greater than 2, ship's speed in knots and length in feet). In a further passage, Crenshaw explains that this whole curve (Figure 1) shifts to the left in shallower water because of longer wave lengths (p35, [9]). Thus, in shallow water the resistance of the ships rises more rapidly as speed increases. However, the peak of the wave resistance will be at a speed-length ratio smaller than in deep water. Note that beyond this peak the wave resistance actually decreases. Given that the peak occurs at a lower speed in shallow water, it is possible for very high speed ships to reach a higher maximum speed in shallow water than in deep water.

For Fonseca (p650-651, [15]), the cause for increased resistance in shallow waters is the reduced space for water flow around the underwater hull, so pressure increases and so the surface waves formed at the bow and stern. Thus, for a given power, speed is reduced in shallow water because some power is lost to form these increased waves. However, a phenomenon still not explained is that there is a critical velocity above which the increase in velocity does not increases resistance:

$$V_c \cong 2 \times \sqrt{L} \qquad (6)$$

Hence, for ships that develop speeds such that $V/\sqrt{L} \cong 2$ (ship's speed in knots and length in feet), there is no increase in resistance in shallow water.

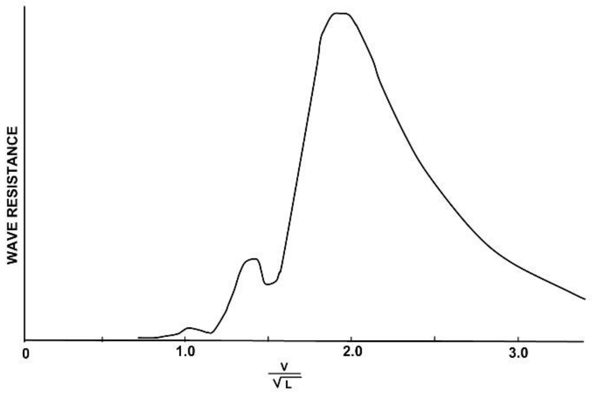

Figure 1. Wave resistance in deep water as a function of the speed-length ratio [9].

Barrass also agrees that the ship's resistance will increase when she operates in shallow water conditions (i.e., bellow the corresponding value of F_D – see eq. 1) and her speed will reduce despite the same input of engine power, although explaining that is beyond the scope of his work. He also states that one out of nine indications that the ship has entered shallow water is "*wave making increases at the forward end of the ship*" ([2], p23).

MacElrevey and MacElrevey do not separate shallow and narrow water effects on resistance and explain both effects very briefly as follows: "*Since a ship in confined waters can be compared to a piston in a cylinder, it is obviously more difficult to drive the ship ahead as the blockage factor increases. There is therefore a practical limit to the speed at which a ship can proceed up a channel – the ship that makes 16 knots at eighty revolutions in open water might make only 9 or 10 knots with the same number of revolutions in shallow waters*" ([32] p90). In fact, they do not directly state that this decreased velocity is due to increased resistance. It is open to the reader's interpretation.

2.4 TRIM

As UKC is reduced, the change in pressure on the hull causes the trim to change, the draft increasing more at the bow or stern depending on hull form, and the pivot point (PP) moves along the length of the ship. Will the PP move forward or aft? Will the trim occur by the head or by the stern for a given hull form?

2.4 (a) Trim and Pivot Point

MacElrevey and MacElrevey concludes that ships trimmed by the head are directionally unstable and "*this condition is indicated by the shift forward of the apparent PP of the ship, so the ship seems to pivot about a point nearer the bow than normally expected*" ([32] p71-72). They explain it by looking at the immersed sections of a ship in a turn. From their explanation, we summarize that:

- in the initial stage of a turn all ships are directionally unstable, which is indicated by a PP forward of the center of gravity;
- as the ship stabilizes in a turn:
  - ships trimmed by the stern have their PP shifted aft of the center of gravity so the ship becomes directionally stable;
  - and ships trimmed by the head have their PP remained ahead of the center of gravity and the ship continues to be directionally unstable.

Fonseca states that if the ship is trimmed by the bow, PP moves forward, and if trimmed by the stern, PP moves aft ([15], p647). He does not provide any explanation for that.

