Assessment of the Attraction Flow of a Fish Passage

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Abstract: *An attraction flow can be used to increase the effectivity of a fish passage. In 2004 a fish passage with a perpendicular attraction flow was built at Oudenaarde (Belgium) on the Upper Scheldt river. The design of the passage was based on scale model tests. In order to evaluate the hydraulic effectivity of the attraction flow, field measurements and new scale model tests are done. Velocities in the attraction flow and the fish passage entrance are assessed quantitatively and data of the scale model tests (1/15) are compared with the field measurements. The measured reach of the attraction flow seems to differ from results of the original scale model tests due to design modifications of the fish passage entrance. Results of the new scale model tests compare well with the data from the field measurements. Based on the results, a re-examination of the basic design rules for the attraction flow and fish pass entrances seems imperative.*

Keywords: *fish passage, perpendicular attraction flow, scale model, field measurements.*

1. INTRODUCTION

Both European and Belgian legislations aim at restoring and enhancing the ecological strength of the water systems (EC, 2000; BEU, 2009). Besides improvement of water quality and protection through legislation, restoration of free fish migration on the rivers and main waterways is an important and necessary goal. To solve the problem of the disruption of longitudinal habitat connectivity by man-made obstacles, fish passages are constructed.

The effectivity of fish passages is mainly determined by the passability and attractiveness. The passability requires limitations of the maximum velocity and minimal depth along the fish passage. The attractiveness is defined as to which extent the fish can find the entrance of the fish passage. To obtain maximum attractiveness, an attraction flow at the passage entrance is usually required.

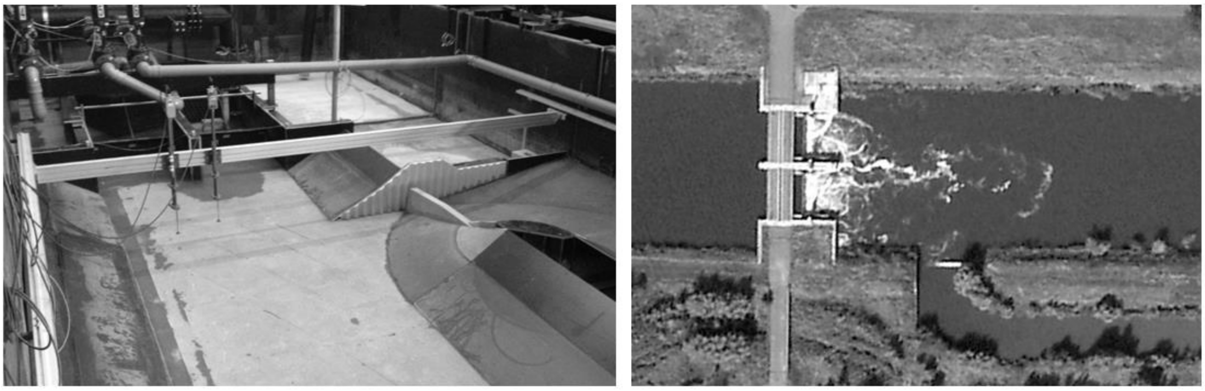

Figure 1 – Scale model and prototype of the fish pass entrance of Oudenaarde, Belgium

At the end of the nineties of the previous century, scale model tests of fish passages in the Upper Scheldt river (Belgium) were carried out at Flanders Hydraulics Research (FHR) (Meersschaut et al., 1998, Vereecken et al., 2004). Several types of passages were investigated and it was finally decided to select a so called close-to-nature type of fish pass, consisting of a bypass channel with increased roughness elements and a particular V-slot type entrance configuration to generate a distinct attraction flow. Results of this research led to design rules aiming at effective perpendicular attraction flows, which are currently used in Dutch and Flemish design manuals (Kroes and Monden, 2004). Among others, the fish passages in Asper and Oudenaarde on the Upper Scheldt river were designed and constructed, based upon the aforementioned generic scale model results.

