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Fish Behaviour in the Vicinity of a Navigation Lock Complex: The Challenges

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Abstract: *Hydraulic structures such as navigation locks, pumping stations, and hydropower plants play an important role in navigation, water management, and sustainable energy production. However, these structures may severely impact the aquatic ecosystem and freshwater fish in particular. In Belgium, the Albert Canal connecting the river Meuse to the river Scheldt is an important migration route for European eel (Anguilla anguilla) and Atlantic salmon (Salmo salar). Both critically endangered species have a downstream migrating phase in their lifecycle (respectively silver eels and salmon smolts), during which they are hampered by hydraulic structures. In the coming years, Archimedes screws are to be installed at the navigation lock complexes present in the Flemish part of the canal, which can function both as pumping stations and hydropower generators. A first installation is already present at the navigation lock complex of Kwaadmechelen. Before fish mitigation measures can be implemented, it is important to gain understanding on how the downstream migrating fish are affected by hydrodynamics around the complex. In this paper we focus on the challenges in investigating fish behaviour related to the acoustic telemetry used to determine fish positions as well as on the complexity of a hydrodynamic CFD model for the studied site. Additionally, we present some preliminary results. In the next phase of the research, observed fine-scale behaviour of the fish in front of the navigation lock complex will be compared with predicted flow patterns by means of a CFD model.*

Keywords: *Navigation locks, fish behaviour, acoustic positioning telemetry, CFD modelling, hydrodynamics*

1. Introduction

Among the fish species impacted by hydraulic structures, European eel (*Anguilla anguilla*) and Atlantic salmon (*Salmo salar)* are some of the most strongly affected. These species are representative for fish (respectively catadromous and anadromous) with a downstream migrating phase (van Ginneken and Maes, 2005), during which they must pass sluices, navigation locks, pumping stations, and hydropower plants. In the last decade, a drastic decline in eel populations has become undeniable (Limburg and Waldman, 2009). The European eel stock has declined dramatically (EIFAC; Moriarty and Dekker, 1997; Dekker, 2004) and is now judged to be outside safe biological limits (ICES, 1999) and therefore protected by European regulation (Council Regulation EC no.1100/2007). Atlantic salmon begin their lifecycle in freshwater and migrate downstream as smolts to spend the major part of their lives in salt water (McCormick et al., 1998). This species is listed as critically endangered in the IUCN Red List of the Flemish region of Belgium (Verreycken et al., 2014). Stagnant water upstream of hydropower stations may lead to disorientation, migration delay, and predation (Johnson and Moursund, 2000).

In Belgium, the Albert Canal is an important migration route for eel and salmon (Stevens et al., 2011). Both species can use the canal as a connection between their feeding and respective birth habitats, in the river Meuse and the river Scheldt, being their gateway to the sea (**Figure 1**). Although the river Meuse also provides a connection to the sea (neither free of fish migration barriers), former research showed that the choice of eels between both routes is divided quite equally: of 15 tagged eels, 5 passed via the Meuse, 7 via the Albert Canal, and the remaining 3 were never detected (Bayens, unpublished). In this project, we focused on the Albert Canal. The canal has to bridge 60 m of height difference between both rivers, realised by the presence of 6 navigation lock complexes (**Figure 1**). Archimedes screws are installed at 2 of the 6 complexes and will be installed at the remaining 4 complexes in the coming years. These can function both as pumping stations to recover lockage water in dry periods and as hydropower generators to produce energy in high flow periods. The presence of pumping stations and turbines can cause significant migration problems to fish, adding up to the potential migration delay caused by the navigation lock complexes solely. In particular the elongated bodies of eels are vulnerable to strikes, cuts, bruises, and fractures during passage, in some cases leading to mortality (Buysse et al., 2014).