In disagreement with all presented above, Hensen writes: "*When a ship is down by the head ... the pivot point lies further aft than when on an even keel*" ([21], p44).

2.4 (b) Trim and Hull Form

According to MacElrevey and MacElrevey, *"This can only be determined with accuracy by the observation but a commonly accepted rule of thumb is that a ship with a large C_b (> 0.75) will tend to squat [combination of trim and sinkage] by the head ... ships with finer lines such as containerships with C_b < 0.7 have been found to trim by the stern"* ([32], p90-91).

According to Barrass, considering that ships are on even keel when stationary (i.e., trim is zero), as soon as each ship moves she will: trim by the head if her $C_b > 0.7$; trim by the stern if her $C_b < 0.7$; and usually not trim if her $C_b = 0.7$ ([2], p24).

Lewis does not specify if the ship will trim by the head or stern for given forms. Based on Tuck's theory [43], Lewis provides a "*nearly universal nondimensional curve for sinkage and trim which is almost independent of ship form*" ([30], p290).

2.5 STEERING MANOEUVRABILITY

Lewis writes that "*From the Esso Osaka trials* [8], *checking and counterturning ability were reduced as water depth decreased from deep to an intermediate depth [UKC/T = 0.5] and then increased at the shallower depth [UKC/T = 0.2]. This phenomenon is related to an apparent reversal in controls-fixed course stability…*[as shown in the spiral test results in Figure 2], *where stability first decreases but then increases as water depth becomes very shallow*" ([30], p281). Checking and counterturning ability are the capacity of a ship to steady on a straight course after a rate of turn is initiated. Here we assume that Lewis has strictly related these terms to directional stability, i.e., increased (reduced) checking and counterturning ability means increased (reduced) directional stability. The spiral test [10] identifies the directional stability characteristics of a vessel by associating the rudder angle with the dimensionless turning rate $r' = ROT \times L/V$. Note that the more unstable the ship, the greater r' with the rudder fixed at zero.

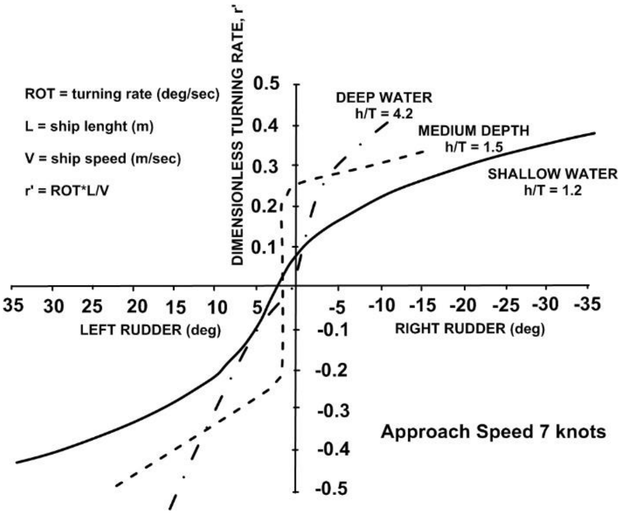

Figure 2. Smooth spiral test results of the 278,000-dwt Esso Osaka, showing dimensionless steady turning rate as a function of rudder angle, from 7 knots [30 & 8].

According to MacElrevey and MacElrevey, it is expected "*improved steering characteristics as the UKC decreases until, in shallow water, a directionally unstable ship becomes easier to steer and less unstable. This is true only if the ship does not squat so much forward that she goes by the head, in which case the stabilizing effects of the shallower water are negated by the change in trim*" ([32], p17). These authors relate steering with directional stability: "*Directional stability becomes more positive in shallow water (steering 'improves')*" ([32], p18-19). Note that "*a ship that tends to steady up when the rudder is put amidships has positive directional stability*" ([32], p18-19).

Hensen states that small UKC results in a decrease in rudder effectiveness ([21], p72 and p81). This could be related to an increase in course stability, since Hensen defines that "*a course stable ship needs relatively large rudder angles for course changing*" ([21], p.vi). However, he does not directly make such a relation.

