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Evaluation of the Fish Spiral Sluice Gate as a fish migration facility under experimental conditions

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EVALUATION OF THE FISH SPIRAL SLUICE GATE AS A FISH MIGRATION FACILITY UNDER EXPERIMENTAL CONDITIONS

Stijn Bruneel, Arc'hantael Labrière, David Buysse, Nico De Maerteleire, Johan Coeck

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English abstract

Context: Well-functioning fishway passes are needed worldwide to promote fish migration as the number of barriers is unlikely to decrease in the future. The Fish Spiral Sluice Gate (FSSG) was designed to provide a simple, compact solution for fish to overcome barriers between 1 m and 10 m high. It features a multi-chamber valve system with adjustable current options in both the inflow and outflow chambers. The principle is as follows: fish are attracted by the flow at the lower valve when it starts to open, enter the system when the lower valve fully opens and make their way towards the upper valve, to then exit when the upper valve opens.

Aim: Before new designs of fishway passes are introduced, there should be some rigorous testing of the attraction, entrance, passage and overall efficiency. The aim of this report was to assess how well the FSSG functions under experimental conditions and to understand how fish behave before, during and after passage.

Methods: Testing consisted of three experiments with ide (*Leuciscus idus*). Pit tags were inserted in fish, which allowed to determine when tagged fish passed the lower valve and upper valve as both were equipped with antennas. In addition, the opening and closing of the valves were monitored. The obtained data allowed to determine the different types of fishway efficiency, the time of entrance and passage, the moment of entrance and exit in function of the valve openings, and the effect of length, weight and species on aforementioned aspects.

Results: Despite operational settings of the FSSG throughout the experiments being fixed, entrance efficiency and passage efficiency varied substantially as they ranged from 70 % to 98 %, and from 68 % to 84 %, respectively. Entrance time (time from release to entry) and passage time (time from entry to exit) were relatively high. 50% of all tagged fish had an entrance time of 100 to 200 minutes, while the entered fish had a passage time of 225 to 1200 minutes. The length and weight did not seem to have any effect on whether fish were able to successfully use the fish spiral, nor did it have an effect on the time it took fish to move up the fish spiral. Fish generally wait until the valves are completely open before entering and leaving the FSSG, though for the upper valve a relatively large amount of fish also seem to leave the FSSG when the valve is opening or closing. Some preliminary tests with other species indicated there was no clear difference between species in the passage success or passage timing.

Implications: Under the experimental conditions tested, entrance and passage efficiencies were relatively high and within the range reported for several other fishway types. Direct comparison with field-tested fishways should, however, be interpreted cautiously because of major differences in experimental conditions. The high variability of both efficiencies is also in line with findings in literature of other fishway designs and highlights the strong effect local conditions and placement could have. However, it should be noted that the calculated entrance and passage efficiency are most likely to be overestimated and underestimated, respectively, from the actual efficiencies that were obtained in this lab setting. It was unfortunately not possible to quantify these levels of uncertainty. Therefore field testing under representative conditions is needed to assess how the FSSG performs in real-life situations. In addition, attraction efficiency could not be tested in this set-up, but might be an important aspect to consider, especially given its strong link with local conditions and placement. As attraction flow can be adapted in the FSSG, it will be important to test out different settings per site. The relatively long transit times were to be expected because the FSSG works in phases and the speed with which a fish can travel is therefore not only determined by its own traits and motivation, but also by the operational settings of the FSSG.

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Nederlandstalige samenvatting

Context: Goed functionerende vispassages zijn cruciaal om vismigratie te bevorderen, aangezien het aantal barrières in de toekomst waarschijnlijk niet zal afnemen. De Fish Spiral Sluice Gate (FSSG) werd ontworpen om een eenvoudige, compacte oplossing te bieden voor vissen om barrières tussen 1 m en 10 m hoog te overwinnen. De FSSG bestaat uit een verticale Archimedesschroef met drie “kanalen” die alle drie onderaan en bovenaan een afsluitbare schuif hebben met instelbare openingsopties, en die zowel bovenaan als onderaan uitkomen in 1 instroom- en 1 uitstroomcompartiment. Het principe is als volgt: vissen worden aangetrokken door de stroming bij de onderste klep wanneer deze begint te openen, komen in het systeem wanneer de onderste klep volledig opent en banen zich een weg naar de bovenste klep, om er vervolgens weer uit te zwemmen wanneer de bovenste klep opent.