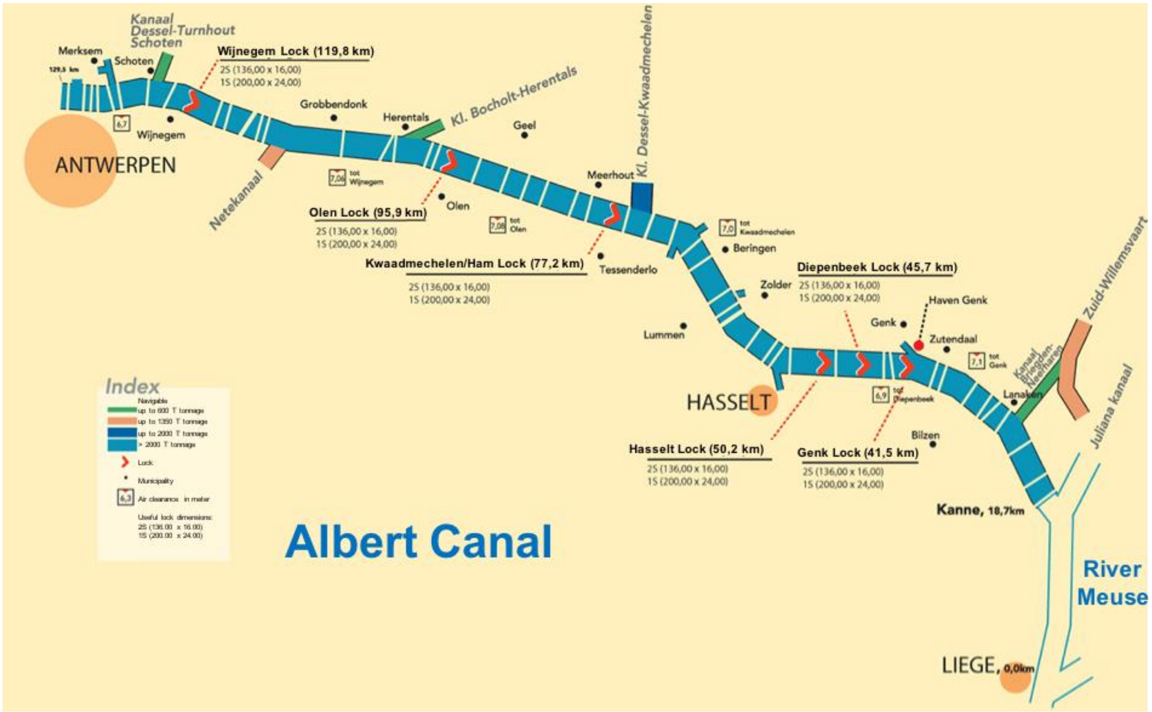


Figure 1: Albert Canal connecting river Scheldt and Port of Antwerp to River Meuse (source: Promotie Binnenvaart Vlaanderen)

Breukelaar et al. (2009) assessed the influence of sluices, which are only temporarily open during high river discharges, on route choice and migration delay of silver eel. Also Piper et al. (2013) investigated how barriers such as sluices, locks, and weirs impact the seaward silver eel migration. Acou et al. (2008) put forward that migration delay because of such barriers can lead to increased mortality due to energy expenditure. For silver eel, this can cause increased vulnerability to diseases, predation, and exhaustion during the long route to the spawning fields. Gardner et al. (2016) investigated the behaviour of Atlantic salmon smolts in reaction to sluice gate operation for water level regulation.

The hydrodynamics at sluices and navigation locks is very complex and strongly dependent on operating conditions. Before mitigation measures can be implemented, it is important to know how fish behaviour is influenced by the prevailing hydrodynamic conditions. Therefore, we used the Vemco Positioning System (VPS) to track fish behaviour in front of the navigation lock complex at the Albert Canal in Kwaadmechelen (Belgium), and we are investigating the hydrodynamics using Computational Fluid Dynamics (CFD) modelling. This paper gives an overview of the challenges related to the VPS acoustic telemetry system and to hydrodynamic modelling of this specific kind of study sites, and presents some preliminary results related to the impact of the navigation lock complex on silver eel and salmon smolt migration.

2. Materials and Methods

2.1. Study Site

The navigation lock complex on the Albert Canal in Kwaadmechelen (Belgium) consists of three adjacent locks (**Table 1** and Figure 2). The two smaller and older ones are called the Northern and the Middle Lock, and pass on average 25 ships per day during 22 lockages (both upstream and downstream). The larger and newer one is called the Pushed Convoy Lock and passes on average 40 ships per day, equally during 22 lockages (as this lock is more than twice the volume of the smaller ones). Since 2012 a bypass channel with a combined pumping/hydropower installation is operational. This installation consists of four Archimedes screws of 22 m length, three of them mounted in an open casing (4.30 m diameter, 3, 4 or 5 m^3/s pumping or turbining flow) and one mounted in a closed casing (3.30 m diameter, only pumping, 2 m^3/s flow). In periods of low flow in the river Meuse, the installation acts as a pumping station, whereas in periods of sufficient flow in the Meuse, hydropower will be generated. The area of interest in the present study is the zone directly upstream of the navigation lock complex, where downstream migrating fish are faced with the presence of the three locks and the inlet of the channel to the pumping/hydropower installation. It is an area about 300 m in length and 250 m in width, covered with receivers for the tracking of tagged fish (Figure 2).