Although the perpendicular attraction flow of fish passages was further investigated qualitatively in later scale model studies at FHR (Viaene et al., 2009, 2012), flow velocities in the entrance of the fish passage and in the attraction flow itself, were not yet investigated quantitatively. Also the hydraulic effectivity of the constructed passages was not yet assessed in the field.

Therefore the fish passage of Oudenaarde (see Figure 1) was examined in the context of a master thesis at Ghent University and in close cooperation with FHR (Ruys, 2014). Field measurements as well as scale model tests were performed. The research has a dual purpose. At first the velocities in the attraction flow and the extent of the attraction flow are assessed quantitatively. Secondly the research gives a unique opportunity to compare the results of scale model tests with field measurements.

2. METHODS & MATERIALS

Field measurements

The research started with field measurements on March 16, 2014. Figure 2 shows a plan view of the site and the location of the different measurements. During a measurement period of two hours, the discharge on both the river and the fish pass were measured using two ADCP's (Acoustic Doppler Current Profilers). Simultaneously, the attraction flow was investigated making use of four drifters equipped with GPS-signals loggers to measure the flow trajectories and flow velocities. Each of the drifters was attached to a pair of orthogonal submerged plates hanging at a different depth below the water surface, in order to capture variations in velocity over the water depth. During the same two hours period, several vertical velocity profiles were measured in the fish pass entrance using a propeller-type velocimeter.

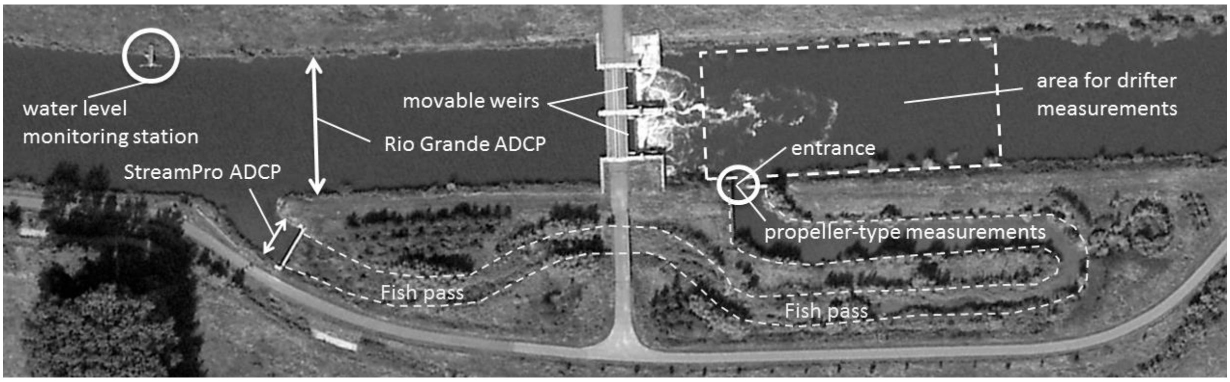

Figure 2 Location and type of field measurements

For the discharge measurements, each ADCP was continually towed in a transect (materialized by a rope extending from bank to bank). The measurement of the river discharge upstream of the weirs was carried out with a Rio Grande ADCP, whereas the discharge over the fish pass was measured on the upstream side of the fish pass with a StreamPro ADCP. At the beginning of the measurements, the weirs where lowered in order to simulate a relative large discharge on the river. During the measurements, the weirs where lifted again so that the discharge over the weirs decreased to almost the same value as the discharge over the fish pass.

The water levels up- and downstream of the weirs are continually monitored (with a one minute time interval) at permanent measurement stations (of which Figure 2 indicates the location of the upstream station). Besides the water levels, this station also registers the height and position of both movable weirs. These measurements are used for the automatic operation of the weirs and can be acquired from the ABBA-database of the Flemish Government. Although no direct discharge measurements are carried out at the (upstream) measurement station, weir discharges are determined indirectly by using a calibrated discharge formula. These calculated weir discharges are also stored in the ABBA-database and can be compared with the measurement results of the Rio Grande ADCP during the two hours of measurements.

