A Model of Navigation-Induced Currents in Inland Waterways and Implications for Juvenile Fish Displacement

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ABSTRACT / The likely extension of commercial inland navigation in the future could increase hazards directly impacting on the nurseries of freshwater fish, especially for smaller individuals with limited swimming abilities. One limitation of the evaluation of inland navigation on fish assemblages is the lack of suitable hydraulic models. This article presents a hydraulic model to assess the increase of navigation-induced physical forces due to higher vessel speed, length, and drought in a low-flowing waterway related to maximum swimming performance of fish to (1) foresee hazards of enhancement of inland navigation, (2) derive construction measures to minimize the hydraulic impact on small fish, and (3) improve fish recruitment in waterways.

The derived model computed current velocities induced by passing commercial vessels in inland waterways experimentally verified and parameterized in a German lowland waterway. Results were linked with a model of maximum fish swimming performance to elucidate consequences for freshwater fish populations. The absolute magnitude of navigation-induced current limits the availability of littoral habitats for small fish. Typical navigation-induced current velocities of 0.7–1 m/s in the straight reaches of waterways will be maintained by fish longer than 42 mm only. Smaller juveniles unable to withstand those currents could become washed out, injured, or displaced. In contrast, in small local bays, the navigation-induced current declined significantly. According to our model, in a 20-m extended bay, the return current drops below 0.11 m/s, corresponding to the maximum swimming speed of a 9-mm-long fish. Thus, enhancing shoreline development by connecting oxbows, tributaries, and especially by purpose-built bays limits the impact on fish recruitment without restricting navigation resulting in more precautionary and sustainable inland navigation.

The planet's freshwater habitats and aquatic life are being undermined at an unprecedented rate as freshwater resources and ecosystems around the globe are consumed and degraded. However, a strange type of "water blindness" pervades much of the discussion of conservation and sustainability, and fish diversity is losing out in the rising conflict between human consumptive usage and the maintenance of aquatic integrity (Stiassny 1999). In fresh waters, the projected decline in species diversity is about five times higher than it was estimated for terrestrial ecosystems (Pimm and others 1995; Harrison and Stiassny 1999), at a rate similar to the historical great extinctions (Malmqvist and Rundle 2002). Of 172 freshwater fish extinctions, 93% occurred during the last 50 years, indicating their deprivation as a serious and accelerating global trend (Harrison and Stiassny 1999).

Habitat loss is the greatest single threat to biodiversity in general and accounted for 94% of fish species affected in the United States (Wilcove and others 1998). In this respect, running waters play a crucial role, because these ecosystems belong to the most severely human-impacted habitats on Earth (Dynesius and Nilsson 1994; Malmqvist and Rundle 2002). Humans live disproportionately near waterways; over 60% of the world population within 1 km of surface water, primarily along rivers and the coastline (Tockner and Stanford 2002). Humanity, even today, extensively modifies riparian zones and uses the rivers (regulated to waterways) for sewage disposal and as transportation corridors (Sala and others 2000). It has been argued that human beings are simply an "invention" of water as a device for transporting itself from one place to another (Farber 1994), a phrase underlined by the dimen-

sions of the world's waterway network. The global navigation network has been enlarged from 8750 canal-km and 3125 river-km altered for navigation before 1900, to 63,125 canal-km and more than 500,000 km of regulated rivers in 1985 (Revenga and others 2000), and to 638,528 km of inland waterways today (CIA 2002), which is more than half of the 1,201,337-km-long global railway network (CIA 2002). As a consequence, at a global scale, the capacity of freshwater ecosystems to support fish diversity and to provide ecological services for society (Costanza and others 1997; Holmlund and Hammer 1999) is highly threatened. Dramatic population declines, fish assemblage changes, species extinctions, and decreasing diversity and productivity have been commonly observed due to habitat loss from river regulation for navigation purposes resulting from damming, dredging, straightening, and artificial shoreline embankments (e.g., Holland and Sylvester 1983; Nielsen and others 1986; Lelek and Buhse 1992; Zauner and Schiemer 1994; Wolter and Vilcinskas 1997; Wolter 2001a, Wolter 2001b; Arlinghaus and others 2002a). Moreover, increasing traffic and fossil-fuel combustion were identified as major sources of greenhouse gas emissions (United Nations 1997; Colvile and others 2001; European Commission 2001) and the related environmental concerns and hazards of climate change (Ahas 1999; Stenseth and others 2002; Walther and others 2002; Parmesan and Yohe 2003). In view of the threats of global warming, inland navigation is currently promoted as the "most environmentally sound" and "most sustainable" transport mode of the 21st century, because shipping goods over long distances in inland waters accounted for only around 7% of the CO_2 emission of the transport sector (Council of the European Union 2000; European Commission 2001; GraBl and others 2002). Thus, it is planned to improve commercial inland navigation by larger and faster vessels as well as by an extension of waterways (Bartell and Campbell 2000; Council of the European Union 2000; European Commission 2001; Fletcher 2001; Sparks Companies 2002; ECE 2003). However, this CO_2-emission-orientated transport policy overlooks the severe impacts of inland navigation on aquatic organisms, especially fish, originating, first, from the above-mentioned extension-related habitat losses and, second, from operation-related impacts caused by navigation-induced shear stress (Morgan and others 1976; Holland 1986; Killgore and others 2001), towboat propeller entrainment (Gutreuter and others 2003), drawdown (Bradford and others 1995; Bradford 1997; Adams and others 1999; Saltveit and others 2001), dewatering

(Holland 1987), and return currents (Wolter and Arlinghaus 2003). Generally, this contradicts the sustainable use of water resources as a guiding principle, which has to take into account ecological dimensions as well as socio-cultural, socio-economic, and institutional dimensions (Costanza and others 1998; Arlinghaus and others 2002b).

