USING ETHOHYDRAULICS TO FIND A SUITABLE SUBSTRATUM FOR FISH PASSES

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In principle, German standards to construct functional fish passes demand basically the installation of a raw-textured substratum to facilitate upstream migration of benthic invertebrates and inefficient small sized fish as well as juveniles. It is expected that fishes would find sufficient stagnant retreats there behind elements of roughness during resting periods.
Using ethohydraulic tests it was analyzed how different structured types of substratum meet the requirements of fishes. Therefore the bottom of a glazed model flume in a water research laboratory was arranged in sections with different types of roughness. Next, the behavior of small sized fish as well as juveniles of larger species was studied in combination with different types of arranged substratum respectively different types of roughness especially in regard to habitats and swimming behavior.
These tests bring home that zones behind elements of roughness are no areas of moderate flow velocity; on the contrary flow gets small scaled vortices and therefore such zones will be avoided by many specimen. To get a positive and supporting effect to upstream migration the substratum of fish passes has to fulfill certain properties: The level of a 30 cm thick substrate layer should be covered only by a small number of larger supporting stones which should not overtop the substrate layer for more than 5 to 15 cm. The distance between the supporting stones should be at least more than 50 cm.

1 INTRODUCTION

Obeying the specifications of relevant standards of fish passes in Germany, a 20 cm thick substrate layer of river typical rough substrate has to be built in erosion-proofed [1, 2]. A corresponding and continuous gap-system should facilitate migrations of benthic invertebrates. For juveniles and inefficient species of fish it is also thought that they use areas of low flow velocity behind elements of roughness, for example stones, during resting periods. Until now, there has been no comprehensive and consistent study whether these ideas will be in line with the natural requirements of fishes. Furthermore there are no studies in arrangement of elements of roughness especially in frequency and dimension.
To answer this practical issue, ethohydraulic tests questioned on substrate preferences of inefficient and small sized fish taking place in corporation with hydraulic engineers of the Institute of technology (KIT) at the university of Karlsruhe and were funded by Deutsche Bundesstiftung Umwelt. The focus of the study was the impact of different types of roughness on used migration corridors and the resting behavior of fishes.

2 METHODS

2.1 Probands

For behavioral observations within the context of ethohydraulic tests all in all 66 fish out of 11 species (table 1) were used. Probands were small sized fish and juveniles respectively preadult individuals of larger species with a total length between 7 and 26 cm.

Table 1. Number and total length of observed species of fish

species of fish		number [n]	total length [cm]
brown trout	*Salmo trutta f. fario*	7	16 - 22
bitterling	*Rhodeus amarus*	4	7 - 8
common bream	*Abramis brama*	10	17 - 26
European perch	*Perca fluviatilis*	6	17 - 20
gudgeon	*Gobio gobio*	8	12 - 13
white bream	*Blicca bjoerkna*	3	18 - 19
Northern pike	*Esox lucius*	1	25
roach	*Rutilus rutilus*	9	15 - 26
tench	*Tinca tinca*	9	12 - 25
Sibirian sturgeon	*Acipenser baeri*	7	11 - 26
bleak	*Alburnus alburnus*	2	13

2.2 Model flume design

The ethohydraulic tests taking place in a 30 m long and 1 m wide model flume (Figure 1) which was fitted with safety barriers at the entry and the outlet to prevent the escape of fish. One side of the model flume was glazed on a length of 15 m for behavioral observations as well as film and photographic documentation. Within these 15 m, the model flume was divided into three interruption-free sections of 5 m length with substratum of different types of roughness (Table 2). In between the coarse gravel as filling substrate with grain sizes of 20 mm to 60 mm, several supporting stones of different sizes and different distances were integrated. Behavioral observations taking place in the following set-ups, seen against the direction of flow:

1. type 1 - type 2 - type 3
2. type 3 - type 1 - type 3.

Comparing the individual behavior towards supporting stones with different sizes, a larger stone bar about 0.3 cm length and 0.5 cm was positioned in one part of the model flume.