Four drifters were used for the measurements of the attraction flow at 0.5, 1.5, 2.5 and 3.25 meters below the water surface, respectively. The average water level during the measurements was +8.50 mTAW (TAW is the datum level in use in Belgium) and the average bottom level was at +4.75 mTAW, hence the average water depth in the area where the drifter measurements take place is about 3.75 m. The four drifters were consecutively released in the water just downstream of the fish pass entrance. The GPS-location was logged every three seconds while the drifter followed the flow. About 100 meters downstream of the entrance the drifters were recovered by boat and taken back to the fish pass entrance for another measurement. This procedure was repeated ten times during the two hours period of ADCP measurements.

An Ott propeller-type velocimeter was used to measure velocities in the middle of the V-slot type fish pass entrance at six heights. The device was lowered in the water by means of a cable. To improve the verticality of the cable and the device, a heavy weight was attached below the device. Point measurements were done at 0.10, 0.55, 1.35, 2.15, 2.95 and 3.60 meters above the bed, respectively. The bed level at the fish pass entrance is situated at +4.75 mTAW. For each measurement point the number of revolutions of the propeller was measured during 70 seconds, and was converted to flow velocities based on the calibration curve of the device. It took about 10 minutes to measure one vertical profile. As with the drifters, the measurements with the Ott-propeller were repeated during the two hours period of ADCP measurements.

Scale model

After the field measurements, a physical model of the fish pass, the weirs and the downstream part of the main stream was built, adopting Froude scaling at a scale of 1/15 (see Figure 3). This scale was the maximal allowable scale to both fit into the testing tank and still obtain reasonably high Reynolds numbers (Re_{-scale}>1,7*10^3 and Re_{-field} > 9.8*10^4).

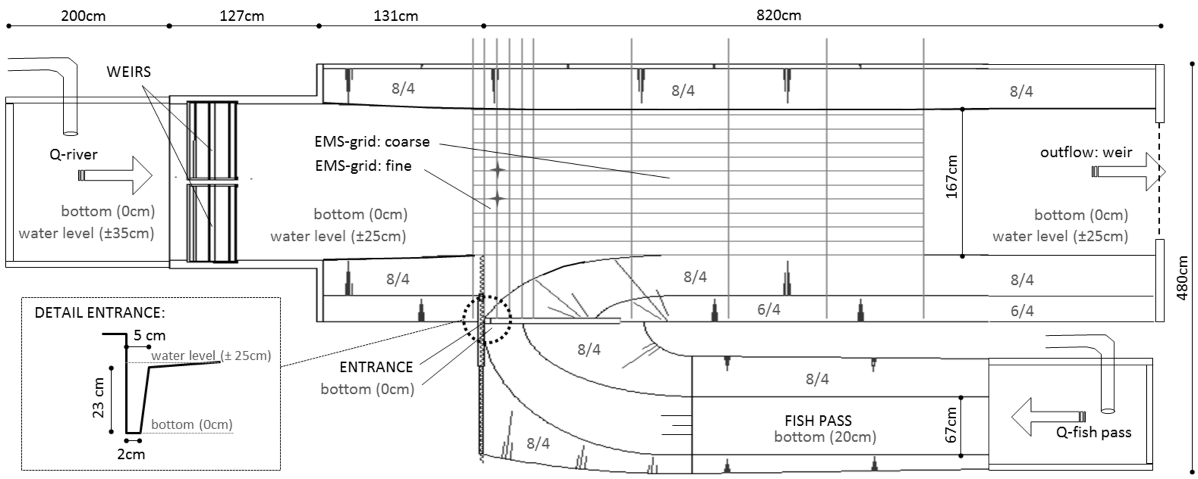

Figure 3 Plan view of scale model (scale factor 1/15) and indication of EMS-measurement grid

Based on the data from the field measurements, three characteristic scenarios were deduced: the design situation as specified in the original scale model study of 1997 (scenario 1) and two normative situations as observed during the present field measurements, i.e. one normative situation with a relatively high weir discharge (scenario 3) and one with a low weir discharge (scenario 2). The corresponding time intervals within the two hours of field measurements are shown in Figure 4. Each of the scenarios was simulated in the scale model as a stationary flow condition, with given discharges and up- and downstream water levels. Table 1 shows the specifications for each of the scenarios in both the prototype (P) and the scale model (M).