The operation of larger and faster commercial vessels to improve inland navigation will induce higher hydraulic forces during ship passages and, thus, increase the operation-related impacts on fish, even without any further river engineering work or enlargement of waterways. This further fish decline can be predicted according to the recently published navigation-induced habitat bottleneck hypothesis (NBH) considering restricted availability of essential nurseries for early fish life stages as the main limiting factor for fish recruitment in waterways (Wolter and Arlinghaus 2003). Commercial navigation traffic generates the maximum hydraulic forces close to the shore in the upper half of the bank slope (Mazumder and others 1993; ASCE Task Committee 1998), where most fish have their essential, low-flowing, littoral nursing areas (e.g., Copp 1992; Scheidegger and Bain 1995; Staas and Neumann 1996; Downes and others 1998; Lamouroux and others 1999; Gaudin 2001; Bischoff 2002). Fish have to withstand those currents to maintain their preferred habitats and, therefore, their swimming performance becomes highly ecologically relevant and was modeled as a prerequisite for this study (Wolter and Arlinghaus 2003). The bottleneck emerges when the navigation-induced currents exceed the maximum swimming performance of fish.

Habitat availability and, correspondingly, fish recruitment should be negatively correlated with increasing hydraulic forces due to larger and faster vessels; however, neither data nor applications are available to foresee these hazards. Therefore, our study aimed at deriving and presenting an analytical model for the prediction of navigation-induced increases of return currents along the shorelines of waterways as a prerequisite to link hydraulic and biological models to predict impacts of inland navigation on fish (Wolter and Arlinghaus 2003). In a second step, the modeling results of potential "navigation hazards" were coupled with the general model of maximum swimming performance of fish described in Wolter and Arlinghaus (2003)) to (1) show how inland navigation in its present form will lead to further fish decline if not properly addressed by ecosystem management practices and (2) derive management implications that sustain fishes without constraining navigation, suggesting ecologically more sustainable waterway construction modes.

Figure 1. Main physical effects induced by navigation in restricted waterways [according to Bhowmik and Mazumder (1990)]: propeller wash (U_p), bank-directed slope supply current (U_s), return current (U_r) opposite to the moving direction of the vessel (with the speed U_0), and dynamic water level sinkage or drawdown (δh).

Before detailing our results, a brief rationale behind our approach is presented next.

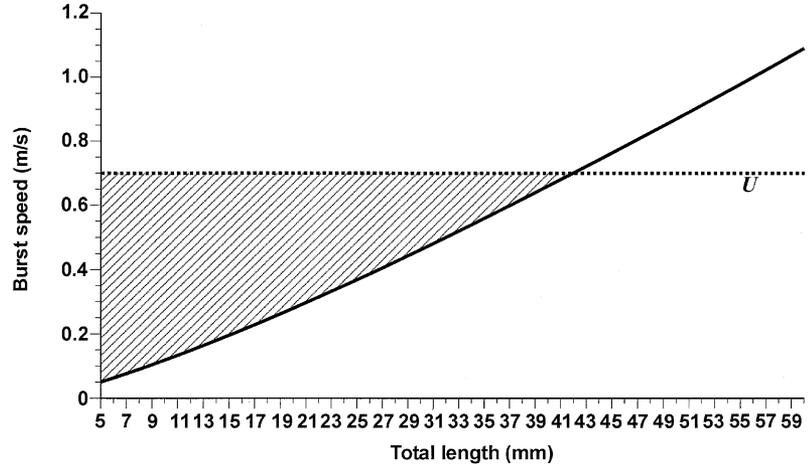## Hydraulic Forces Versus Physiological Performance of Fish

Inland waterways are generally restricted in depth and width. Vessel movement in restricted waters induces characteristic, dynamic flow patterns (e.g., Bhowmik and Mazumder 1990): The ship's displacement creates a front wave accompanied by return currents opposite to the movement direction and water-level fluctuations (drawdown) due to a pressure gradient acting along the vessel's hull. At the vessel's stern, the water level will be equalized, the flow is turning again, creating a stern wave and bank-directed slope supply currents opposite to the return flow (Figure 1). These forces last normally for less than 1 min. Their magnitude depends on displacement, the vessel cross section in relation to channel cross section, the clearance between the vessel's hull and bank, the speed and length of the vessel (e.g., Bhowmik and Mazumder 1990; Mazumder and others 1993; Hüsig and others 2000).

Hydrological studies of navigation effects on embankment structures revealed bank-directed current velocities of 0.7 to >1 m/s close to the shoreline (ASCE Task Committee 1998; Hüsig and others 2000; Maynord 2000; Rodriguez and others 2002; Arlinghaus and others 2002a). These current velocities constitute absolute performance thresholds, which have to be sustained by

individual fish to inhabit shoreline structures and to impede being displaced or washed out of the water or against artificial embankments such as rip rap or sheet pile wall. Fish swimming performance is characterized by the relation of swimming speed and endurance time and was classified by Brett (1964), Webb (1975), and Beamish (1978) into the following categories: burst (maintained for less than 20 s until fatigue), critical (60 min), prolonged (200 min), and sustained swimming (>200 min). Absolute burst or highest critical swimming speeds (fatigue after 1–2 min) are ecologically relevant with regard to the physical forces during vessel passage, because navigation-induced disturbances set absolute current velocity thresholds lasting for about 1 min (ASCE Task Committee 1998; Rodriguez and others 2002; Arlinghaus and others 2002a).