Doel: Voordat nieuwe concepten van vispassages worden geïntroduceerd, moeten de attractie-efficiëntie, de ingangsefficiëntie, de passage-efficiëntie en de algehele efficiëntie grondig worden getest. Het doel van dit rapport was om te beoordelen hoe goed de FSSG functioneert onder experimentele omstandigheden en om te begrijpen hoe vissen zich gedragen voor, tijdens en na de passage.

Methoden: Tests bestonden uit drie experimenten met winde (*Leuciscus idus*). Er werden pit-tags ingebracht in de vissen, waardoor bepaald kon worden wanneer de gemerkte vissen de onderste klep en de bovenste klep passeerden, aangezien beide waren uitgerust met antennes. Bovendien werd het openen en sluiten van de schuiven opgevolgd. De verkregen data maakten het mogelijk om de verschillende types van efficiëntie van de FSSG te bepalen, het tijdstip van binnenkomen en passeren, het moment van binnenkomen en verlaten in functie van de klepopeningen, en het effect van lengte, gewicht en soort op voornoemde aspecten.

Resultaten: Ondanks het feit dat de operationele instellingen van de FSSG tijdens de experimenten vast stonden, varieerden de ingangsefficiëntie en de passage-efficiëntie aanzienlijk, respectievelijk van 0,70 tot 0,98 en van 0,68 tot 0,84. De ingangstijd (tijd van loslaten tot binnenkomen) en de passagetijd (tijd van binnenkomen tot verlaten) waren relatief hoog. 50% van alle gemerkte vissen had een ingangstijd van 100 tot 200 minuten, terwijl de binnengekomen vissen een passagetijd hadden van 225 tot 1200 minuten. De lengte en het gewicht leken geen effect te hebben op de vraag of vissen in staat waren om met succes gebruik te maken van de FSSG, noch op de tijd die vissen nodig hadden om zich omhoog te bewegen in de FSSG. Vissen wachtten over het algemeen tot de schuiven helemaal open zijn voordat ze de FSSG binnengaan en verlaten, hoewel voor de bovenste klep ook relatief veel vissen de FSSG lijken te verlaten wanneer de klep open of dicht gaat. Uit enkele preliminaire testen met andere soorten bleek dat er geen duidelijk verschil was tussen de soorten wat betreft het succes of de timing van de passage.

Implicaties: Onder de geteste experimentele condities, waren de ingangs- en passage-efficiëntie relatief hoog en vielen binnen de gerapporteerde waarden van andere vispassage-types. De hoge variabiliteit van beide efficiënties komt ook overeen met bevindingen in de literatuur over andere ontwerpen en benadrukt het sterke effect dat lokale omstandigheden en plaatsing kunnen hebben. Er moet wel opgemerkt te worden dat de berekende ingangs- en passage-efficiëntie hoogstwaarschijnlijk respectievelijk overschat en onderschat worden t.o.v. de echte waarden die bereikt werden in dit experiment. Het was helaas niet mogelijk om de onzekerheidsniveaus van deze metrices te kwantificeren. Daarom zijn veldtesten onder representatieve condities nodig om na te gaan hoe de FSSG werkt in echte situaties. Daarnaast kon de attractie-efficiëntie niet worden getest in deze opstelling, maar dit zou een belangrijk aspect kunnen zijn om rekening mee te houden, vooral gezien het sterke verband met lokale omstandigheden en plaatsing. Aangezien de attractiestroom in de FSSG kan worden aangepast, is het belangrijk om verschillende instellingen per locatie te testen. De relatief lange doorlooptijden waren te verwachten omdat de FSSG gefaseerd werkt en de snelheid waarmee een vis zich kan verplaatsen dus niet alleen bepaald wordt door zijn eigen toestand en motivatie, maar ook door de operationele instellingen van de FSSG.