For each of the three scenarios, the attraction flow was investigated in the scale model by means of two EMS-devices (Electromagnetic velocimeters). The measurement locations were defined by means of a grid, shown in Figure 3. At each grid point, flow velocities were measured at three different positions above the bed, 33, 67, 135 mm (model scale), respectively. In the direction normal to the river axis, the spacing of the grid points is 16 cm. Along the river axis, (x-direction) a fine grid spacing (20 cm) is used near the fish pass entrance whereas the spacing is coarser (80 cm) further downstream. In each measurement point, the EMS collects a time series during 90 seconds with a measurement frequency of 2 Hz.

Table 1 Specification of the 3 scenarios simulated in the scale model (scale factor 1/15). P refers to the prototype whereas M refers to the scale model.

	Units		Scenario 1		Scenario 2		Scenario 3	
	P	M	P	M	P	M	P	M
Discharge weirs (river)	m^3/s	l/s	20	22.9	3.6	4.1	31	34.4
Discharge fish pass	m^3/s	l/s	2.5	2.9	2.6	3.0	2.5	2.9
Water depth upstream	m	cm	5.0	33	5.3	35	5.3	35
Water depth downstream	m	cm	3.5	23	3.70	25	3.71	25

The (Eulerian type) flow velocities acquired in the three abovementioned scale model scenarios can be compared with the (Lagrangian type) drifter data acquired during the field test. To further visualize the attraction flow in the scale model, potassium permanganate ($KMnO_4$) is used. Together with the EMS measurements these data can be used to assess the reach of the attraction flow.

As a relative small scale (1/15) had to be used, it was not possible to measure the velocities in the entrance, since the opening (2-5 cm) of the V-slot type in the model was too narrow for the available measurement devices.

3. RESULTS AND DISCUSSION

Weir discharge and up- and downstream water levels

Figure 4 shows the results of the discharge and water level measurements. The discharge measurements with the ADCP Rio Grande (Q-riv_adcp) were carried out from 10:10h to 12:10h. Since the water levels at the monitoring station are constantly being measured, these results are indicated in a broader time span (from 09:00h to 13:00h) on Figure 4.