The model flume was charged with a flow of 320 l/s up to 350 l/s for adjusting different flow velocities with a water depth about 0.6 m (Figure 2). Flow velocities near the bottom and within the water body were measured by using a current meter for three minutes at several points of the model flume, so minimal and maximal values can be documented. According these measurements the flow velocity at the bottom was between 0.15 m/s and 0.4 m/s and increased in parts of type 2 and 3 up to 0.6 m/s in middle respectively 0.9 m/s in the upper third part near to the water surface.
These point measurements were specified by three-dimensional flow velocity measurements using an acoustic-Doppler-velocimetry (ADV).

Figure 1. Model flume with substratum

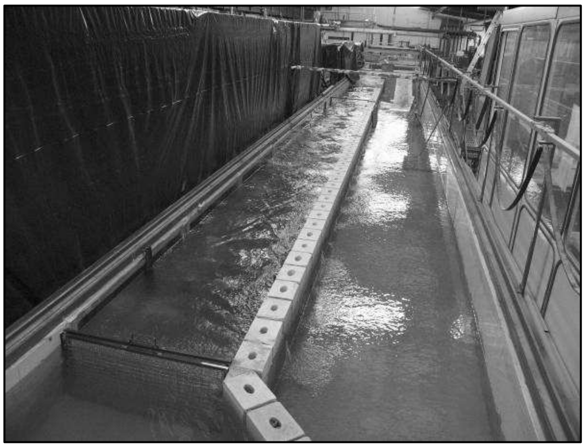
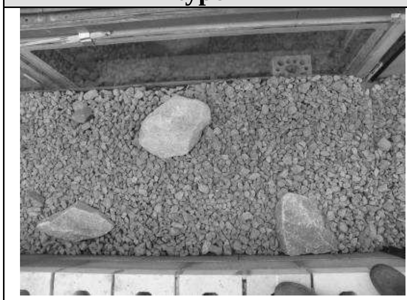


Figure 2. Model flume during a test

Table 2. Charakteristic of different types of roughness in the model flume

type 1	type 2	type 3
		
supporting stones: clear height: 0.08 - 0.16 m space: 0.40 - 1.00 m max density: 5/m²	supporting stones: clear height: 0.18 - 0.29 m space: 0.20 - 0.50 m max density: 7/m²	supporting stones: clear height: 0.11 - 0.40 m space: 0.10 - 0.25 m max density: 9/m²

2.3 Progress of the observation

The probands were divided into two equal groups. With the beginning of a test one group was taken into a starting-box in the downstream part of the model flume (Figure 3) for acclimatizing toward the flow velocity before starting the observation time after a while with opening the starting-box.

During a test the mean flow velocity of v_{min} = 0.1 m/s was increased successively by steps of 0.1 m/s up to v_{max} = 0.9 m/s. Mean observation time with low velocities < 0.4 m/s was about 30 minutes, whereas the mean observation time with flow velocities < 0.4 m/s lasted more than 2 hours. All behavioral observations were documented in “ad libitum” protocols [5] as well as photos and films (Figure 4). After the test the probands was taken carefully out of the model flume and into a provided tank, before the same test with the second group of fish was repeated.

During the tests of several hours the study of fish behavior was focused on the following aspects:

- How is the swimming behavior of fish in relation to different flow velocities and flow conditions within a different roughed flow path?
- Where are the fish located preferentially?

The focus of the comparative observations was the behavior of fish within the three different types of roughness. As relevant and meaningful noticed were only these behavioral reactions which were reproducible under same hydraulic conditions.

Figure 3. Group of fish in starting box

Figure 4. Darkened observation post (non flooded)

3 RESULTS OF THE ETHOHYDRAULIC TESTS

3.1 Swimming in current

On principle all specimen showed active and positive rheotactic behaviour at flow velocities > 0.2 m/s while they orientated with their heads against the current and swam upstream. As soon as the specimen interrupted their swimming against the flow direction, they moved to the bottom in order to stay in a preferred position with few slow fin movement. Especially clear was this behaviour at currents > 0.4 m/s, because the specimen more and more gave up their preferred passageway near the water surface and swam to the bottom (see 3.2.1).

