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Powerful ships - weak fish: the potential role of inland navigation as structuring factor for fish assemblages in waterways

C. Wolter & R. Arlinghaus
Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany

ABSTRACT: In restricted waterways moving vessels induce dynamic flow patterns acting along the shoreline: return currents of 0.1-1.1 m s^{-1}, slope supply waves and 0.05-0.45 m drawdown. Shoreline habitats are essential nurseries for juvenile fish. Inland navigation's potential structuring influence on fish assemblages emerges from the miss-match between the maximum swimming ability of newly hatched fish ranging between 0.05-0.13 m s^{-1}, and the necessity of fish to meet the physical thresholds mentioned above, which is only possible at a total length between 42-71 mm. It is argued that inland navigation induces displacements of fish which might increase fish mortality resulting in shipping as a structuring factor for fish assemblages.

1 INTRODUCTION

Global (climate) change is one of the main catchwords today. Over the past 50 years, human influences have been the dominant detectable effect on climate change significantly exceeding the natural variability. As pointed out by Karl & Trenberth (2003), there is still considerable uncertainty about the rates of change that can be expected, but there is no doubt that these changes will be increasingly manifested in changing extremes of temperature and precipitation, decreases in seasonal snow and ice extent, and sea level rise. The environmental concerns and hazards of global climate alterations have been broadly discussed (Ahas 1999, Stenseth et al. 2002, Walther et al. 2002, Parmesan & Yohe 2003), and climate change was estimated to be behind habitat loss the second major driver of expected biodiversity change for the year 2100 (Sala et al. 2000).

Today, humans alter global climate mainly by changing the atmospheric composition as a result of anthropogenic greenhouse gas emissions (Karl & Trenberth 2003), especially from increasing traffic and fossil fuel combustion (United Nations 1997, Colvile et al. 2001, European Commission 2001). Interestingly, among all transport modes, shipping goods over long distances in inland waters was judged by the European Union to constitute the by far most environmentally sound and sustainable transport mode, accounting for only around 7% of the CO_2 emission of the transport sector (European Commission 2001, Graßl et al. 2002). Thus, in view of the threats of global warming, inland navigation is currently promoted as the "most environmentally sound and sustainable" transport mode of the 21st century, and it is planned to improve commercial navigation by bigger and faster vessels as well as by an extension of waterways (Hüsig et al. 2000, European Commission 2001, Fletcher 2001, Sparks Companies 2002, ECE 2003).

However, this CO_2 emission-orientated transport policy overlooks possible operation related impacts of inland navigation on aquatic organisms, even without any further enlargements of waterways or river engineering works. Operation related impacts on fish assemblages were indicated by corresponding distribution patterns of juvenile fish within different existing waterways: the Rhine River (Staas & Neumann 1996), the British lowland river Great Ouse (Copp 1997) and a German lowland canal (Arlinghaus et al. 2002). Field observational studies showed a restriction of juveniles to artificial or natural side waters indicating their significantly limited abilities to use shore line habitats in the navigation channel. Thus, empirical evidence emerged, that navigation-induced disturbances limit habitat availability for juveniles and therefore fish recruitment, resulting in the formulation of a habitat bottleneck hypothesis by Wolter & Arlinghaus (2003).

This paper aims to summarize miss-matches between navigation-induced hydraulic forces and the size-dependent swimming ability of freshwater fish as a prerequisite to identify endangered life stages or species and to clarify the basic principles of operation-related navigation-induced fish mortality in further studies.

2 POWERFUL SHIPS

Vessel movement in a restricted waterway is associated with significant temporary changes of the aquatic environment. Their magnitude is determined by the cross section of the vessel in relation to the waterway cross section, the clearance between vessel's hull and bank, and the vessel speed, their duration by speed and vessel length.

Vessel's displacement creates a front wave resulting in increased hydraulic pressure at the bow. The conversion of pressure into kinetic energy results in increasing return velocities directly related to the height of the front wave. At the vessel's stern the water level will be equalized and the flow turns creating a stern wave and bank-directed slope supply currents, both directly related to the magnitude of return current. Corresponding to the vessel-induced displacement velocities the dynamic water level sinkage alongside the ship raises up. This drawdown begins near the bow and rebounds near the stern producing a single wave and causes dewatering of shallow areas along the shoreline during vessel passage (Bhowmik et al., 1992, 1995, Oebius 2000).