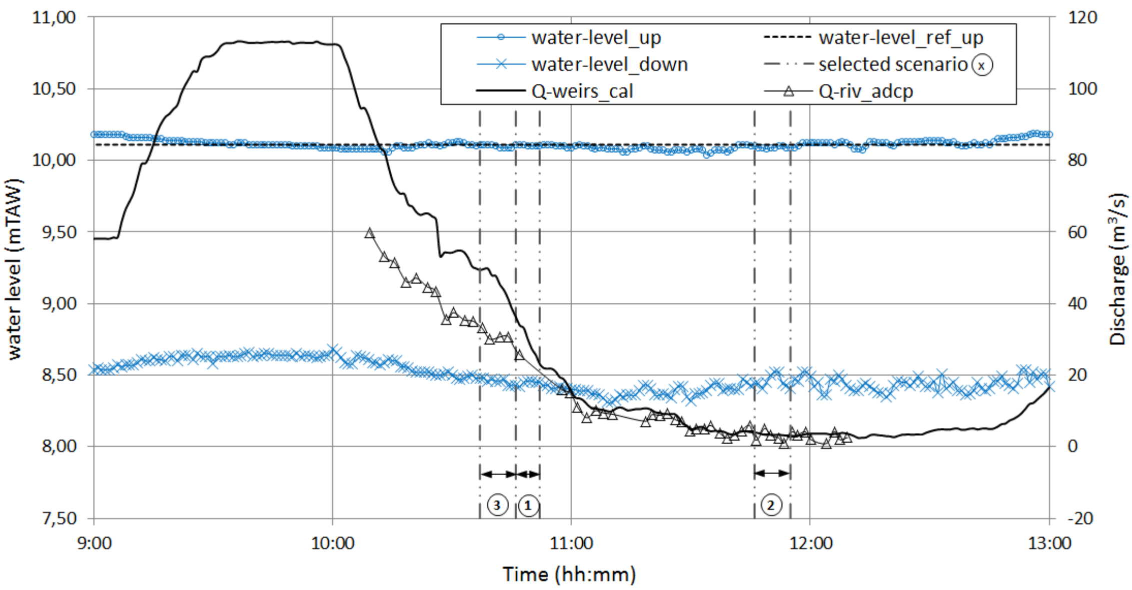

Figure 4 Results of the river discharge and water level measurements

Prior to the ADCP measurement period, the weirs were lowered to reach a high river discharge at the onset of the ADCP measurements. In the first part of the measurement period, i.e. between 10:00h and 11:00h, the weirs are gradually lifted again causing the weir discharge to reduce from about 60 m^3/s to 20 m^3/s. This procedure is continued (though at a smaller rate) in the second hour of the measurement period, resulting in a reduction of the discharge over the weirs from 20 to about 3 m^3/s. In Figure 4 can be clearly seen that the calculated weir discharge (i.e. based on a calibrated discharge formula) is predicting an overestimate, in case the discharge exceeds a value of about 20 m^3/s.

As can be expected, the effect of changes in the weir discharge is visible in both up- and downstream levels, though the effect is somewhat larger in case of the downstream water level. With the increase of the discharge, the upstream water level diminishes and the downstream level increases, and vice versa.

Within the measured period three short intervals are chosen which represent the stationary flow conditions of the three scenarios that are tested in the scale model (see Table 1). For each of these scenarios the drifter results are compared with the velocity measurements in the scale model.

Discharge over the fish pass

As the roughness of the (close-to-nature type) fish pass does not change during the measurements, the discharge over the fish pass is determined by the upstream water level, as can be seen in Figure 5. Overall a good correlation between the latter two quantities can be observed. During some short time intervals (e.g. around 10:55h), however, the correlation shows anomalies, the reason of which is not clear.

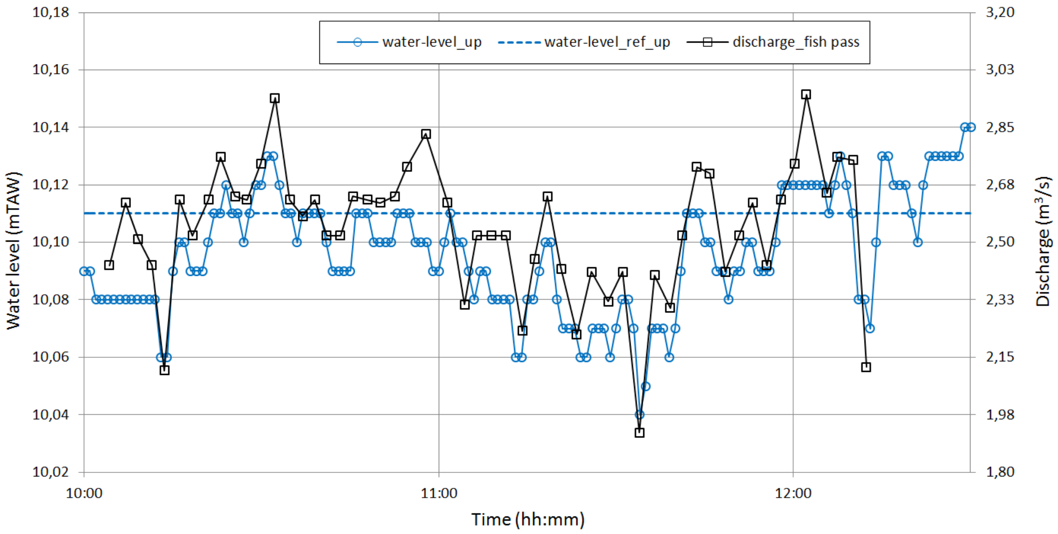

Figure 5 Comparison of the fish pass discharge and the upstream water level

With an average discharge of 2.51 m^3/s and amplitude of about 0.5 m^3/s the strength of the discharge relates quite well to the design criterion of 2.5 m^3/s (Meersschaut et al., 1998). From this, it can be concluded that the required roughness in the fish pass, as calculated in the design phase, is realized.