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Résumé français

Contexte : Des passes à poissons performantes sont absolument nécessaires pour favoriser la migration des poissons, car il est peu probable que le nombre d'obstacles diminue à l'avenir. Le Fish Spiral Sluice Gate (FSSG) a été conçu pour fournir une solution simple et compacte permettant aux poissons de franchir des obstacles d'une hauteur comprise entre 1 et 10 m. Il est doté d'un système de vannes à plusieurs chambres avec des options de courant réglables à l'entrée comme à la sortie. Elle est dotée d'un système de vannes à chambres multiples avec des options de courant réglables dans les chambres d'entrée et de sortie. Le principe est le suivant : les poissons sont attirés par le courant au niveau de la vanne inférieure lorsqu'elle commence à s'ouvrir, entrent dans le système lorsque la vanne inférieure s'ouvre complètement et se dirigent vers la vanne supérieure, pour ensuite sortir lorsque la vanne supérieure s'ouvre.

Objectif : Avant d'introduire de nouveaux modèles de passes à poissons, il convient de tester rigoureusement l'attraction, l'entrée, le passage et l'efficacité globale. L'objectif de ce rapport était d'évaluer le fonctionnement de la FSSG dans des conditions expérimentales et de comprendre le comportement des poissons avant, pendant et après le passage.

Méthodes : Les essais ont consisté en trois expériences avec l'ide (*Leuciscus idus*). Des marques de fosse ont été insérées dans les poissons, ce qui a permis de déterminer quand les poissons marqués passaient la vanne inférieure et la vanne supérieure, toutes deux étant équipées d'antennes. En outre, l'ouverture et la fermeture des valves ont été surveillées. Les données obtenues ont permis de déterminer les différents types d'efficacité des passes à poissons, le temps d'entrée et de passage, le moment de l'entrée et de la sortie en fonction de l'ouverture des vannes, et l'effet de la longueur, du poids et de l'espèce sur les aspects susmentionnés.

Résultats : Bien que les paramètres opérationnels du FSSG aient été fixes tout au long des expériences, l'efficacité d'entrée et l'efficacité de passage ont varié de manière substantielle, allant respectivement de 0,70 à 0,98 et de 0,68 à 0,84. Le temps d'entrée (temps écoulé entre la libération et l'entrée) et le temps de passage (temps écoulé entre l'entrée et la sortie) étaient relativement élevés. 50 % de tous les poissons marqués avaient un temps d'entrée de 100 à 200 minutes, tandis que les poissons entrés avaient un temps de passage de 225 à 1 200 minutes. La longueur et le poids ne semblent pas avoir d'effet sur la capacité des poissons à utiliser avec succès la spirale à poissons, ni sur le temps qu'il faut aux poissons pour remonter la spirale à poissons. Les poissons attendent généralement que les vannes soient complètement ouvertes avant d'entrer dans le FSSG et d'en sortir, bien que pour la vanne supérieure, un nombre relativement important de poissons semble également quitter le FSSG lorsque la vanne s'ouvre ou se ferme. Des tests préliminaires menés avec d'autres espèces ont indiqué qu'il n'y avait pas de différence significative entre les espèces en termes de taux de réussite ou de durée de passage.

Implications : Dans les conditions expérimentales testées, les efficacités d'entrée et de passage étaient relativement élevées et se situaient dans la fourchette rapportée pour plusieurs autres types de passes à poissons. Une comparaison directe avec des passes à poissons testées sur le terrain doit toutefois être interprétée avec prudence en raison de différences majeures dans les conditions expérimentales. La forte variabilité de ces deux efficacités est également conforme aux résultats de la littérature concernant d'autres conceptions de passes à poissons et souligne l'impact majeur que peuvent avoir les conditions locales et l'emplacement. Cependant, il convient de noter que les efficacités d'entrée et de passage calculées sont très probablement respectivement surestimées et sous-estimées par rapport aux efficacités réelles obtenues dans ce cadre de laboratoire. Il n'a malheureusement pas été possible de quantifier ces niveaux d'incertitude ; par conséquent, des essais sur le terrain dans des conditions représentatives sont nécessaires pour évaluer le comportement du FSSG en situation réelle. De plus, l'efficacité d'attraction n'a pas pu être testée dans ce dispositif, mais elle pourrait constituer un aspect important à prendre en compte, notamment en raison de son lien étroit avec les conditions locales et l'emplacement. Le débit d'attraction