Table 1: Characteristics of navigation lock complex in Kwaadmechelen

	Northern Lock & Middle Lock	Pushed Convoy Lock
Operational since	1940	1974
Useful width of lock chamber	16 m	24 m
Useful length of lock chamber	136 m	200 m
Max. CEMT class (max. tonnage)	Vb (2000 T)	VIb (10000 T)
Upstream lock gate	mitre gates	bottom hinged gate
Downstream lock gate	mitre gates	mitre gates
Maximum lift	10 m	10 m
Levelling system	longitudinal culverts with ports	longitudinal culverts with ports
Volume of water per lockage	22500 m³	50000 m³
Dimensions of water intake (width x height)	3.60 x 3.10 m	9.60 x 4.00 m
Average filling discharge through water intake	13 m^3/s	34 m^3/s

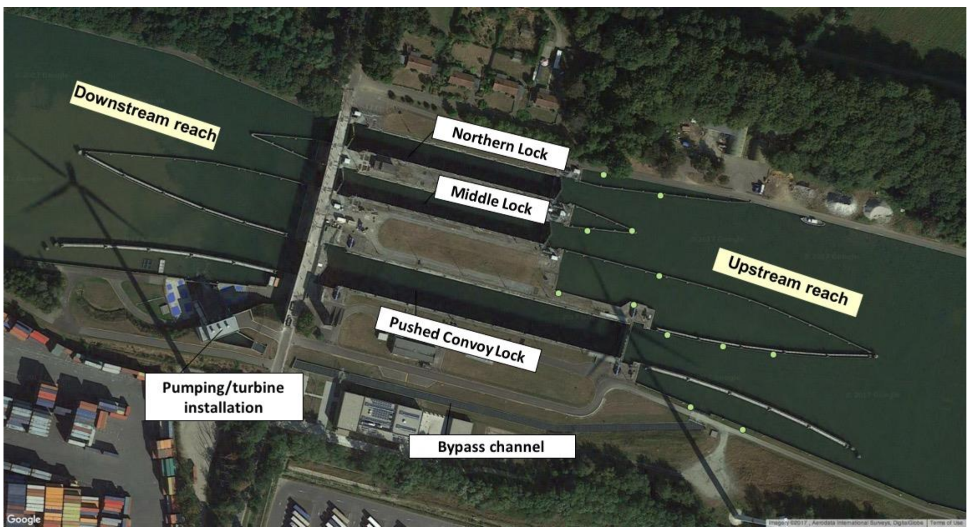


Figure 2. Aerial view of the navigation lock complex in Kwaadmechelen.
The green dots are the locations of receivers in the area of interest.
Source of background picture: Google Maps Satellite.

To measure the filling curve of each lock, we installed Schlumberger Minidivers (accuracy 0.5 cm, resolution 0.2 cm) below minimal water level. We converted the resulting curve to water velocities through the intakes by use of the lock surface areas (2176 m^2 for the Middle and Norther Locks; 4800 m^2 for the Pushed Convoy Lock) and the water intake areas (respectively 11.16 and 68.60 m^2). For convenience, we suppose that the filling discharge is equally divided over both intakes.