According to Rowe, the ship rapidly loses rudder efficiency with the combination of two effects in a turn in shallow water. Firstly, the rudder force has to overcome a much larger lateral resistance and is therefore less efficient. Secondly, at the bow, because of the reduced UKC, water which would normally pass under the ship is now restricted and there is a build up of pressure, both ahead of the ship and on the port bow (for a starboard turn). This imbalance of pressure pushes the pivot point towards the stern and therefore reduces the lever arm of the rudder force ([38], p33).

In a very practical way, Fragoso and Cajaty relate in a single paragraph the known SWEs on ship's manoeuvrability ([16], p50). One of them is: small UKC worsens ship's steering.

According to Barrass, one of the indications that a ship has entered shallow water is: "*vessel becomes more sluggish to manoeuvre*" ([2], p23).

2.5 (a) Turning Diameter

There is a common knowledge that turning diameter increases considerably in shallow waters and this is associated with increased directional stability. MacElrevey and MacElrevey write that "*The ship's turning radius increases until, in shallow water* [$h/T \leq 1.2$] *the radius can be as much as double that experienced at sea*" ([32], p17). The same authors write that the diameter of turning circle in deep water is approximately three times ship's length (p18), so it can be assumed that turning diameter can be as much as six times ship's length in shallow water.

Lewis is more specific but does not contradict MacElrevey and MacElrevey. In summary, he provides the following rough indications ([30], p280-281): (i) in $h/T = 2.5$, 5 to 10% increase in turning diameter; (ii) $1.5 \leq h/T \leq 1.75$, 30% increase; and (iii) $h/T = 1.25$, 60 to 100% increase. Results indicated in (i) and (iii) come from the 278,000-dwt *Esso Osaka* full-scale trials [8], and correlate fairly well with (ii) from report trial data of a 213,000-dwt tanker [34]. A similar tendency was also indicated in the captive model test reported by Fujino for a *Mariner-Class* ship and an oil tanker ([17], [18]).

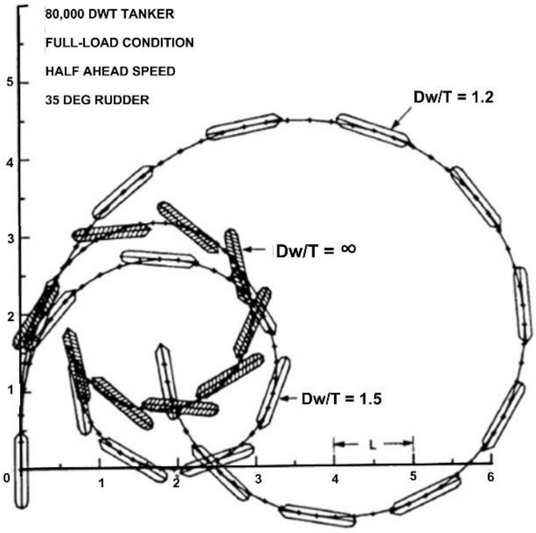

Figure 3. Effect of water depth on computed turning trajectory performance of a 80,000-dwt tanker, with full-load condition, half ahead speed and 35° rudder angle ([13], [30]). D_w is water depth, T ship draft and L ship length.

In deep water, Lewis states, "*the great majority of merchant ships have their turning diameters of from two to four ship lengths at full rudder angle*" ([30], p211). From (iii) in the previous paragraph, we can expect that in $h/T = 1.25$ the great majority of merchant ships have their turning diameter within an interval of from three to eight ship lengths at full rudder angle, i.e., from $2L \times (1 + 60\%) \cong$ 3L to $4L \times (1 + 100\%) = 8L$.

Lewis ([30], p280) also shows examples of turning trajectories obtained in computer model for ships with changes in water depth (Figures 3 and 4) [13]. In accordance with the aforementioned results, the figures show that turning diameter approximately doubles in shallow water.