Conclusion : Les expériences sur le FSSG ont donné des résultats prometteurs. Toutefois, il convient de souligner que les conditions de laboratoire fixes de cette étude ont empêché l'évaluation de l'efficacité de l'attraction, un aspect clé de la conception des passes à poissons qui s'avère souvent être le facteur limitant, et ont également introduit une sérieuse incertitude concernant l'efficacité de l'entrée (surestimation) et du passage (sous-estimation). Toute extrapolation à la vaste gamme de situations réelles doit donc être effectuée avec précaution. Un placement judicieux, un suivi scientifiquement fondé et des ajustements conséquents sont essentiels pour tirer le meilleur parti du potentiel du FSSG.

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1 INTRODUCTION

1.1 CONTEXT

Migration barriers and habitat fragmentation are the main threats impacting freshwater and diadromous fish species globally (Belletti *et al.*, 2020). Though barrier removal is often the preferred course of action, it is not always feasible because of economical or safety-related reasons. Potential other solutions to promote fish movement include fish passes and fish elevators, though their efficiency is often strongly dependent on the local conditions and target species (Noonan *et al.*, 2012). Therefore these systems need to be thoroughly assessed to understand how the efficiency is determined by the environmental conditions and target species.

1.2 DESIGN OF THE FISH SPIRAL SLUICE GATE (FSSG)

The Fish Spiral Sluice Gate (FSSG) of Vandezande was designed to provide a simple, compact solution for fish to overcome barriers between 1 m and 10 m high. It consists of three winded immobile “canals” shaped as a vertical Archimedes’ screw, each with an entry (i.e., the lower valves) and exit (i.e., the upper valves). The lower and upper valves are surrounded by an outflow/inflow chamber. Each canal has an artificial substratum from gravel that is glued on the Archimedes’ screw, is completely filled with water and contains five pressure sensors: three throughout the canal, one at the entrance and one at the exit. The lower and upper valves are adjusted accordingly to the pressure inside of the canal. When the lower valve is fully opened then the upper valve opening is at its smallest. The main idea is for fish to be attracted by the flow at the lower valve when it starts to open, enter the system when the lower valve fully opens and make their way towards the upper valve, to then exit the “canal” when the upper valve opens.

1.3 AIMS

The aim of this study is to assess the **efficiency of the FSSG** and understand how fish of **different species and sizes respond** to its mechanisms. In doing so, recommendations can be formulated on how appropriate and feasible the use of the FSSG for fish passage would be under different conditions. The assessment was done via an experimental set-up under controlled conditions with live fish.

1.4 EXPERIMENTAL SET-UP

As the FSSG is a relatively complex system, designed to enable safe passage via the subsequent opening of multiple valves, a traditional set-up in which fish are provided at the entrance and recaptured at the exit to determine mortality rate and type of injuries, would be insufficient (Bierschenk *et al.*, 2018). To really understand the system and how it affects migrating fish, there are more questions to be answered than the general question: How many fish make it through the exit? More specifically, questions that need to be answered are: When do fish enter the FSSG, when do they leave it, how much time (or cycles) does it take them to find the entrance and move up the FSSG, how does experience with the system alter fish behaviour and how does the fish size and species determine the passage efficiency?

The unique operating conditions of the FSSG and multiple questions to be answered, required an alternative assessment approach. In 2023 preliminary tests were conducted to test different methodologies. Fyke net experiments and pit telemetry experiments were evaluated and fine-tuned to come up with a sound

methodology that was used during multiple experiments of 2024. The fyke net experiments, which involved fish release and recapture, were found insufficient to provide sound insights as only few fish could be recaptured. For this reason, in 2024, fyke nets were replaced with a recapture method that utilises dip nets, offering the fish more space and shelter in the upper basin and inflow compartment. In 2023 multiple fish species were used during the preliminary tests, but to provide enough statistical power to draw sound conclusions it was decided to use one species instead for which sufficient individuals were used. The aim of this set-up was to encourage fish to remain in the upper basin until the end of each experiment. The PIT telemetry experiments on the other hand were found to be very suitable in combination with the new recapture method and after some tests to optimize placement and detection probability, the methodology was fixed.