3.1.1 Behaviour at currents $v_m < 0.4$ m/s

Nevertheless the juvenile tenchs (*Tinca tinca*) retreated already at moderate increased flow velocities active in the interstitial spaces, where they stayed until the end of the tests.
Smaller sized exemplars of the other species of fish moved close to the bottom and searched there for an upstream passageway between the supporting stones. In doing so they altered their swimming direction in the section with high density of the supporting stones (type 3) and moved from one side of the model flume to the other while they swam around the supporting stones. So they reached the end of the model flume not in straight way but after a longer and winding distance.

3.1.2 Behaviour at currents $v_m > 0.4$ m/s

At a rise of the current beyond $v_m > 0.4$ m/s the only few centimetres long bitterlings (*Rhodeus amarus*) and the juvenile Sibirian sturgeons (*Acipenser baeri*) reached their power limit and drifted with the current against the safety barrier at the end of the model flume. These exhausted probands were drew out of the model flume carefully and were not at further disposal for the rest of the test with higher flow velocities.
The more powerful and active swimming probands shown a different behaviour against higher flow velocities which manifests in the different horizontal and vertical use of the passageway: from $v_m > 0.4$ m/s they more and more gave up the closeness to the bottom and used the superior third of the body of water as passageway. Furthermore they looked for the practicable straight way to move upstream.

3.2 Reactions on elements of roughness

A stay of specimen in the leeside “shadow of the current” of supporting stones was never seen. Rather the probands stayed always downstream beside the elements of roughness, although there existed higher flow velocities, caused of the reduced flown through cross-section between the supporting stones.

3.2.1 Stay in sections with different roughness

While the specimen distributed at flow velocities < 0.4 m/s steady in each of the three types of roughness of the model flume, at higher flow velocities they consequently switched over to the section with the minimal density and clear height of supporting stones (type 1), which corresponded to the height of the body of the fishes.
From a middle flow velocity of 0.7 m/s no individuals stayed permanent in the sections of type 2 and type 3 (Figure 5). This reaction of the different types of roughness was reproducible in all tests. After the remodelling of the model flume in sections with the following sequence of type 3, type 1 and again type 3, the probands assembled equivalent in the middle section of the model flume with the lowest roughness (Figure 6).

Figure 5. Fish emptiness in section type 3 …

Figure 6. while all fish are assembled in section type 1

3.2.2 Behaviour to more compact elements of roughness

If fish draw head against the flow direction near to the leeside of a more compact supporting stone, they turned around there at 180° and stayed head downstream close to the bottom. Problematical was the short time of the turning, when the side of the body of fish was affected most by the current. Especially the less powerful species drifted away in this situation with stronger currents.
Similar to the behaviour against the single positioned elements of roughness the specimen left also the leeside of the compact supporting stone if the current gets stronger and switched over into the section with the type of lowest roughness (type 1).