2.2. Fish Tracking

To investigate fish behaviour, we used acoustic positioning telemetry, more precisely the Vemco Positioning System (VPS). In VPS, autonomous receivers are installed in a configuration so that every location in the area of interest is covered by at least three receivers. At the guiding structures upstream of the navigation lock complex, we attached 12 VR2W 69 kHz-receivers spaced 30 to 60 m apart and covering an area of about 8000 m^2 (Figure 2). The fish are tagged with acoustic transmitters and each individual emits a unique acoustic signal at a specific frequency (69 kHz in this case). If a signal is heard by at least three receivers, a position can be calculated by use of hyperbolic positioning (also known as the time difference of arrival technique). Additional receivers (which only detect the presence of tagged fish and do not take part in positioning) are present upstream and downstream of the VPS area, in the bypass channel leading to the pumping/hydropower station, and in each lock chamber. The use of the 69-kHz system allows to track the fish in their further migration throughout the Albert Canal and the Scheldt River towards the North Sea, where more receivers of the same system are installed as part of the Belgian Fish Tracking Network (http://www.lifewatch.be/en/fish-acoustic-receiver-network).

After capture 36 km upstream of the study site, we tagged 81 silver eels with V13 acoustic tags (diameter 13 mm, length 36 mm, weight in water 6 g) by a minor surgical operation in the abdominal cavity (Figure 3), and released them again 13 km upstream of the study site. The release location was a trade-off that provided sufficient swimming distance to create natural conditions and avoided other navigation lock complexes acting as barriers before passing Kwaadmechelen. Because salmon smolts are less abundant and difficult to catch in the canal, they were provided by the nursery station of Érezée (Belgium). After tagging with V7 tags (diameter 7 mm, length 18 mm, weight in water 0.7 g), we released 70 smolts 300 m upstream of the study site. We opted for this much smaller distance to the complex (compared to 13 km for eels), because hatched salmon smolts are observed to have a higher risk to get predated (Einum and Fleming, 2001). If the hatched smolts would have to swim 13 km before reaching the study area, chances to lose our animals, transmitters and, hence, data would be too high. From November 2015 until June 2017, we collected swimming tracks of 77 silver eels and 61 salmon smolts with the VPS system.

Figure 3. Tagging of a silver eel (left) and a salmon smolt with abdominal incision during the tagging operation (right). Pictures: Jenna Vergeynst (left), Ine Pauwel (right).

3. The Challenges

3.1. Tracking Fish in a Reflective Environment

The acoustic transmitters emit coded signals with a random time interval between each emission. Each pulse train, representing one coded signal, takes 3 to 5 seconds (depending on the transmitter type). To calculate the position of a tagged fish, at least three receivers have to detect and decode the emitted signal. The position is then calculated based on difference in detection time between pairs of receivers. Environmental noise and physical obstructions can hamper the ability of receivers to detect signals. Moreover, the acoustic signals can be reflected on walls, decreasing the accuracy of the calculated position. This is particularly the case in a canal system, surrounded by hard, concrete walls.

The VPS system tries to overcome this problem by providing a receiver time-out period of 260 m/s after the direct signal is received (Frank Smith, personal communication, June 6, 2016). However, when the direct signal is missed, for instance due to an obstruction, or when the reflection path takes longer than 260 m/s, the reflected signal can still be detected. Both issues are present in Kwaadmechelen. The protruding (northern) lock chamber wall of the Pushed Convoy Lock creates for most of the receivers a shadow zone, from which no signal can reach the receiver (e.g., Figure 4). If a transmitter (i.e., a tagged fish) is present in one of these zones, its direct signal cannot be detected by a receiver outside line-of-sight, but its reflected signal can. Also passing ships can be responsible for a similar obstruction (or can act as a reflecting wall). To overcome the 260 m/s time-out period, a reflection path has to be at least 390 m long (assuming a sound speed of about 1500 m/s). In other words, the fish has to be at 195 m of one of the walls to create this path length, which is perfectly possible in an area of 250 m width.

Figure 4. Aerial view with indicated in red the shadow zone of receiver S16.
Source of background picture: Google Maps Satellite.

Biological track analysis is one of the methods to filter out bad positions. However, this requires biological prescience and a high tracking resolution in order to make the real path visible beneath the noise. The 69 kHz-system used in this telemetry study cannot have a resolution better than about 23 seconds on average because of two reasons. Firstly, the transmission pulse train takes 3.6 seconds to emit, determining a physical lower bound to the time interval. Secondly, the time interval between two emissions is randomized. This precaution avoids that two accidentally synchronized fish transmitters would emit continuously colliding signals when present simultaneously in the study area, but it cannot prevent that collisions still take place from time to time. Therefore, the average time interval has to be large enough to minimize the chance of collision.