Velocities in the fish pass entrance

Figure 6 shows the results for 12 vertical profiles of velocities measured in the fish pass entrance using the Ott-propeller device. Also an average profile is shown based on the measured values of the profiles P4 to P12. The first three profiles were not taken into account for determining the average profile because they differ in shape and strength from the other profiles. Changes in fish pass discharge could influence the velocities in the entrance. But in this case the discharges during the measurements of profile P1 to P3 were not so low that it could explain the observed differences.

On the other hand, a relatively high downstream water level is seen during this period (see Figure 4). Because of the shape of the entrance (see detail in Figure 3), the wetted area of the cross section increases fast at high downstream water levels. Given a relatively constant fish pass discharge, this increase in wetted area causes velocities to drop in the fish pass entrance. Interestingly this also seems to change the shape of the velocity profile.

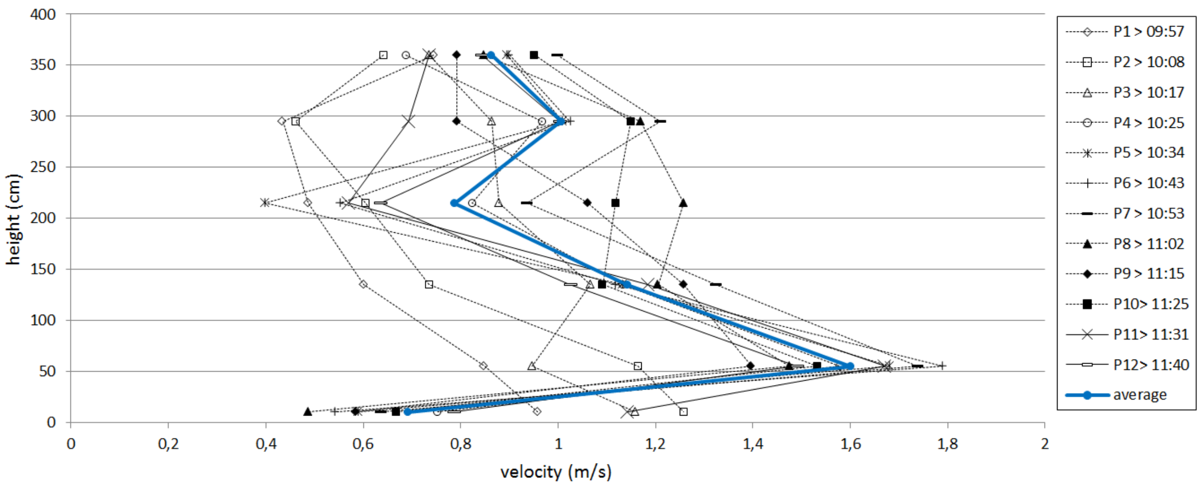

Figure 6 Measured vertical velocity profiles in the fish pass entrance

Due to the shape of the entrance the higher velocities are found in the lower part of the profiles, with maximal velocities at a height of 0.5 meter above the bottom. These maximal velocities range between 1.4 and 1.8 m/s and are slightly higher than the maximal permissible “sprint speed” of the representative fish species, which was determined at 1.5 m/s over distances shorter than 1 to 2 meters. Still representative fish species should be able to pass as velocities near the bottom (< 0.5 m) drop to 0.5-0.8 m/s. Also in the upper part of the vertical profile (1.0 - 3.6 m) lower velocities are measured, ranging from 0.7 to 1.0 m/s. Recent monitoring of fish migration at Oudenaarde has shown that the representative species are indeed capable of entering the fish pass (Huysecom et al., 2012).

In several profiles a peculiar drop in velocities can be seen around 2 meters above the bottom, where velocities drop to 0.5-0.7 m/s. The cause of this drop is not clear and could be the result of a very turbulent situation causing the propeller rotation to be less constant.

Velocities and reach of the attraction flow

The field measurements of the attraction flow (left column in Figure 8) are compared with the scale model results (right column in Figure 8) for each of the three scenarios. Although discharges were not constant during the drifter measurements, drifter paths were chosen for a period with an average discharge that came as close as possible to the discharge of the selected scenario (see Figure 4).