Typically, inland cargo vessels operate at subcritical vessel speeds (depth-related Froude number $F_d < 0.8$) (Hüsig et al. 2000). Given this, the strongest hydraulic forces generated by moving vessels act in the littoral, especially in the upper half of the bank slope (Fuehrer 1998). Field and laboratory studies of navigation effects on embankment structures reported return currents between 0.1-1.1 m s^{-1} depending on the clearance between vessel and bank. While at total barge length to channel width ratios of 0.4-0.8 the observed return current ranged between 0.1-0.5 m s^{-1} (Maynord & Martin 1997, Maynord 1999, Stockstill & Berger 2001) it increased to 0.7-1.1 m s^{-1} at ratios of about 1 and higher (Fuehrer 1998, Maynord 2000, Stockstill & Berger 2001, Arlinghaus et al. 2002, Brunke et al. 2002). Corresponding drawdowns have been measured between 0.05-0.45 m (Jähne et al. 1993, Maynord & Martin 1997, Fuehrer 1998, Maynord 1999, Heibaum & Soyeaux 2002), and transversal stern (wash) waves along the shore up to 0.7 m height (Heibaum & Soyeaux 2002). Thus, embankment structures of European waterways were designed for drawdowns of 0.6 m and bank-directed currents of 2 m s^{-1} (Fuehrer 1998). The main hydraulic impacts generated by a passing vessel last typically for about 60 s, in maximum up to 2-3 min, depending on vessel speed and length (Bhowmik et al., 1992, 1995, Fuehrer 1998, Oebius 2000, Heibaum & Soyeaux 2002). Especially in relatively narrow canals, each moving vessel inducing 0.8 m s^{-1} return current and 0.2 m drawdown on average for about one minute represents a significant disturbance for littoral aquatic communities affecting all shore line habitats in the navigation channel on its way.

3 WEAK FISH

For fish, swimming performance, i.e. speed in relation to the time until fatigue, strongly determines the availability of food and habitats as well as escape from predators, and, thus, simply the survival (Kolok 1999, Plaut 2001). According to the endurance time it has been classified into sustained, prolonged, critical and burst swimming maintained for >200 min, >60-200 min, ≤60 min and ≤20 s respectively (Webb 1975, Beamish 1978). The individual swimming performance depends on species, swimming mode, size, temperature, ontogenetic stage, photoperiod, oxygen tension, pH, salinity, and various pollutants and toxins, with total length as paramount trait (reviewed in Randall & Brauner 1991, Videler 1993, Hammer 1995, Wolter & Arlinghaus 2003).

While sustained and prolonged swimming speeds are particularly important for long distance migrations, an immediate response to predators or physical impacts depends on burst and to a lesser extent critical speeds. Therefore, burst and critical swimming performance were computed for freshwater fish of various ecological guilds as function of total length (Wolter & Arlinghaus 2003). A total of 168 experimental studies produced comparable results for altogether 75 fish species potentially inhabiting waterways in the temperate zone (listed in Wolter & Arlinghaus 2003). All findings in a temperature range between 10-20°C have been selected and standardized to total length and absolute speed (m s^{-1}). A power model fitted best and was used for regressions of total length and swimming speed.