4 DISCUSSION

All observed specimen belonged to juvenile stadiums and species with low efficiency, which showed positive rheotactic behaviour at a flow velocity > 0.2 m/s and a specific behaviour against elements of roughness. This principle behaviour is also the cause of the reaction of specimen on the leeside of compact elements of roughness: in this area of a local reversed current the fish also turned around their head and stayed against the main flow direction of the model flume.
Nevertheless the spectrum of species of fish for the ethohydraulic tests contained with bitterlings (*Rhodeus amarus*), juvenile Sibirian sturgeons (*Acipenser baeri*) and juvenile tenchs (*Tinca tinca*) species and age groups, which reached their performance limit with a flow velocity of 0.4 m/s. While this result corresponds with the stagnophile habits from the bitterling in waters with no or only weak currents, the cause of the lack of condition of the juvenile sturgeons is not clear. Experiences from America (Alex Haro, oral communication) suggest the suspicion, that it is caused by their origin from a fish-hatching, where they grown up in basins without current.
The observed swimming behaviour, that the fish give up their contact to bottom wile the current is increasing and switch to the free body of water, seems to be a fundamental strategy. Same results are known from the nocturnal downstream migration of eels (*Anguilla anguilla*), which prefer a migration corridor with a distinct distance to the bottom until to the water surface [6]. If possible the specimen avoids with this behaviour a collision with towered up obstacles when the conditions to manoeuvre are unfavourable or while a less of visibility. In the presented tests the only species which swam independent from the flow velocity on principle in the free body of water above the supporting stones was the pelagic bleak (*Alburnus alburnus*).

The consequent behaviour to avoid the leeside of the flown around elements of roughness can be explicabled with the existence of so called "Kàrmàn vortex streets", which develop at the edge of flown around bodies [7]. It is the matter of opposed vortices, which produce on both sides of the contours of an element of roughness a downstream spreading street of turbulent currents. The intensity of the vortices and with it the turbulence increases with the flow velocity and the density of the elements of roughness.

These different conditions of turbulence can be shown with a primitive „harp of filaments" (Figure 7 und 8) and measured with an acoustic-Doppler-velocimetry (ADV) (Figure 9). In this way it gets clear that fish have to spend a lot more power to keep their swimming course and not drifting away in the sections of the model flume with strong, sometimes overlayed and with interferences intensified turbulences. The observed vehemence of fin movement with the increased frequency indicates that the manoeuvre under such conditions requires to a high degree power and dexterity.

With this background at such hydraulic conditions it is clear that small sized and less efficient specimen avoid the turbulent flow conditions within the free body of water and searching as much as possible less and directional currents close to the bottom. Corresponding the fish avoid verifiable the turbulent flow conditions leeside an element of roughness. Consequently there exist no potential resting-places for fish leeside of the supporting stones. Otherwise small fish find more or less directional currents in the water layer onto the bottom if the supporting stones are not higher than their bodies, so they can persist there nearly unlimited with permanent swimming speed.