1.5 PIT (PASSIVE INTEGRATED TRANSPONDER) TELEMETRY

PIT telemetry is a widely used technology, enabling the tracking of fish or terrestrial animals, especially in narrow systems (Thorstad *et al.*, 2013). Similar to other telemetry techniques, it relies on a tag inserted or fixed on a fish but also on an antenna, which generates a magnetic field, charging the tag which then emits a response that can be read by the system (Bubb *et al.*, 2002). Two types of PIT telemetry exist: Half-Duplex (HDX) and Full-Duplex (FDX). In FDX systems, the antenna continuously generates a magnetic field and the tag response can constantly be detected and recorded. HDX systems switch between the “generating a magnetic field” mode and “reading tag response” mode. Antennae are simpler in HDX, can be larger and also require less power. They are usually made from single or multiple loops of insulated wired electrical cable, generating the magnetic field. This antenna is then connected to a tuning box, which is linked to a reader box where the data logging computer is located (Barbour *et al.*, 2011). The tracked animal is usually tagged internally in the abdominal cavity with a different tag depending on whether the system is HDX or FDX. Tags of different sizes can be used, with the large ones having a strong signal and the smaller ones having a weaker signal. The signal range can be impacted by the presence of metal around the antennae, although it is often still usable. **HDX telemetry was used in the present study.**

2 METHODS

2.1 DESCRIPTION OF THE FSSG

The FSSG or Fish Spiral Sluice Gate or 'Fischwendelschleuse' is a fish passage with an adjustable attracting current aimed for all fish species (Fig. 2.1). This system enables continuous sluice operation and should also accommodate bottom-dwelling fish. It features an individually doped multi-chamber lock system with adjustable current options in both the inflow and outflow chambers.

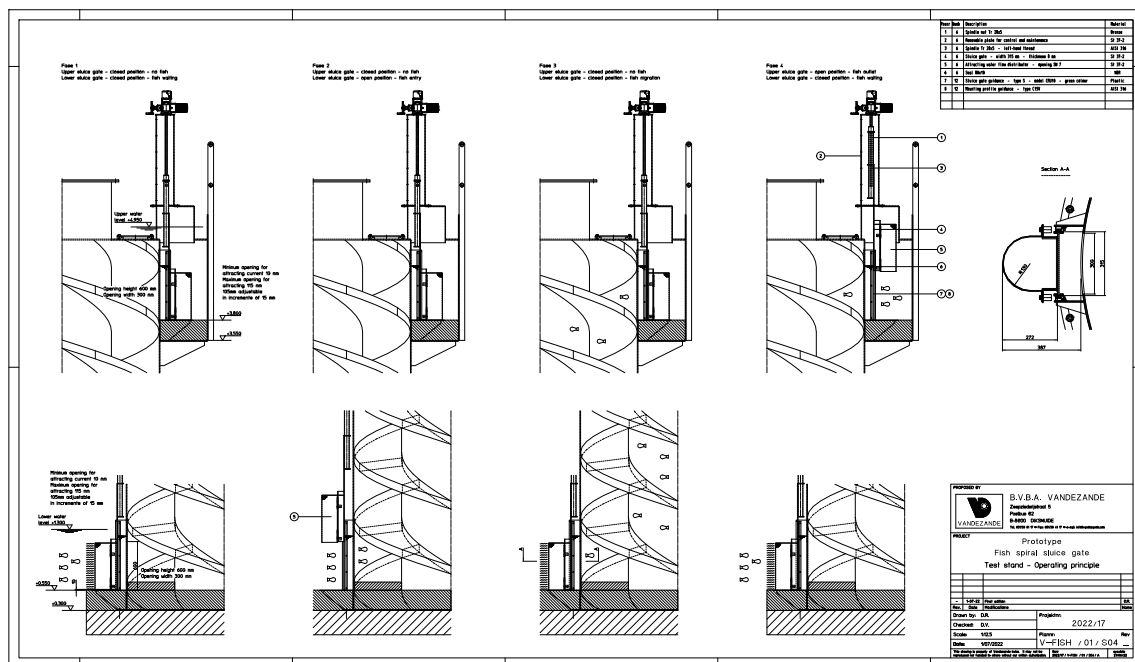


Figure 2.1: Operating principle of the FSSG.