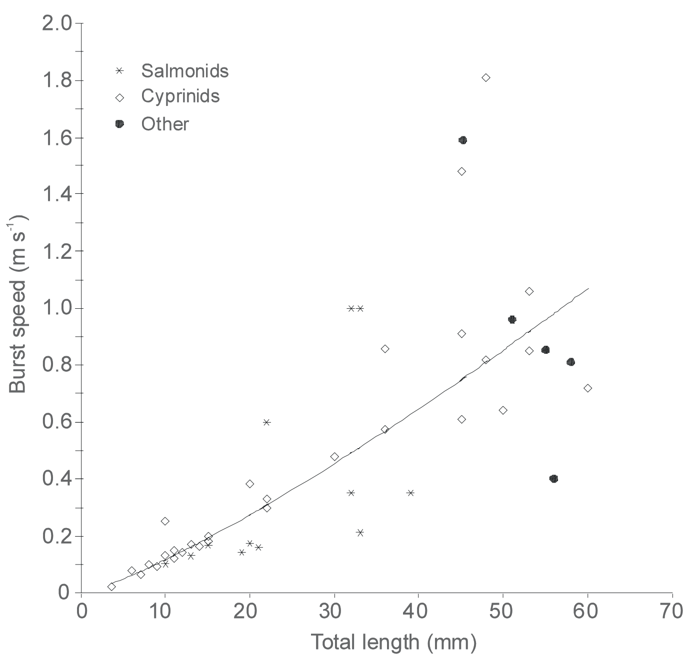

Figure 1 Burst swimming performance of pooled salmonids, cyprinids and other fish species up to 60 mm total length (TL) $U_{burst} = 0.0068 * TL^{1.24}$ (d.f.= 84; $R^2 = 0.83$; $p < 0.001$) (modified from Wolter & Arlinghaus 2003).

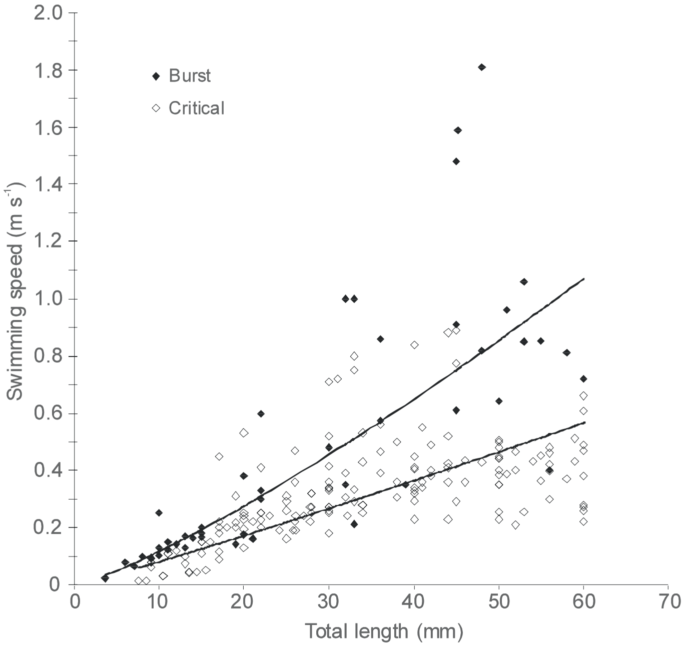

Figure 2 Comparison of burst and critical swimming performance (U_{crit}= 0.0067 * $TL^{1.09}$; d.f.= 155; R^2= 0.60; p< 0.001) of small fish up to 60 mm total length (TL).

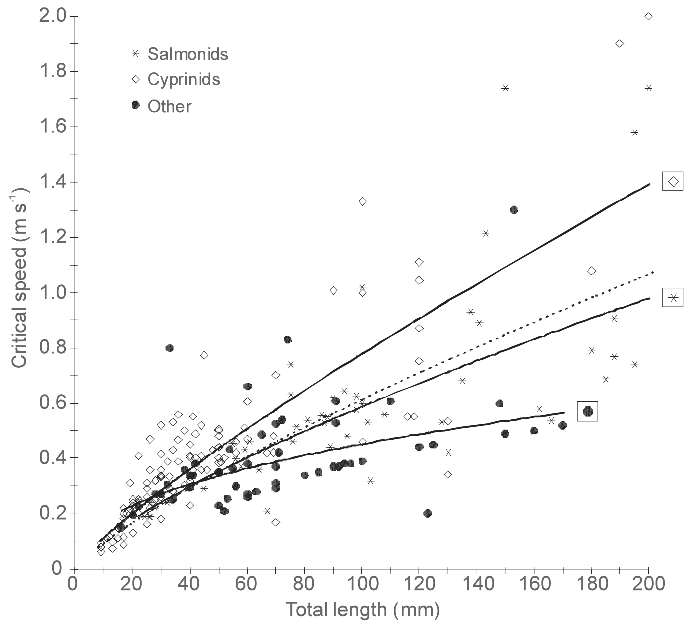

Figure 3 Critical swimming performance of all fish pooled up to 200 mm total length (TL) (dottet line, U_{crit}= 0.0158 * $TL^{0.80}$; d.f.= 239; R^2= 0.65; p< 0.001), salmonids (U_{crit}= 0.0198 * $TL^{0.74}$; d.f.= 49; R^2= 0.71; p< 0.001), cyprinids (U_{crit}= 0.0165 * $TL^{0.84}$; d.f.= 111; R^2= 0.76; p< 0.001) and other species (U_{crit}= 0.0654 * $TL^{0.42}$; d.f.= 50; R^2= 0.33; p< 0.001).