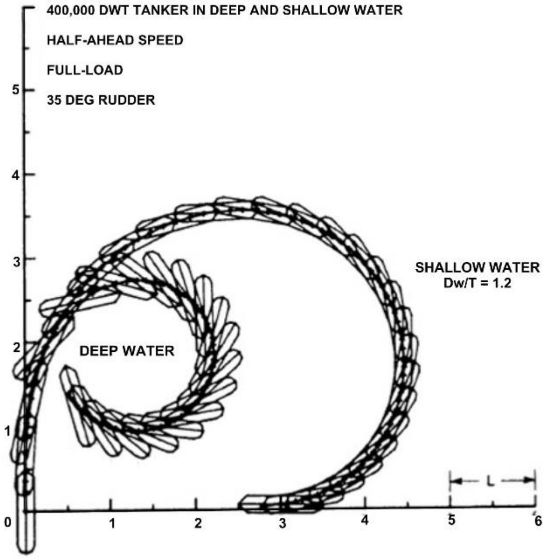

Figure 4. Effect of water depth on computed turning trajectory performance of a 400,000-dwt tanker, with full-load condition, half ahead speed and 35° rudder angle ([30], [13]). D_w is water depth, T ship draft and L ship length.

Hensen writes that "*When in shallow water, such as in most port areas, turning diameter increases considerably, due to the larger hydrodynamic forces opposing the turn*" ([21], p44) and "*Small UKC … results in a larger turning diameter…*" ([21], p72).

Likewise, Fragoso and Cajaty state that one of the effects of small UKC is an increase in turning diameter ([16], p50).

2.5 (b) Rate of Turn (ROT)

The ROT describes the rate of change of the ship's course per unit time, usually in degrees per minute [32] or degree per second. The navigation bridge normally has a ROT indicator to permit monitoring of the ship's performance during a turning manoeuver [41].

It was seen (section 2.5 (a) Turning Diameter) that the turning diameter may be as much as twice the diameter found for the same ship in deep water. However, "*ROT is essentially the same as for deep water*" ([32], p18). Note that "*since for practical purposes the rate of turn is about the same whether maneuvering in shallow or deep water, the larger area required to complete a turn is not immediately obvious to an observer"* ([32], p10).

According to Lewis, a reduction in ROT is associated with the increase in turning diameter. He summarizes experimental data on turning rate from the *Esso Osaka* trials [8] as follows ([30], p280-281). Taking angular velocity in deep water as 100%, the shallow water ROT are generally: (a) in $h/T = 2.5$, 90 to 95% (roughly 5 to 10% increase in turning diameter); (b) in $h/T = 1.25$, 50 to 60% (roughly 60 to 100% increase in turning diameter).

Hensen associates decrease in the initial ROT with increase in turning diameter, although he does not provide the magnitude of decrease/increase. "*The turning circle radius in shallow water is much larger than in deep water. The initial rate of turn is much smaller. Maneuvering a bend in really shallow water is therefore more difficult…"* ([21], p81).

Finally, according to Fragoso and Cajaty ([16], p50) and Fonseca ([15], p652), one of the SWE is a reduction in ROT.

It seems that there is a relationship between directional stability, rudder effectiveness, turning diameter and ROT. In general, the SWE is to increase directional stability, decrease rudder effectiveness, increase turning diameter and decrease ROT.

2.6 STOPPING

Considering a ship stopping from 6 knots to dead in the water, with engine half astern and rudder amidships, MacElrevey and MacElrevey then write: "*Despite the differences in ship behavior in shallow water as compared to deeper water, there is not much difference in the stopping distance required"* ([32], p13-14).

According to Lewis, "*Stopping distance in the Esso Osaka trials [f*rom 3.8 knots to dead in the water, with 45 rpm astern and rudder 35º (either left or right) [8] *was largely independent of water depth ... Inoue, et al* [26] *have also shown that stopping distance ... become smaller ... with a decrease in water depth*" ([30], p281). The adverb 'also' is literally written by Lewis in this passage, which is confusing, since Crane concludes that stopping distance does not alter, whereas Inoue concludes that stopping distance becomes smaller.

Conversely, Hensen states that "*Small UKC ... results in an increase in stopping distance"* ([21], p72). He further explains: *"in shallow water a ship drags a large amount of water along with her, increasing to as much as 40% of her displacement when UKC reduces to 20% of draft. When UKC is small, more astern power and consequently more tug power are needed to stop a ship than in deep water"* ([21], p81). This effect caused by the so-called 'added mass' is introduced by both Hensen and the Nautical Institute ([27], p7). They explain that when a ship comes to an abrupt stop in shallow confined waters, the following mass of water needs time to slow down and may push the ship ahead, turn her and/or push her sideways. Hensen then makes a second point: *"However, it is more likely to be the water flow in the channel following the ship and filling the gap behind which causes the delayed effect when a ship comes to an abrupt stop [instead of the added mass]"* ([21], p81).