Fish swimming performance depends on a variety of biological and physiological factors, but one of the paramount traits is body length [reviewed by Wolter and Arlinghaus (2003)]. The absolute swimming speed increases with size (e.g., Wardle 1975; Beamish 1978; Videler 1993; Hammer 1995; Drucker 1996; Haefner and Bowen 2002). Wolter and Arlinghaus (2003) compiled a power function to assess absolute burst swimming speeds of small fish (Figure 2) using 82 studies reporting maximum swimming speeds obtained under similar experimental conditions for juveniles of a total of 44 freshwater fish species. Corresponding to this model, 15-mm-long fish perform a maximum speed of 0.20 m/s; in contrast, typical navigation-induced return currents of 0.7 m/s can be maintained by fish from 42 mm in total length upward (Figure 2). Unfortunately, larvae of common freshwater fish species hatch at total lengths of less than 10 mm and swim free at 6–15 mm (Koblickaya 1981; Pinder 2001); that is, their maximum swimming performance will not exceed 0.20 m/s. Thus, especially those small-size classes essentially depending on shoreline habitats, where they are exposed to navigation-generated forces, perform the lowest absolute swimming speed. According to these considerations, in waterways the availability of shoreline habitats is substantially restricted for small fish during ship passages.

The development of a model able to predict magnitudes of return velocities resulting from ship movement is the first step in assessing hydraulic impacts of navigation in inland waterways. The specific physical conditions of towboat movement in an artificial, low-flowing, narrow, and shallow navigation canal with steep banks enabled us to derive a simplified hydraulic model predicting near-bank velocities and to determine the model coefficients experimentally.

Figure 2. Modeled burst swimming speed of fish up to 60 mm total length (TL) according to Wolter and Arlinghaus (2003); $U_{burst} = 0.0068/TL^{1.24}$ in relation to the typically observed navigation-induced return flow velocities U (dotted line). The hatched area marks the resulting habitat bottleneck for fish.

Methods

Derivation of the Model for Return Velocity

A moving vessel expends energy to overcome the resistance of water. In doing so, the water gains kinetic energy from this interaction with the vessel which has to be transported and dissipated. This energy transfer can be described by the advection–diffusion equation

$$\frac{\partial k}{\partial t} + \mathbf{u}\,\frac{\partial k}{\partial \mathbf{x}} - \frac{\partial}{\partial \mathbf{x}}\,D\,\frac{\partial k}{\partial \mathbf{x}} = 0 \qquad (1)$$

where t is time, $\mathbf{x}$ is a vector of coordinates, $\mathbf{u}$ is a vector of the characteristic velocity of the kinetic energy transfer, D is a coefficient of kinetic energy diffusion, and k is the dimensionless kinetic energy defined as

$$k = \frac{U^2\,h}{U_2^0\,h_0}$$

with velocity U_0 and draught h_0 of the vessel, flow velocity U, and depth h of the waterway.

In restricted inland waterways, the width rarely exceeds the total length of commercial vessels or towboats, and the waterway depth is only slightly higher than the draught of loaded barges. Therefore, in restricted waterways, the vessel-induced disturbances occupy the whole water column and the maximum return velocity is observed in a cross section during the vessel passage. This allows the simplification of Eq. (1) to consider only a depth-averaged, steady-state energy transfer with a constant coefficient of diffusion. For the transverse direction, this can be written as

$$\frac{\partial^2 k}{\partial y^2} - a\,\frac{\partial k}{\partial y} = 0, \qquad (2)$$

$$a = \frac{u}{D}$$

where y is the cross-section distance measured from the centerline of the vessel's hull. The condition of steadiness is a much longer period of velocity field disturbance T compared to the relation of cross-section distance y and the typical flow patterns coefficient u:

$$T \gg \frac{y}{u} \qquad (3)$$

Under these conditions of steadiness, the kinetic energy k in Eq (2) can be substituted by the relation $\zeta = \frac{\partial k}{\partial y}$, which yields

$$\frac{\partial \zeta}{\partial y} - a\zeta = 0, \frac{d\zeta}{\zeta} - a\,dy = 0 \qquad (4)$$

After integration, Eq (4) converts to

$$\ln \zeta - ay + C = 0 \qquad (5)$$

where C is an integration constant. Applying an inverse transformation to Eq. (5) results in

$$\zeta + C_1 e^{-ay} = 0, \text{ or } dk + C_1 e^{-ay}\,dy = 0, C_1 = e^C \qquad (6)$$

When substituting the cross-section distance y with the distance relation $\eta = y/B$, with B as distance between the vessel and the bank of the waterway, Eq. (6) can be written as

$$dk + C_1 e^{-aB\eta}\,d\eta = 0 \qquad (7)$$

The integration of Eq. (7) yields

$$k = \frac{C_1}{aB} e^{-aB\eta} + C_2 \qquad (8)$$

where C_2 is an integration constant. Because C_2 is small, it can be neglected at long distances in still water with $k \approx 0$. Substituting the expression for kinetic energy in Eq. (8) yields

$$\frac{U^2}{U_2^0}\frac{h}{h_0} = \frac{C_1}{aB}e^{-aB\eta}, \frac{U}{U_0} = \sqrt{\frac{C_1}{aB}}\sqrt{\frac{h_0}{h}}e^{-(aB/2)^\eta}. \quad (9)$$

Finally, Eq. (9) can be rewritten as

$$\frac{U}{U_0} = \alpha\sqrt{\frac{h_0}{h}}e^{-\beta\frac{y}{B}}, \alpha = \sqrt{\frac{C_1}{aB}} = \sqrt{\frac{C_1 D}{uB}}, \; and \; \beta = \frac{aB}{2}$$

$$= \frac{uB}{2D} \quad (10)$$

Although the general relationships of the coefficients α and β and the flow parameters are known, their values have to be determined experimentally due to the lack of suitable mathematical descriptions for the diffusion coefficient D and an unknown C_1 value.