Wolter & Arlinghaus (2003) developed a regression model for the burst performance (U_{burst}) depending on total length (TL, mm) for all species and specimens up to 1 m total length. Accordingly, a 10 cm long fish would perform more than 1 m s^{-1} (R^2= 0.77, p< 0.001, see Wolter & Arlinghaus 2003 for graph).

Calculated for specimen up to 60 mm, the model revealed a significantly (F-test, p< 0.05) higher slope of the regression curve corresponding with the higher relative (in body length) swimming performance of small fish. Consequently, speeds of 1.0 m s^{-1} would already be maintained by a 56 mm long fish for 20 s (Fig. 1). However, similar fish would performs only 0.54 m s^{-1} in the critical mode (Fig. 2). This is especially relevant when physical forces last for more than 20 s as it commonly occurs when barges pass. No significant differences of swimming performance were detected between small-sized individuals of different taxonomic orders (Figs. 1, F-test, p= 0.142). Thus, the thresholds of swimming performance shown in Figures 1 & 2 apply for all fish smaller than 60 mm. This is important as one would intuitively think that rheophilic fish perform superiour to limnophilic fish.

With regard to navigation related disturbance, the burst performance tends to undervalue the impact, because the maximum swimming speed drops rapidly down with increasing duration, while the critical speed maintained up to one our is substantially lower than a speed which can be maintained for 3 min only (e.g. Videler 1993, Hammer 1995, Fig. 2). Thus, the critical performance tends to overestimate navigation-induced impacts. The resulting function between both graphs in Fig. 2 may be a useful approximation of the relevant exercise performance.

Unfortunately, only very few studies examined swimming speeds maintained for about 3-5 min until fatigue (Wolter & Arlinghaus 2003). Using a precautionary approach, no operation-related impacts of inland navigation have to be expected if the induced hydraulic forces meet the critical swimming performance of fish. Therefore critical swimming performance was calculated for fish up to 200 mm total length too, a length range where differences between fish orders became significant (Fig. 3). According to this approximation, a return current of 0.7 m s^{-1} on average will be maintained for one hour by 124 mm long salmonids, 87 mm cyprinids and 283 mm "others" including e.g. eel and sturgeons. However, these models should be used for fish larger than 60 mm only, while small fish were better characterized by the model given in Fig. 2 that was independent of fish orders.

4 CONCLUSIONS FOR POTENTIAL IMPACTS

Freshwater fish larvae hatch at total length of 2.7-9.5 mm and swim free between 6-15 mm. In this stage their burst performance ranges from 0.06-0.20 m s^{-1} and their critical one from 0.05-0.13 m s^{-1}, which is significantly below an average physical threshold of 0.7 m s^{-1} at the shore line. The navigation induced current velocity corresponds to the burst swimming speed of a 42 mm long fish respectively to the critical speed of a 71 mm fish. Because most of the freshwater fish juveniles depend essentially on the availability of shallow, low flowing shore line refugees for feeding and shelter, the discrepancy between navigation-induced currents and swimming performance becomes significant. Small juveniles fish are generally not able to withstand the hydraulic forces and to maintain their essential nurseries. Thus, fish could become washed out, stranded, injured or killed due to bank-directed slope supply waves and dewatering. Further fish mortality could result from navigation-induced displacements, which are expected to act in several ways: 1) the physical stress during each vessel passage can prevent fish from feeding or lead to elevated, "non-natural" energy cost, 2) juveniles may become displaced into less favorable habitats with poorer feeding conditions, 3) fish displaced into deeper water may be exposed to substantially higher predation, and 4) juveniles could be impacted by shear forces when displaced in the mid-channel section.

Further investigations have to be performed to verify the basic principles of vessel operation-related fish mortality presented in this paper. Field studies or controlled experiments are recommended to show the fish mortality suggested by the present analysis.

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