As an alternative for biological track analysis, the VPS positions need to be filtered out, retaining only the positions with the highest probability of being accurate (Figure 5). This filtering method is based on the performance of receiver clusters in positioning fixed transmitters in the study area (Vergeynst et al. in preparation). Fish positions calculated by well performing clusters of receivers are more likely to be correct than fish positions calculated by badly performing receiver clusters. The assessment of the cluster can be adapted according to the study questions.

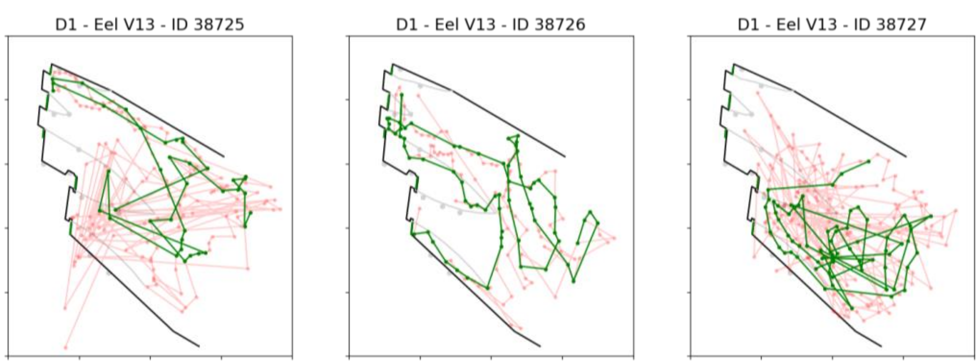


Figure 5. Three examples of original tracks (red) and corresponding filtered tracks (green). The retained positions originate from receiver clusters that positioned at least 95% of the fixed transmitters with 2.5 m accuracy.

Recently (June 2017), Vemco developed a high-resolution system in which the long pulse train is replaced by a single pulse of 6 m/s. This system is preferential for new studies requiring sub-meter precision and high-resolution tracks, but it emits at a frequency of 180 kHz and is therefore not compatible with the Belgian receiver network. Another high resolution and precision system is Hydroacoustic Technology Inc (HTI, neither compatible with the Belgian receiver network). HTI is a cabled system, providing the advantage of fast signal transmission and easy synchronization, whereas autonomous systems like VPS need mutually detected synchronization transmitters in the array. However, a cabled system is hard to install in the study area under consideration and is very likely to fail due to damage by passing ships.

3.2. A Simple Model for a Complex Situation

From the hydrodynamics point of view, a complex situation is present in the study zone. In some periods, there is virtually no (or very little) flow, whereas clearly localized and temporal flow patterns might be generated due to various, sometimes concurrent, operations. Firstly, ships sailing in or out of a given lock produce a localized propeller wash and return flow. Note that the decision as to which of the three locks in the complex is used by a specific ship is made by the lockmaster, taking into account the size, number, and times of arrival of transiting ships. Secondly, when filling a specific lock chamber, water is subtracted from the upstream reach and a localized pattern of flow accelerating towards the intakes of the longitudinal culverts develops. These intakes are located on either side of a lock entrance. While filling, the flow rate at an intake (hence the local velocities upstream of the intake) vary in time. The flow rate first increases from zero towards a maximum and then decreases again to zero. The flow pattern generated by an intake might be influenced by the guiding structures in the vicinity of the lock entrance. These structures (Figure 6) consist of horizontal beams fixed on poles (spaced 30 m apart). The lower beams block the upper part of the water column over 0 to 0.50 m, depending on the water level.

Figure 6. Picture of the guiding structures between the Middle Lock and the Push Convoy Lock. Picture: Jenna Vergeynst.

Thirdly, when the pumping/hydropower installation is in pumping mode, a jet-like flow is entering the study area at the upstream extremity of the bypass channel. In hydropower mode, on the other hand, water is subtracted from the study area at the aforementioned location. In both modes, the flow patterns might be influenced by the neighbouring guiding structure of the Pushed Convoy Lock. The flow rate entering or leaving the study area depends on the number of Archimedes screws that are in operation. The latter is decided by the river manager, based on discharge and economic needs. A fifth source of flow in the study area are the translatory waves, that travel back and forth in the canal, reach between Kwaadmechelen and Hasselt due to the filling process of locks in the complex of Kwaadmechelen, as well as due to emptying of locks in the complex of Hasselt. These waves induce water level changes (Figure 7) and a limited flow velocity (with an estimated maximum of ca. 25 cm/s) over the full cross-section of the canal. For the sake of completeness, one should also mention the lower-frequency water level variations as a result of weather and general water management.