Equation (3) can be rewritten to account for the specific case $u = \sqrt{gh}$, which is a well-recognized depth-related velocity limit for shallow-water navigation (Sukhodolov and others 2004):

$$T = \gamma\frac{L}{U_0} \gg \frac{y}{\sqrt{gh}} \quad (11)$$

Here, L is the length of the vessel and U_0 is its speed. The coefficient β is expected to equal 1 and the practical threshold value to satisfy condition (11) is in an order of magnitude of one decimal higher. Thus, the period of the ship passage should be at least 10 times longer than the propagation of the transversal wave to the bank.

Equations (10) and (11) comprise a simple model allowing predictions of return velocities in a low-flowing waterway of known dimensions for a vessel with a certain draught and speed. The model requires the experimental determination of the coefficients α and β for specific waterway geometries (e.g., trapezoidal shape) and comparable types of vessel.

Model Calibration and Verification by Field Experiments

In the lowland waterway Oder-Havel-Kanal at waterway-km 63.5 at 52°85'N and 13°73'E, a calibration experiment has been completed in 2002 to determine the coefficients α, β, and β and to verify the model performance. The Oder-Havel-Kanal is an artificially constructed waterway, straightened, 34 m wide, 3 m deep, with artificially embanked shorelines (95% rip rap), steep bank slopes (mean 33%) and a negligible flow velocity (<0.05 m/s) [see Arlinghaus and others (2002a) for more site details]. During the passage of a total of 10 commercial tows (Table 1), flow velocities were measured close to the bottom (0.15 m) at three locations across a transect of the waterway by simultaneously working acoustic Doppler velocimeters (ADV,

SonTek, San Diego, California, USA). Each acoustic Doppler Velocimeter (ADV) record was visually inspected for abrupt discontinuities or spikes in the time series. Spikes were removed by a replacement strategy using linear interpolation according to Sukhodolov and others (1998). ADV measurements were processed using the software tool TFC Studio (Microsoft® Windows 9x, NT). The hydrographic survey of the waterway reach, positioning of ADV sensors, and the determination of coordinates for vessels (Figure 3) were performed with a total station Elta® R55 (Carl Zeiss Geodetic Systems, Germany; distance = 5 mm, range = 1300 m). Waterway depth (h) was measured directly. The cross-section distances between each vessel and the ADVs (y) were backcalculated. The draught (h_0) was recorded from the draught scale of the vessels, and the length (L), width and capacity were obtained from the official calibration registers. The speed of vessels was calculated from time consumed by each vessel to pass a defined reference reach.
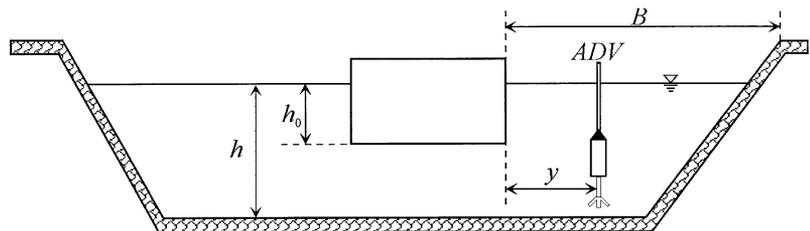
Results

Table 1 shows the results of the field measurements. Exponential regression analysis by the ordinary least squares method used to determine the coefficients of the model Eq. (10) and (11) yielded values of $\alpha = 2.04$, $\beta = 2.41$ ($R^2 = 0.92$, $P < 0.001$), and $\beta = 0.94$ ($R^2 = 0.95$, $P < 0.001$). The comparison of measured and modeled values of return velocity (Figure 4) and disturbance duration (Figure 5) exhibited a reasonable scatter. As derived from the model, the return current will raise by both increasing vessel speed or increasing draught. The return velocity decreases with increasing distance from the ship's hull, corresponding to an increasing $y : B$ ratio (Figure 4). For example, $y : B = 0.98$ represents a point 1 m distant from shore in a 100-m-wide waterway, when a vessel moves in the centerline ($B = 50$ m). The corresponding dimensionless value on the y axis is 0.19. Resolving the y axis equation for a typical pushing tow with $h_0 : h = 0.53$ (draught $h_0 = 1.6$ m, depth $h = 3$ m) moving with a speed of 2.1 m/s in the middle of a straightened, 100-m-wide waterway will obtain a return current of $U = 0.29$ m/s. Directly at the shore when $y : B = 1$, the same pushing tow generates a return flow velocity of 0.28 m/s. These currents drop down to 0.21 m/s and 0.20 m/s at $y : B = 0.98$ and $y : B = 1$, respectively, when the same pushing tow has half draught only corresponding to $h_0 : h = 0.27$.