For scenario 1 and 3, it can be seen that the deepest drifters have a further reach than the drifters in the upper part of the water column. This can be expected as the velocity measurements in the entrance itself showed the highest velocities in the lower part of the vertical profile (see Figure 6). Still the two deepest drifters are not able to reach the river bank opposite of the fish pass entrance. The same can be observed in the scale model results. In both the field and scale model results the attraction flow reaches only towards halfway the main stream. This result differs from the results of the original scale model tests which were done before the realization of the fish pass in Oudenaarde (Meersschaut et al., 1998). In the 1997 model tests, the attraction flow was able to reach the opposite bank given the conditions of scenario 1.

The reason for the difference in reach of the attraction flow are attributed to design modifications in the fish pass entrance lay-out (see Figure 7). During the scale model tests of 1997, the entrance was located closer towards the main stream and was more oblique to the river axis (see Figure 7). In addition to this, there might also be an effect of different roughness of the sidewall close to the V-slot type entrance. In the final design this wall is made of sheet piles, whereas in the 1997 scale model tests a smooth wall was assumed.

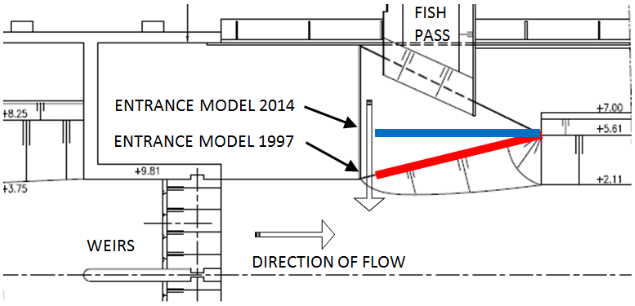

Figure 7 Difference between scale model tests of 1997 and 2014

Both the scale model test and the field measurements show the presence of a small recirculating eddy just downstream of the entrance. With higher discharges over the weirs (scenario 3) this eddy is pushed further towards the river bank, as is the attraction flow itself. The drifter measurements show that the eddy is mostly present in the upper part of the water column.

In the situation of very low discharges over the weirs (situation 2) the attraction flow is able to reach the opposite bank at all four measured depths. For this scenario the scale model shows a large eddy reaching the opposite bank and then turning back towards the fish pass entrance. Although three of the four drifters also tend to flow back a little towards the centre of the main stream, this large eddy is not as clear as in the scale model tests.

The average velocities in the main stream of the scale model (0.19-0.24 m/s) are in line with the drifter velocities of the field measurements (0.16-0.22 m/s). To compare the measured velocities of the attraction flow maximal velocities in an area 2-4 meters (at model scale) downstream of the entrance are considered. Also for this area the velocities of the drifter measurements (0.8-1.1 m/s) correspond well with the velocities measured in the scale model (0.6-0.9 m/s).