The fish pass is designed to be as natural as possible via a natural substrate base and upright built (i.e., not rotating) (Fig. 2.2). The lock control is adaptable for each lock chamber to suit different target fish species. The FSSG lock is compact, suitable for fall heights of 1 to 10 meters. It has few moving parts and simple controls. Currently, the FSSG lock is being designed with diameters of 2 to 5 meters and flow rates of 50 to 500 liters per second. An additional attracting flow of approximately 500 to 2500 liters per second can be realized for both inflow and outflow.

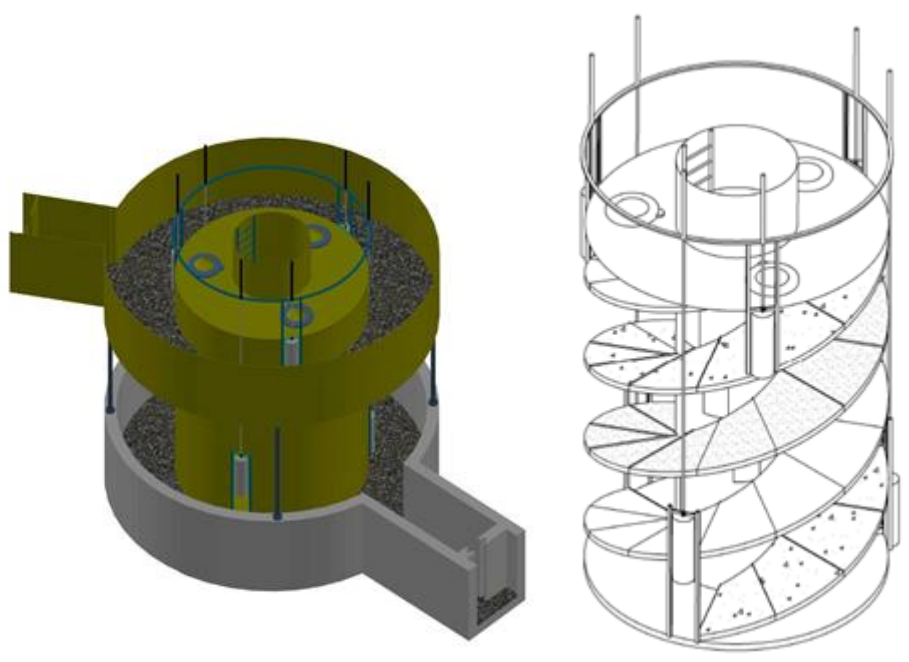


Figure 2.2: The entire fish pass is designed to be as natural as possible via a natural substrate base (left) and upright built (right).

2.1.1 Underwater connection via the outflow chamber and guide flow opening

The FSSG lock is installed underwater within a custom-designed outflow chamber, which also serves as its foundation (Fig. 2.3). This chamber guides fish either ascending to the lock doors or descending to the guide flow opening. To mimic a natural environment, the outflow chamber is filled with base substrate.

Table 2.2: Before the start and end of each experiment water temperature (WaterTemp in °C), pH (unitless), dissolved oxygen percentage (OxygenPerc in percentage), dissolved oxygen concentration (OxygenConc in mg/L) and air temperature (AirTemp in °C) were measured. Water temperature and pH could not be measured at the end of exp3 due to issues with the measuring equipment.