In relation to the NBH model of the maximum swimming speed of fish, a 0.29-m/s return current corresponds to the burst swimming performance of a 20.5-mm-long fish, whereas newly hatched 6–15-mm-long

Table 1.   Observed data of ship movement and vessel-induced currents from field measurements in the canal Oder-Havel-Kanal at waterway-km 63.5 on 06/14/2001 and 06/12/2002
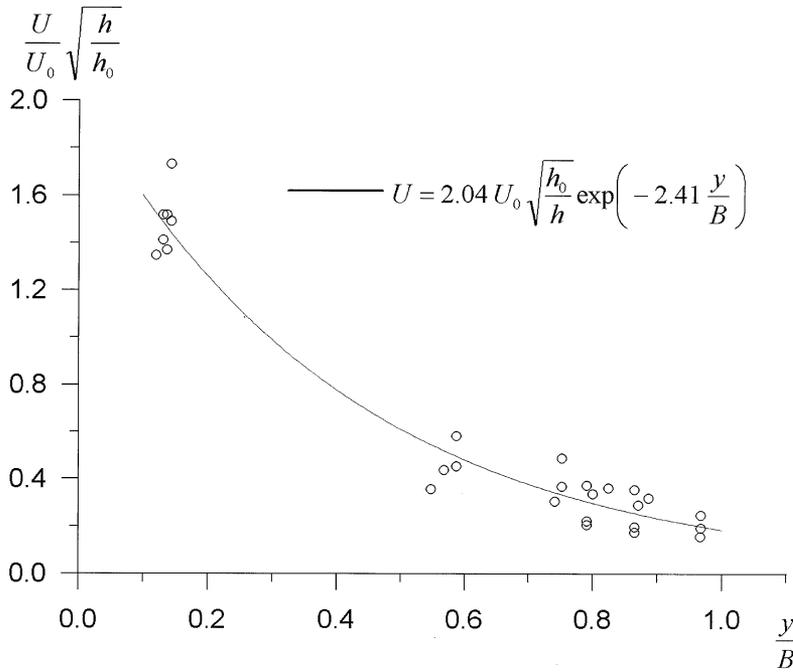
Type	Name	Capacity (tons)	Total length (L) (m)	Width (W) (m)	Draught (h_0) (m)	Distance to bank (B) (m)	Distance to ADV (y) (m)	Vessel speed (U_0) (m/s)	Return current (U) (m/s)
Inland cargo ship	BM 5282	510	56.71	7.58	1.3	24	22.25	1.813	0.23
							17.30		0.44
							13.50		0.54
							3.00		1.81
Pushing tow	ZPC 0593	957	112.99	8.91	1.5	23	22.25	1.942	0.34
							17.30		0.67
							13.50		0.80
							3.00		1.94
Pushing tow	DBR 3737	1295	123.16	8.2	1.6	22	21.25	1.754	0.20
							16.30		0.39
							12.50		0.56
							3.00		1.75
Inland cargo ship	Hildegard	751	67	8.3	1	21	18.15	2.175	0.22
							16.60		0.28
							11.50		0.45
							3.00		2.18
Inland cargo ship	BM 5270	466	56.6	7.58	1.3	22	19.15	1.942	0.37
							17.60		0.43
							3.00		1.94
Inland cargo ship	Transbode11	468	56.7	7.6	1.35	21	18.15	2.266	0.54
							16.60		0.57
							3.00		2.27
Inland cargo ship	Nike	630	65	6.3	1	21	18.15	2.092	0.24
							16.60		0.25
							3.00		2.10
Pushing tow	ZPB 8012	973	111.07	8.98	0.5	24	No data	2.266	No data
Inland cargo ship	Transbode 9	502.8	56.5	7.58	1.65	25	12.15	1.942	0.46
							20.60		0.52
							3.00		1.94
Pushing tow	ZP-0-5118	1339	111.57	8.2	1.1	22	No data	2.000	No data

Figure 3. Scheme of the cross-section-related measurements: draught (h_0), depth (h), distance between vessel hull and bank (B), and distance between vessel hull and ADV probe (y). ADV stands for the acoustic Doppler velocimeter and the rectangle represents the vessel hull.
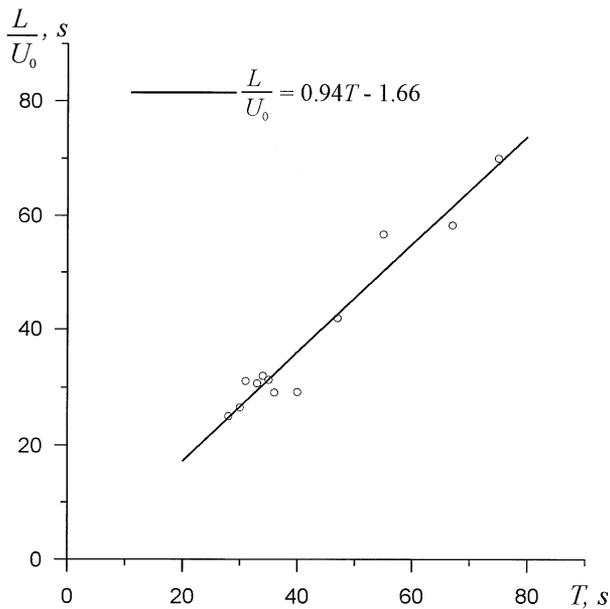

fish perform maximum swimming speeds of 0.06–0.20 m/s (Figure 2). According to the model presented here (Figure 4), the swimming ability of the very small juveniles will be met at $y : B$ ratios between 1.6 and 1.1 when using our above-mentioned fullydraught pushing tow ($h : h_0 = 0.53$, $U_0 = 2.1$ m/s) and keeping the initial hydraulic forces induced by the moving vessel constant. This might apply in small bays and at the mouth of oxbows or tributaries (which could also be purpose-build during construction works), when the channel cross section is punctually enlarged and $y > B$ (Figure 6). In a small bay of around 10 m corresponding to a ratio $y : B = 1.2$, the resulting return flow velocity 1 m distant from shore drops down to 0.17 m/s, and in a 20-m bay ($y : B = 1.4$), it drops down to 0.11 m/s, which is well within the range of maximum swimming performance of small fish of 14 mm and 9 mm in total length, respectively (Figure 2).