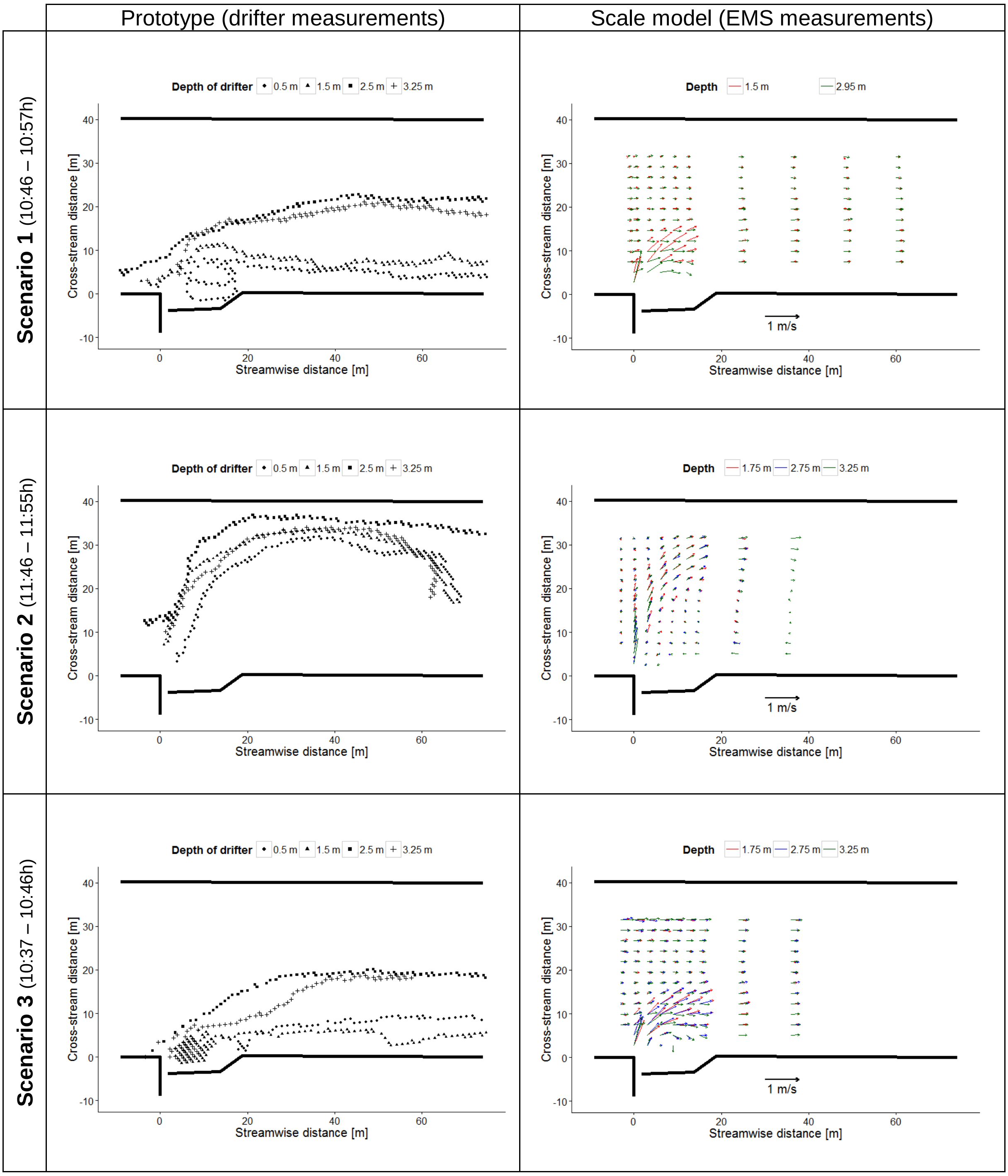

Figure 8 Attraction flow: results of field- and scale model measurements.
Depth in meter below water surface.

4. CONCLUSION

Results of the scale model tests agree relatively well with the data from the field measurements, both in pattern and reach as well as in measured velocities. Velocities in the attraction flow, starting about 2 meters downstream of the entrance, range from 0.6 to 1.1 m/s.

The observed maximal flow velocities up to 1.8 m/s in the entrance itself are slightly higher than the maximal allowable “sprint speed” of the representative fish species, which was determined at 1.5 m/s over distances shorter than 1 to 2 meters. However, there are still enough locations within the vertical profile where conditions are within recommended range (0.7 – 1.0 m/s).

As far as the reach of the attraction flow in the main stream is concerned, both the field measurements and the scale model results show that the current design rule, which requires the attraction flow to reach up to the river bank opposing the fish pass entrance in case of a fish passage discharge of 1/10th of the river discharge, is not met. However, recent fish monitoring shows that representative fish species are able to find and pass the passage (Huysecom et al., 2012). Therefore, the current design rules and approach for the perpendicular attraction flow should be re-examined in order to better fit the field conditions.

As the reach of a perpendicular attraction flow is very much dependent on the discharge on the main river, it is recommended to further investigate the effectivity of perpendicular attraction flows in comparison to parallel attraction flows, as recommended by both German and French manuals (Larinier, 2002; Adam and Bosse, 2014).

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