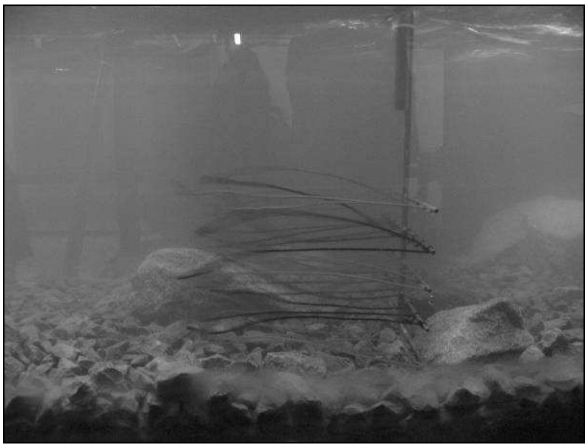


Figure 7. More or less directional current in type 1

Figure 8. Turbulent current in type 3

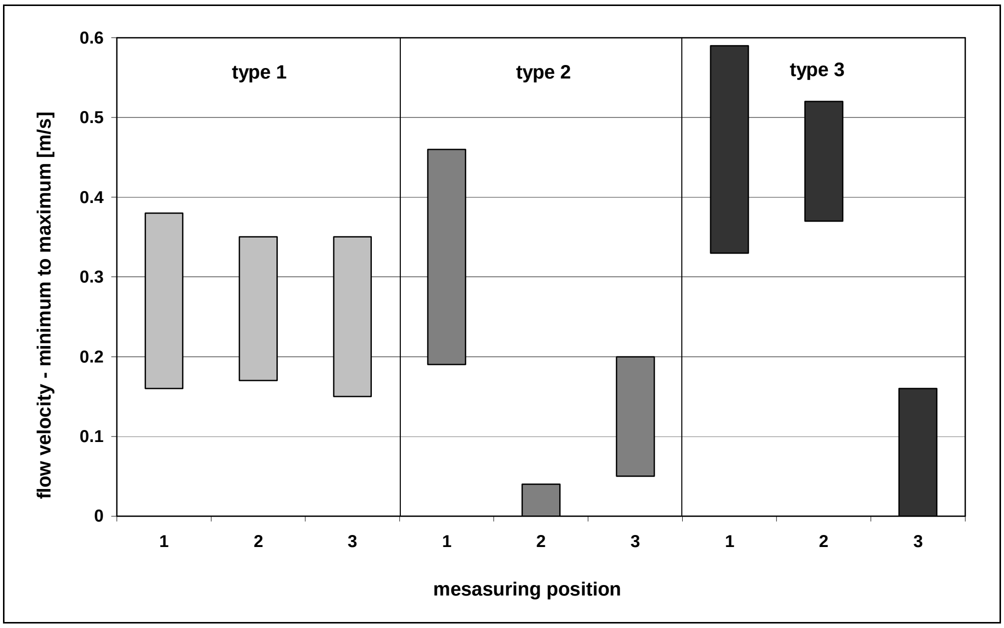


Figure 9. Development of turbulence within the three different types of roughness (v_m = 0.6 m/s)

5 CONCLUSION

The results of the ethohydraulic tests show the necessary, that only on anthropocentric considerations based recommendations for the arrangement of fish passes have to be adapted to the real demands of the fish. So for instance the tests refute the wide-spread interpretation that the fish use the leeside of towered up stones as resting-places. On the opposite the results showed the preference of directional flow conditions with less turbulence direct onto the bottom to stay for a longer time.
From these perceptions derive the generally accepted recommendations in practice for an arrangement of substratum in fish passes (Figure 10):

- The granular size of filling material should amount from 20 mm to about 90 mm and the thickness of the substratum should have minimal 0.2 m.
- Per square meter the filling material should be overtopped from maximal 4 or 5 supporting stones with clear heights of 0.05 m to 0.15 m.

These results of the ethohydraulic tests are already dropped into the revised state-of-the-art technology for construction and operation of fish-passes in Germany [8] and realized within Europe´s biggest fish-pass in Geesthacht at the river Elbe [9].

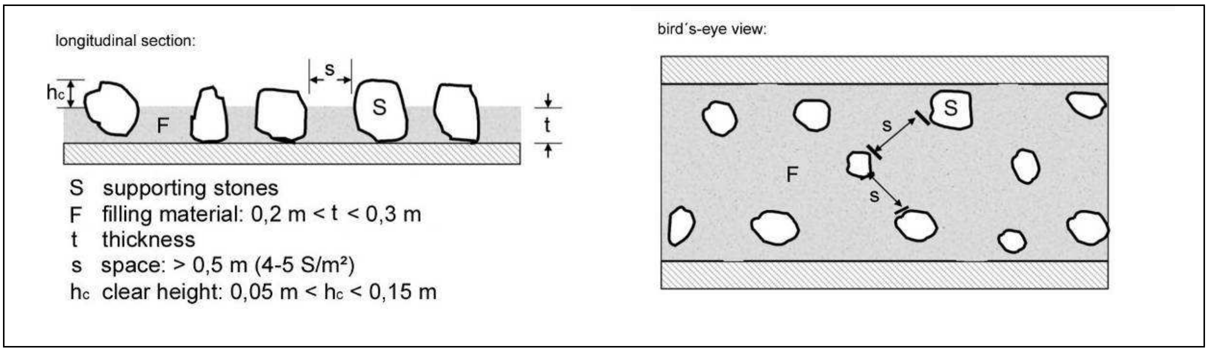


Figure 10. From the ethohydraulic tests derived recommendation for an arrangement of a fish-friendly rough bottom

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