$$\frac{U}{U_0}\sqrt{\frac{h}{h_0}}$$

$$U = 2.04\,U_0\sqrt{\frac{h_0}{h}}\exp\left(-2.41\frac{y}{B}\right)$$

$$\frac{y}{B}$$

Figure 4. Model calibration: measured (circles) and predicted (line) return velocities U at any point between the vessel and the bank given in dimensionless coordinates using the known values of vessel speed (U_0), draught (h_0), and water depth (h).

$$\frac{L}{U_0}, s$$

$$\frac{L}{U_0} = 0.94T - 1.66$$

$$T, s$$

Figure 5. Duration of disturbance (T) measured from ADV records (circles) compared to predicted values using $T = \gamma L/U_0$ (line), where L is the vessel length and U_0 is the vessel speed.
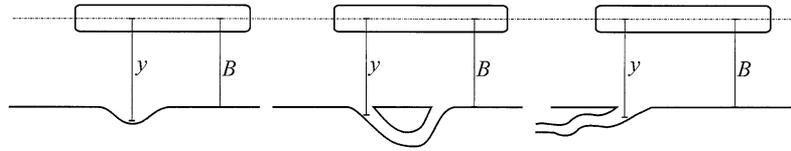
At constant (in waterways, often limited) vessel speed, the duration of the navigation-induced hydraulic impact will increase with increasing length of the vessel [Eq. (11) and Figure 5]. Thus, the improvement

of navigation by longer (larger) vessels will result in rising demands on the swimming performance of fish. Increasing the vessel speed will lower the duration but strengthen the hydraulic forces.

Summarizing, the model predicts increasing physical forces and further operation-related disturbances from the planned improvement of inland navigation by faster and larger vessels with higher draught. Increasing vessel speeds will directly result in higher return flow velocities, whereas the increased ship's capacity could increase the hydraulic forces in three ways: (1) increased duration when using longer ships only; (2) increased return velocity when using ships with higher draught; and (3) increased duration and return velocity when using longer ships with higher draught. Higher hydraulic forces can be maintained by longer fish only, because their absolute swimming performance is determined by body size and will therefore increase the habitat bottleneck for small fish (i.e., limit the availability of essential nurseries and impact the fish recruitment).

Discussion

The hydraulic model presented was derived to underpin the navigation-induced habitat bottleneck hypothesis by Wolter and Arlinghaus (2003) and was parameterized for a low-flowing, trapezoidal lowland waterway embanked with rip rap. Under such condi-

Figure 6. Schematic views on possibilities for the enhancement of shoreline development to provide refuges for fish recruitment with $y > B$ and resulting currents velocities within the range of maximum swimming performance of small fish.
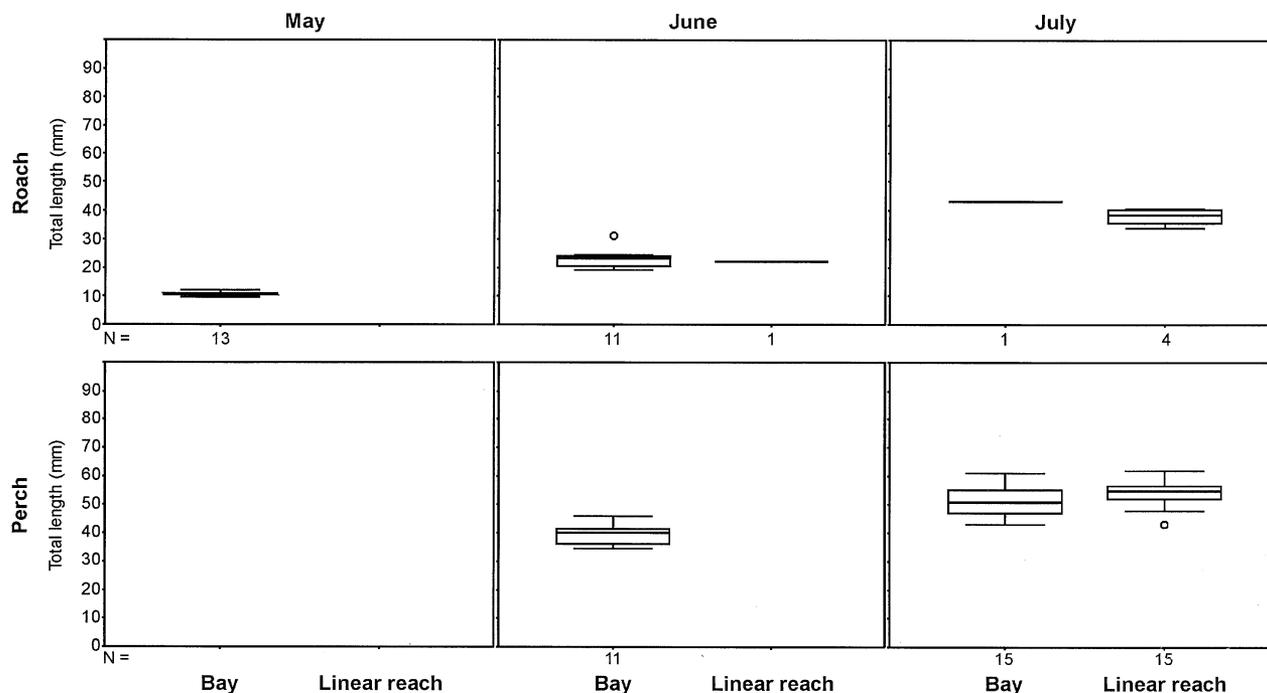
tions, the model predictions matched very well with field measurements of navigation-induced return currents in a linear canal stretch (0.7–0.8 m/s) as well as in a small bay (0.2 m/s; cf. Arlinghaus and others 2002a). Therefore, we are confident that the model can be extrapolated for other depth and width restricted waterways to analyze the hydraulic forces impacting on small fish and to allow predicting navigation impacts. However, the model was not verified for canals with significant natural flow velocities or for waterways where the average width substantially exceeds the length of commercial vessels. In such cases, possibly more complex models have to be derived, as our model might not fit well with field data.