Finally, Fragoso and Cajaty state that one known effect of small UKC is greater time to stop ([16], p50).

2.6 (a) Heading Deviation in Stopping with Engine Astern

It is a common sense that a single-screw ship with a righthand screw has a tendency to turn to starboard when the engine goes astern, as though the blades were bearing against the bottom. The rationale for this is out of the scope of this work, so readers are referred to Crenshaw ([9], chapter 2). Here we are concerned on the change in this so called 'twisting effect' as depth decreases.

Again, considering a ship from 6 knots to dead in the water, with engine half astern and rudder amidships, MacElrevey and MacElrevey write: "*The ship changes heading significantly, in some cases as much as 80 to 90 degrees in shallow water and somewhat less in deeper water"* ([32], p13). Also, they state that "*head falls off in the same direction [to starboard], but at a greater rate, as depth decreases"* ([32], p18).

Likewise, Lewis concludes that heading deviation increases as UKC decreases. Based on the *Esso Osaka* trials [8], he writes that "*Heading deviation in stopping increased from 18 to 50 and then to 88 degrees in going from deep to medium and then to shallow water"* ([32], p281).

Futhermore, Lewis comments on lateral deviations caused by SWE. Based on Inoue et al [26], he writes that "*lateral deviations become ... larger ... with a decrease in water depth"* ([30], p281). Lateral deviation should not be confused with heading deviation. The former is related to sway (i.e., the linear side-to-side motion) and is the lateral distance the ship has been deviated from its original path at the beginning of the stopping maneuver until she comes to a stop. The latter is related to yaw (i.e., the rotation of a vessel about its vertical axis) and is the angle the ship's heading has been deviated at the beginning of the stopping maneuver until she comes to a stop.

3. BANK EFFECTS

If, in addition to being in shallow water, the ship is close to a bank or shoal, there are other effects on her behavior. In summary, authors agree that the overall effect is a bodily attraction towards the bank (bank suction somewhere aft of amidships) and a yawing moment away (bank cushion at the bow), the former being stronger than the latter ([30], p282-287; [32], p20-22 and p47-48; [21], p80-81; [27], p2).

However, only the Nautical Institute adds that "*but the wave system of the ship will also be affected and the bow wave close to the bank will increase in size and form a pressure 'cushion'. This is enhanced if the bank is sloping, when the wave may locally 'go critical' and get even steeper. This 'cushion' will tend to push the bow away from the bank and, if the speed is high enough, the 'push' from the cushion can overcome most of the suction pulling the ship toward the bank so that it tends to be pushed bodily away*" ([27], p2). This is in accordance with Bernoulli's law (i.e., an increase in water speed results in a decrease in water pressure and vice versa), because with a sloping bank some sideways inflow of water is possible, causing a smaller reduction in pressure and so smaller bank suction than with a steep bank.

However, note that MacElrevey and MacElrevey write: "*Bank cushion is [...] often exaggerated in marine texts that describe hypothetical ships "smelling" shallow water and heading away from it, saving themselves from grounding. These tales are untrue and dangerously misleading ... It is more correct to say that 'a ship tends to head away' from shoal water – the effect is not as strong as often indicated...*" ([32], p21).

4. DISCUSSION

Here we raise the most controversial topics for discussion and investigation, i.e.:

- Most authors write that when a ship is down by the head, the PP lies further forward than when on an even keel, whereas only one [21] says exactly the contrary. This is an important point as it leads us to consider why a ship is directionally unstable. The conflicting views on this raise a valid question: was Hensen wrong?
- One states that small UKC results in a decrease in rudder effectiveness [21]. It would be helpful to know if this is related to increased directional stability (i.e., course stability, in accordance with Hensen's glossary of terms) in shallow water.
- Based on Lewis [30], it is reasonable to assume that, in shallow water, the turning diameter of a ship can be as much as eight ship lengths at full rudder angle (section 2.5.1). It would be helpful to know if in real life there is such a sluggish ship.
- All authors agree that turning diameter increases in shallow water. However, all but one agree that ROT decreases. The exception (MacElrevey and MacElrevey, 2004) states that in practice ROT does not alter significantly, although turning diameter increases. This is important to know, because if MacElrevey and MacElrevey are right, a ship making a turn in shallow water experiences the same ROT although turning diameter increases, so the larger area required to complete a turn is not immediately obvious.
- Some authors write that stopping distance (head reach) with engine astern does not alter significantly in shallow water ([32], [8]), while others write that it decreases [26] and yet some authors write it increases ([21], [16]). This is of great importance to avoid collisions and groundings in emergency situations, specially in restricted waters where heading deviation is limited.
- The Nautical Institute [27] is the only which adds that with high enough speed near a sloping bank, bank cushion can overcome bank suction and the ship will reverse her tendency from moving bodily sideways toward the bank to bodily sideways away from the bank. It would be helpful to know if this does happens in real life. And if it does, how fast is "high enough speed" approximately?

More discussion about these topics will be very helpful for mariners, specially the novice perplexed mariner who must learn new concepts, skills, laws, and practices. It is in the maritime industry's interest to encourage improvement and clarification on the theory of SWE and BE, since they need the most efficient training program for a maritime career. Confusing the novice mariner with several different concepts is definitely not efficient. Furthermore, computer simulator modellers will benefit by having more concise information to parameterize their ship model behavior in SRW.

Unfortunately, it is unlikely that experienced mariners will publish texts discussing and clarifying the questions raised in this work. They are very busy in their practical day-to-day profession. Future works in this subject will most likely come from scientists. Here the authors suggest methods that could help investigating what is fact and what is fiction:

- Most SWE and BE can be validated or corrected by more advanced maritime simulators and modelling techniques available today. But one needs to be aware that 'good' models reflect what we expect to happen and we are actually quite poorly informed in this area.
- Interview and questionnaires about SWE and BE to a large sample of experienced pilots would allow one to make statistical inference and determine the probability of something being fact or fiction.
- Exploring the effectiveness of computer modelling versus scale models in the use of hydrodynamic calculations to predict ship behavior.

- DGPS data of modern ships that navigate in SRW together with real-time bathymetry and tide height data can be used to track standard maneuvers in SRW, which can be further compared against already known standard maneuvers of such ship in deep water.

Most of the references in this paper have been used in recent syllabus for pilotage certification or licensing, e.g., in qualification exams for applicants to pilot licensing in Brazilian waters ([11], [12]). Also, these references have been used for validation of recent maritime simulators and modelling techniques, e.g., references [35], [30], [21], [2], and [37] are used in the model for the low-speed manoeuvring simulator at the Numerical Offshore Tank Laboratory of the University of São Paulo (TPN-USP) ([42], [28], [40]). The lack of references on SWE and BE in the last couple of years may suggest that the questions raised in this paper are being considered as solved, at least at a safe level. This level will probably be not safe enough in the future with more and more congested waterways, larger ships and greater drafts, which reinforces the point that more clarification on SWE and BE is necessary.

5. CONCLUSIONS

This work reviewed SWE and BE. This is mostly useful: to refresh the experienced mariner's theoretical background; as a guide to the novice mariner; and as a basis for computer simulator modellers to parameterize their ship model in SRW.

The individual effects when a ship enters SRW are described separately in the literature. Likewise, this paper reviews them separately. In real life, they are all combined together with varying intensities depending on situation. Quantifying precisely the resulting effect for every specific condition is far beyond the scope of any maritime study. However, understanding the individual factors and knowing that they interact with each other in reality, helps in everyday shiphandling as well as in ship simulator modelling.

This paper has also shown that there is not a common agreement about each individual factor. Several authors provide varying definitions, conclusions, opinions and rules of thumb. All that is contained here is based upon documented studies of recognized hydrodynamicists and actual experience of professional mariners. Determining who is right and who is wrong, what is truth and what is myth, is a proposal for future works.

Heretofore, this paper concludes that neither mariners nor ship simulator modelers can rely their theoretical knowledge about SWE and BE on a single publication. They would better study an extensive bibliography to know the main possible effects, be they fact or fiction.

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Figure 1 was adapted from Crenshaw [9]. Figures 2 to 4 were adapted from Lewis [30].

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