Description	Date	Time	WaterTemp	pH	OxygenPerc	OxygenConc	AirTemp
exp1	15-5-2024	13:00	19.1	8.3	73.7	6.8	18.8
exp1	21-5-2024	09:00	17.4	8.8	62.2	6.0	15.0
exp2	22-5-2024	10:00	16.9	8.3	70.2	6.8	16.8
exp2	28-5-2024	07:00	17.2	8.7	102.0	10.7	12.5
exp3	29-5-2024	10:00	16.9	8.4	55.0	5.4	17.0
exp3	05-6-2024	09:00	/	/	62.7	6.1	12.0

Table 2.3: Study period description. Start and stop time for the fish experiment and valve data collection are given.

	start.exp	stop.exp	start.gate	stop.gate
exp1	2024-05-15 12:53:00	2024-05-21 18:00:00	2024-05-15 12:53:00	2024-05-21 18:00:00
exp2	2024-05-22 13:07:00	2024-05-28 18:00:00	2024-05-22 13:07:00	2024-05-28 18:00:00
exp3	2024-05-29 12:08:00	2024-06-05 18:00:00	2024-05-29 12:08:00	2024-06-05 18:00:00

2.4 DATA PROCESSING

All the different sites where fish were either released, detected or recaptured are further on referred to as nodes.

Pit tag data were compressed using the default settings of the function *compress* of the R package *PITCleanr*. This data compression involves determining the first and last detection of a series of subsequent detections on a node as well as the number of detections during each slot (from first and last detection).

The location where the fish were released (i.e., the lower tank) was designated as the initial node, with the corresponding timestamp marking the start of each fish's journey. Conversely, the recapture location was identified as the final node, with the corresponding timestamp indicating the end of each fish's journey. All fish were alive and presumed to still have their tags at the time of release. However, some fish were found dead and/or tagless upon recapture. Due to the low detection rate of the antennas, particularly the upper one, we did not attempt to match unidentified fish with tag IDs from the release data. In a system with higher detectability, it might have been feasible to trace unidentified fish back to known but not-recaptured tag IDs with a reasonable degree of certainty. Unfortunately, this was not the case in our system. For the experiments, for which recapture data was available, fish were only included in the dataset if they were recaptured and identified upon capture. More specifically, detections and observations of fish which were not recaptured, had escaped the system or could not be identified due to tag loss were omitted. For exp1, six fish were found without a tag and 13 fish were not recaptured (six of them because of the absence of a tag). For exp2, three fish were not recaptured. For exp3, one fish was found without a tag and eight fish were not recaptured (one of them because of the absence of a tag).

The temporal resolution and range of the valve-opening and pressure data was different between experiments. In order to harmonize the temporal resolution between experiments and to easily link fish data with valve and pressure data, linear interpolation was applied to yield a temporal resolution of one second. A valve was considered open when the opening was larger than 28 cm. For all experiments the valve was considered closed when the opening was less than 3 cm. For every second the time since the last opening was determined.

3 RESULTS

3.1 EXPERIMENTAL LIMITATIONS AND ASSOCIATED ASSUMPTIONS

Fish which were used for multiple experiments seemed to have a significantly lower travel time from the lower basin to the lower valve. More specifically, it seems that fish that were re-used for a second experiment moved from the lower basin to the lower valve significantly quicker (Figure 3.1). It cannot be said with certainty that this finding, fish being familiar to the system moving more quickly through it, is of a causal nature as the conditions of the experiments themselves might have differed as well. Fish that were used multiple times did not seem to be more or less likely to move up and down the FSSG multiple times within an experiment (Figure 3.2).

Although most fish went through the system (from the lower valve to the upper valve) only once, some went through the system several times (Table 3.1). For exp3, one fish went up to six times through the system.

Table 3.1: Number of fish going through the system (from the lower valve to the upper valve) multiple times, ranging from one to six times.

	Number of loops					
exp	1	2	3	4	5	6
exp1	8	1	0	0	0	0
exp2	24	1	0	0	0	0
exp3	21	3	1	1	1	1

Detection probability at the lower antenna for exp1, exp2 and exp3 were 100%, 83% and 83%, respectively. Detection probability at the upper antenna for exp1, exp2 and exp3 were 6%, 28% and 39%, respectively.