In general, our model represents a first approach to parameterize a hydraulic model in the field and to link it with an ecologically relevant model of physiological performance to predict physical constraints for fish. Additional studies should be performed to implement physical conditions with higher natural flows as well as more complex, turbulent flow patterns into the model. Equation (7) has to be derived for kinetic energies $k > 0$ of the water, and the integration constant C_2 [Eq. (8)] needs to be determined experimentally. Furthermore, the coefficients α, β, and β have to be adjusted experimentally and the model parameterized accordingly for significant different habitat structures with substantially higher roughness such as dense, submerged or emerged macrophyte covers and large woody debris. Rough substrata, bumpiness close to the bottom, and macrophytes provide shelter, lower the flow velocity, and modify turbulence induced by moving ships (Sand-Jensen and Pedersen 1999).

Irrespective of the above-noted limitations, close to the shore in the nurseries of most freshwater fish, our model predictions revealed substantially higher flow velocities when using faster ships and higher ship capacity. Consequently, all planned modes to enhance inland navigation (Bartell and Campbell 2000; Council of the European Union 2000; Hüsig and others 2000; European Commission 2001; Graßl and others 2002; Sparks Companies 2002) will increase the bank-directed hydraulic forces along shoreline habitats and, thus, can considerably reduce fish recruitment in wa-

terways, because larvae and small juveniles are unable to increase their maximum swimming performance along with the temporary higher return currents. The NBH proposal represents a conservative assessment, in a way that only burst swimming performance of fish (up to 20 s) was considered, whereas the navigation-induced disturbances could last up to 2 min, which is within the substantially lower critical performance (Wolter and Arlinghaus 2003). This means that under field conditions even larger fish than discussed in this article might be negatively impacted, but further studies are needed to evaluate this. Furthermore, our model is an indirect approach to the assessment of shipping influences, which should serve to highlight the need to increase research efforts *in situ* and analyze the navigation impacts directly.

Empirical evidence for the theoretical implications presented here was derived from young-of-the-year fish (YOY) studies in a lowland waterway in Germany (Arlinghaus and others 2002a). Roach *Rutilus rutilus* and perch *Perca fluviatilis* are the most environmental tolerant, common, and widespread fish species in the waterways of the northern lowlands in Germany (Wolter and Vilcinskas 1997, Wolter and Vilcinskas 2000; Wolter 2001b). Neither species require specific spawning habitats or substrata or hydraulic conditions, and their spawning has been observed everywhere in the canal, at monotonous linear sites, as well as in bays or oxbows in March (perch) and April (roach) (Arlinghaus and others 2002a). However, the observed distribution of YOY roach and perch respectively corresponded well with the predicted limitations at linear sites resulting from swimming performance (Figure 7). Small YOY fish were restricted to bays and started spreading into the straightened canal stretches after reaching more than 40 mm total length (Figure 7) and 0.66 m/s burst swimming performance (Figure 2). The distribution of juvenile perch requires particular attention, because YOY perch shift their habitat to the pelagic immediately after hatching and shift back to the littoral zone at a size range of 11–30 mm, depending on the predation pressure in the pelagic (Byström and Garcia-Berthou 1999; Byström and others 2003). However, it is unlikely that all perch shifting back to the littoral from the pelagic

Figure 7. Length-dependent distribution (total length in millimeter per sample point) of YOY roach (top) and perch (bottom) at two sampling sites in the straight canal reach and in a small bay of the Oder-Havel-Kanal in 1999. Perch shifted immediately after hatch in March into the pelagic and started shifting back in June. At each site, 6 times 100 points were sampled using random point abundance sampling by electric fishing (details in Arlinghaus and others 2002a). *N* represents the number of points containing at least one YOY specimen of roach or perch. Altogether, 343 roach and 294 perch were caught.

were able to strike small bays in June as observed (Figure 7). Bays are rare in the Oder-Havel-Kanal, but YOY perch were exclusively found here and not in the straight reaches, presumably as a result of the higher hydraulic stress close to the shore in straight reaches as compared to bays. In July, when the median total length per sample point exceeded 50 mm, YOY perch also colonized straight reaches and were evenly distributed in both habitats (Figure 7). This behavioral pattern of YOY perch therefore serves as an additional indication for the NBH.