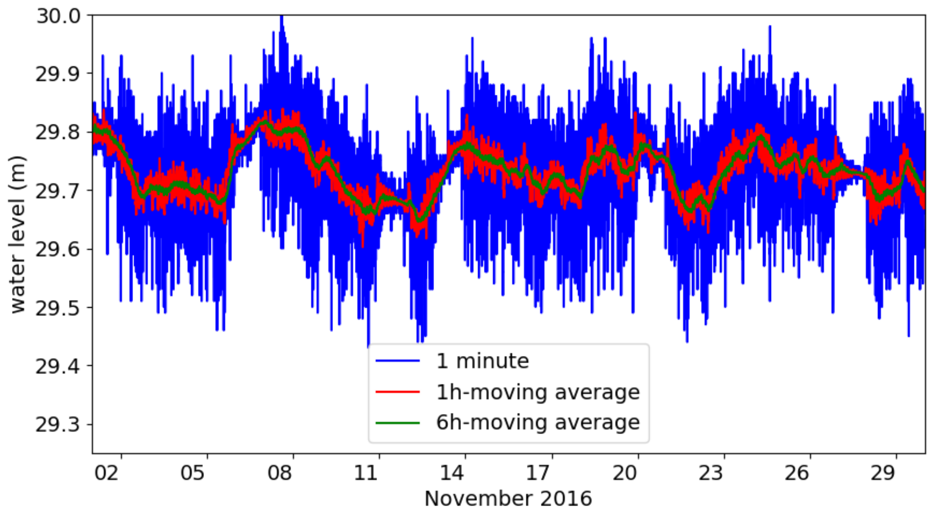


Figure 7. Water level variations for one month (November 2016) measured 500 m upstream of the sluice complex.

Since the present research aims at exploring the link between the hydrodynamic conditions and the fish behaviour in the study area, the flow characteristics need to be quantified. To this end, two complementary means are available: measurements and numerical simulations. Both means, however, have their limitations due to the characteristics of the study area and the different operating scenarios that are possible.

Measuring the (unsteady) hydrodynamics over the entire study area during each one of the scenarios is practically impossible. Moreover, instruments such as an Acoustic Doppler Current Profiler (ADCP) have difficulties in measuring close to walls and in locations with high concentrations of air bubbles (propeller wash). Even when mounted on a survey vessel, the extent of the study area, the presence of the guiding structures and the passage of ships sailing in or out of the locks complicate the measurement campaign. In addition, measuring from a boat in front of a water intake is not without danger (despite the presence of trash racks). Nevertheless, measurements are important for (partial) validation of numerical models.

To be able to model for future reference some time intervals for which (reliable) fish tracks are available, first a global CFD model has been set up for the study area (by means of the OpenFOAM software). Where relevant, more spatially resolved sub-models will be set up and validated to simulate in detail specific localized flow patterns (like flows near the intake of the lock levelling systems or the bypass channel, e.g., Figure 8). Nevertheless, modelling time periods involving sailing ships will remain a challenge. Though numerical techniques are available nowadays to account for a moving ship and the action of its propeller in a CFD model, the exact timing of a passing ship is by no means reproducible from the lockmaster's loggings. These loggings contain the timing of first communication with an arriving ship and the approximated start (and end) moment of the lockage. The timeframe between both is too large to deduce the exact timing of ship movements in order to find out how this could have influenced the behaviour of present fish. In addition, the exact track of a ship sailing in the study area is not known either. Yet, CFD simulations can be used to quantify flow velocities and turbulence characteristics corresponding to well-chosen scenarios and time intervals. Such time intervals comprehend periods for which a fish track is available and the timing of lock levelling and operation of the pumping/hydropower are known exactly.