Obviously, with increasing body length; fish were able to colonize the straight reaches of waterways with less risk of being washed out or impeded by ship waves (Arlinghaus and others 2002a). Correspondingly, from the River Great Ouse (UK), Copp (1997) reported significantly higher numbers of YOY fish in off-channel water bodies and marinas (considered as artificial bays), suggesting the importance of those structures as refuge for small fish in regulated rivers to avoid navigation-induced return currents. Although the observed spatial and temporal distribution patterns of YOY could potentially result from habitat preferences, numerous field studies indicated commercial navigation as significant structuring factor for fish assemblages. Fish communities across many waterways changed compared to more natural rivers, because fish species with shoreline-bounded larvae declined dramatically (Lelek and Buhse 1992; Scheidegger and Bain 1995; Copp 1997; Wolter and Vilcinskas 1997; Lamouroux and others 1999; Gaudin 2001), whereas species with pelagic larvae remained nearly unimpacted (Wolter and Vilcinskas 1997). A most obvious explanation is that pelagic larvae seem less exposed to bank-directed return currents and, therefore, the probability of their navigation-induced mortality is comparatively lower than for littoral-bounded larvae. As a result, the relative abundance of fishes with pelagic larvae increased when navigation-induced physical forces substantially impacted on the shore-bounded nurseries, which is illustrated, for example, in the dominance relation of roach and perch. Although in more natural conditions the roach is, by far, more dominant than perch, in restricted waterways with heavy navigation the perch exceeds the relative abundances of the roach (Wolter and Vilcinskas 1997).

There is no doubt, however, that the basic cause–effect relationship of navigation-induced fish mortality according to the NBH has to be addressed in further

experiments. Juvenile fish could become stranded, injured, or killed due to dewatering and bank-directed slope supply waves (Holland 1987; Bradford and others 1995; Bradford 1997; Adams and others 1999; Saltveit and others 2001). Not all larvae once washed out necessarily die (Saltveit and others 2001), but could become seriously injured when washed back into the waterway again. However, this wash-wave-related mortality has not been quantified until now.

In contrast to direct wave impacts, the NBH assumes return currents as a limiting factor for fish recruitment (Wolter and Arlinghaus 2003). Although direct injuries or kills related to bank-directed currents will occur, more likely the majority of fish kills results from displacements. Navigation-induced fish displacements are expected to act in several ways: First, juveniles are not able to maintain their position at preferred feeding grounds and the physical stress during each vessel passage prevents them from feeding. Second, juveniles become displaced into less favorable habitats with poorer feeding conditions. Food deprivation is a serious hazard for fish, because it significantly reduces the glycogen stores in the white muscle; in contrast, burst swimming is largely supported by anaerobic glycolysis therein (reviewed in Kieffer 2000). Decreased glycogen levels ultimately limit the anaerobic capacity of fish; therefore, fasted fish display a lower burst performance compared to fed fish (Beamish and others 1989; Gregory and Wood 1999). Third, juveniles displaced into deeper water are exposed to substantially higher predation (e.g., Bischoff 2002; Byström and others 2003). Fourth, juveniles could be impacted by shear forces when displaced in the mid-channel section (Morgan and others 1976; Holland 1986; Killgore and others 2001; Gutreuter and others 2003). Further experiments and enclosure, fish-tagging, or mark-recapture studies have to be performed to verify the basic principles of operation-related navigation-induced fish mortality.

Notwithstanding, both the empirical evidence and the implications derived from our model presented here suggest taking navigation impacts serious. Some management implications can be derived from our analysis. Basically, to meet the aims of a sustainable transport mode, the extension of inland navigation has to be accompanied by habitat improvements for fish. Very simple but highly effective suggestions can be derived from Eq. (10), when the $y : B$ ratio exceeds 1. The modeled current velocities fitted well with the results of a series of numerical experiments conducted by Stockstill and Berger (2001) to assess the influence of forces within secondary channels and backwaters generated by vessels navigating the main channel of the Illinois waterway at Kampsville (USA). The average nav-

igation-induced current dropped by 0.1–0.3 m/s in the backwaters as compared to the currents induced in the main channel, but depending on backwater morphology, wave reflections and standing waves were possible (Stockstill and Berger 2001). In view of the fact that Stockstill and Berger (2001) performed their experiments in a more than 300-m-wide waterway, evidence emerged that our model could be valid for larger waterways too, corresponding with a higher ratio of channel width and vessel length. Using a one-dimensional unsteady flow model (UNET) and field observations in the Illinois waterway at Lagrange Pool, Maynord (1999) reported decreasing return currents in the backwaters from 0.4 to 0.2 m/s shortly after the mouth and further falling with increasing distance from mouth. In contrast, the drawdown increased in the backwater compared to its mouth at a ratio of 1.5–2 (Maynord 1999). However, because backwaters vary in shape, roughness, length, alignment, and connection to secondary waters, hydraulic impacts can vary substantially (Maynord 1999).

Conclusions

The model presented here can be used for depth- and width- restricted waterways with negligible low flow velocities to predict the forces and impacts on fish and to derive management implications with respect to a more sustainable transportation. To conclude, sustainable management of waterways requires minimizing the navigation impacts by enhancing shoreline development and shoreline structures, especially by (1) preserving existing bays and tributaries, (2) reconnecting adjacent water bodies such as oxbows or dammed tributaries, and (3) in particular creating additional (purpose built artificial) bays to reduce the navigation-induced water currents impacting on small fish. These measures are very easily to implement in waterway reconstruction and engineering work. They would provide benefits for fish without any substantial constraints for inland navigation. In contrast, in its present form, the promotion and extension of commercial navigation will substantially impact on the fish assemblages in waterways and cause a further decline of fish species diversity and fish production due to restricted recruitment.

Acknowledgments

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