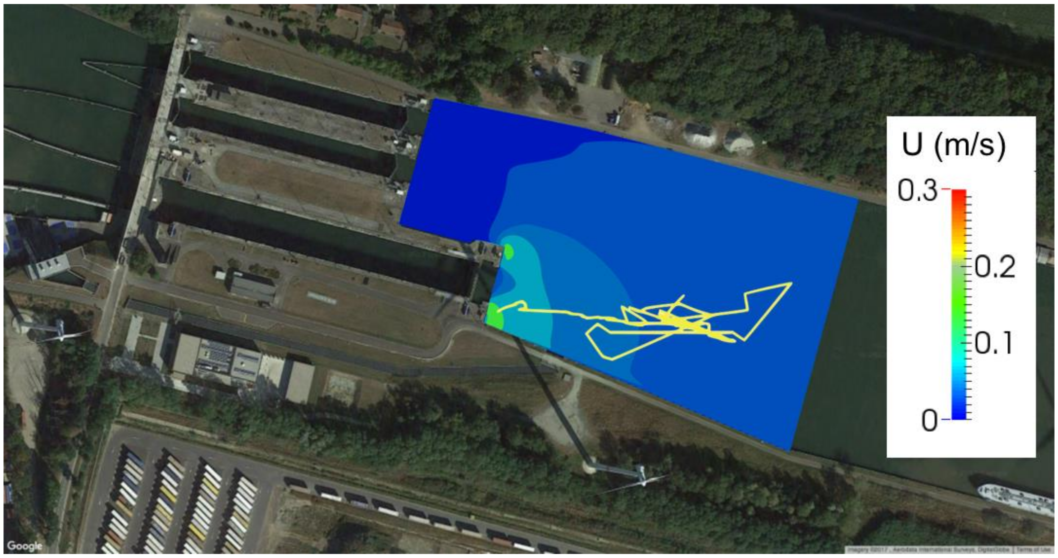
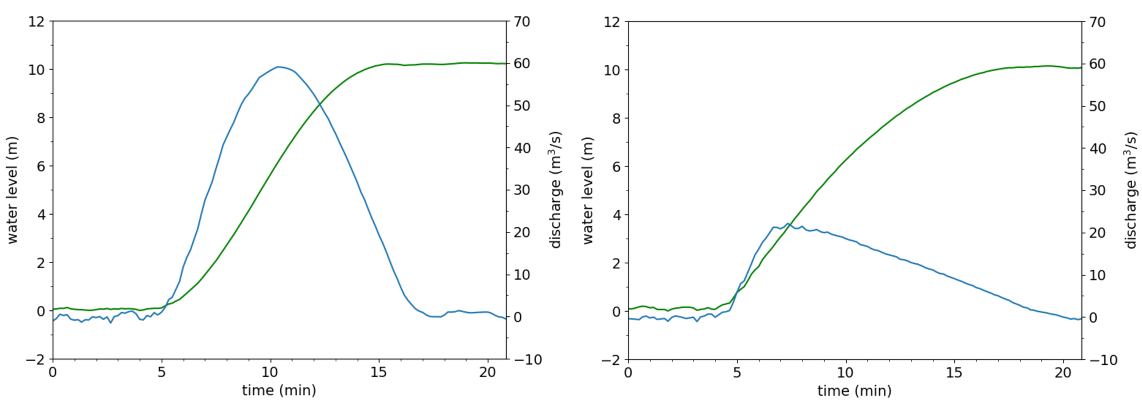


Figure 8. Illustrative example of a CFD simulation of filling of the Pushed Convoy Lock, superimposed with a silver eel track directed towards one of the lock intakes (i.e. towards a zone of higher current). In a next research phase, representative CFD simulated flow velocities will allow us to determine the fish' hydrodynamic preferences.

4. Preliminary Results and Discussion

4.1. Route Choice

Almost double amounts of fish passed via the Pushed Convoy Lock as compared to the two smaller locks, despite the equal number of lock fillings per day. This may be due to the different filling mechanisms (Figure 9). The Pushed Convoy Lock is filling more gradually with a water velocity through the intakes increasing during about 5.5 minutes to a maximum velocity of 1.5 m/s, and then decreasing again during a time interval of equal length. The water velocity through an intake of the two smaller locks increases very rapidly in the beginning, reaching a maximum velocity of about 2 m/s in less than 3 minutes, after which the velocity is gradually decreasing during the remaining 11 minutes filling time. As a result, filling of the Pushed Convoy Lock creates a longer period of water acceleration towards the intake but a lower maximum velocity. However, the discharge going through one Pushed Convoy intake is much larger than for the smaller locks with a maximum of 60 versus 20 m^3/s. Further research and CFD simulations will reveal whether the fish' preference for the Pushed Convoy Lock is explained by an aversion for too high velocities at the smaller lock intakes or by a larger zone of influence (due to higher distance) at the Pushed Convoy Lock intakes.



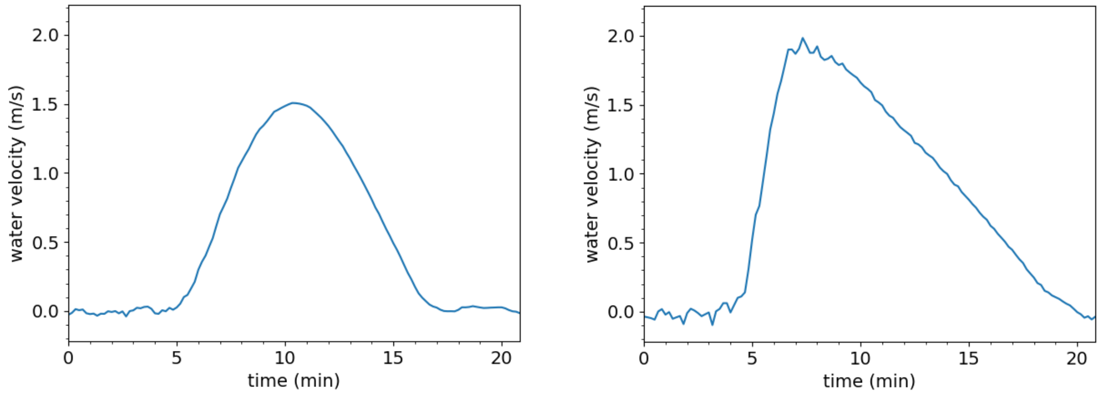


Figure 9. Typical profiles of the time evolution of the discharge (upper) and water velocity (lower) through one water intake of the Pushed Convoy Lock (left) and of the Middle and Northern Locks (right). The green line is the water level in the respective locks, the blue lines are running means of discharge/water velocity over 2 minutes.

4.2. Migration Delay

In general, salmon smolts passed faster than silver eels. The delay shows a wide range for different individuals, for both silver eels and salmon smolts, going from less than an hour to months. The maximal delay time was even 1 year and 4 months for one eel. At least 20% of the tagged fish failed to pass and at least 25% of the fish that passed, lost several days. If this applies to the entire population, the cumulative effect of six of these barriers on migration timing, vulnerability to predation, and exhaustion might be tremendous.

5. Conclusion and Perspectives

Acoustic positioning in a reflective environment turned out to involve some difficulties in acquiring reliable swimming tracks of both fish species because of the limitations of the used system. However, other systems would imply the disadvantage of being incompatible with the rest of the Belgian Tracking Network, resulting in the loss of information on the larger scale of the entire Albert Canal. When starting a new study with the objective to investigate small-scale fish behaviour, one should consider higher-resolution systems. These might still suffer from reflection errors but will possibly result in better swimming tracks after filtering.

The advantage of modelling the hydrodynamics is that different scenarios can be implemented without the need to do measurements for each, the latter being impractical and unsafe. However, the resulting model remains a major simplification of a very complex system. Also, the importance of timing of each hydrodynamics-related event needed to enable the comparison with fish behaviour is difficult to satisfy in this heavily navigated system.

Of the tagged fish, at least 20% failed to pass the ship lock complex and, of the fish that succeeded, at least 25% lost several days at the barrier. Considering that the Albert Canal contains six of these barriers, the cumulative impact of these barriers might have a major effect on migration and survival chances of both species.

The influence of fish passage through an intake is currently unknown. In the study under consideration, recapture of the fish after passage through an intake is impossible, but analysis of further downstream behaviour and survival rates can be linked to its potentially harmful effects. This is subject of future research in the ongoing project.

The preference of both species to pass through the Pushed Convoy Lock is probably related to the different filling mechanism compared to the smaller locks. However, further analysis of fish behaviour in relation to the hydrodynamics around the ship lock complex will reveal what exact conditions make certain routes more tempting and which conditions are deterrent for these species.

6. Acknowledgements

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