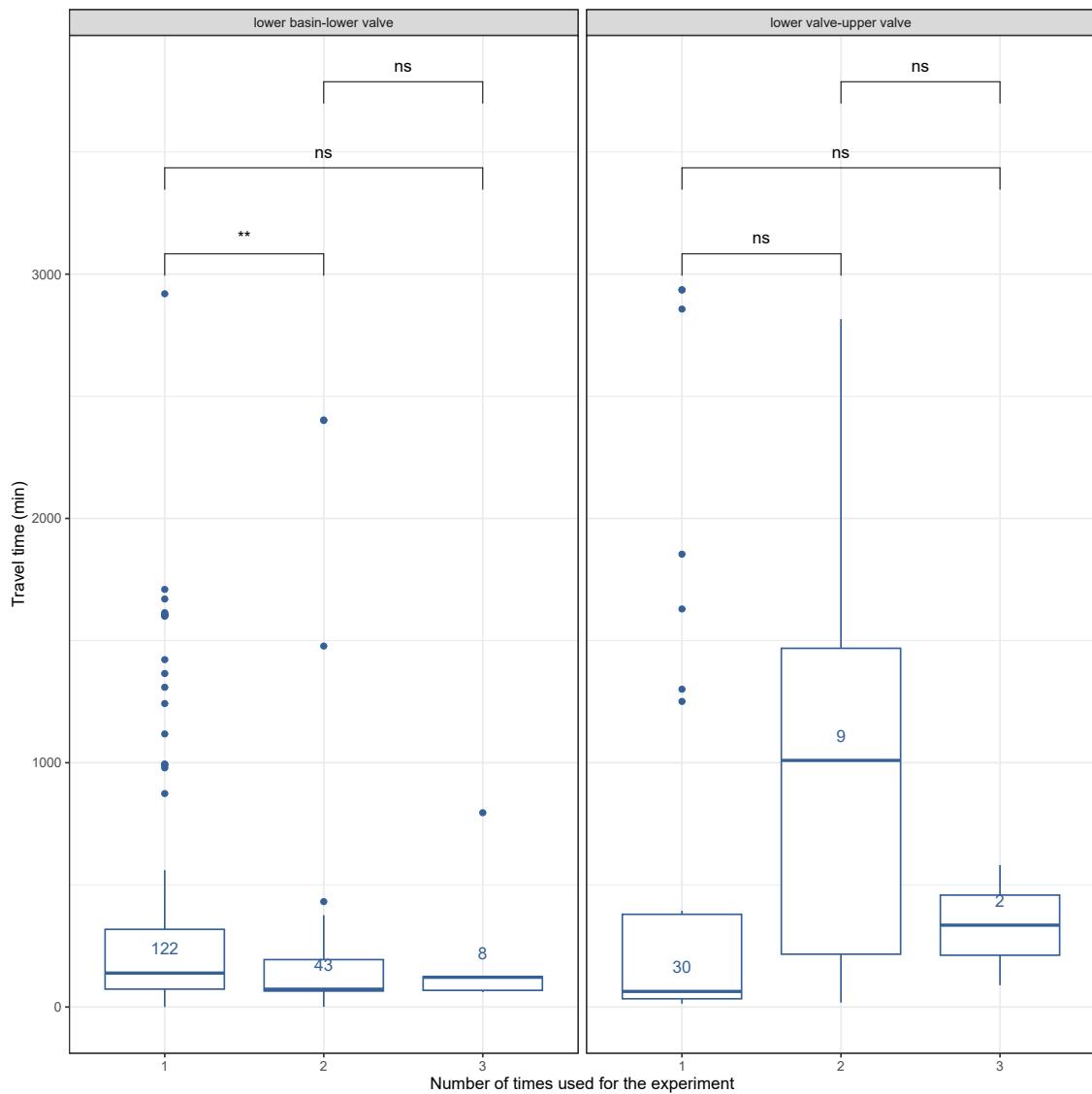


Figure 3.1: Travel time (min) from the lower basin to the lower valve and from the lower valve to the upper valve in function of the number of a times a fish was used in experiments. Pairwise wilcoxon ranks sum tests with Bonferroni correction were applied. p-values were classified as ns (>0.05), * ($0.05-0.01$), ** ($0.01-0.001$), *** ($0.001-0.0001$), **** ($0.0001-0$).

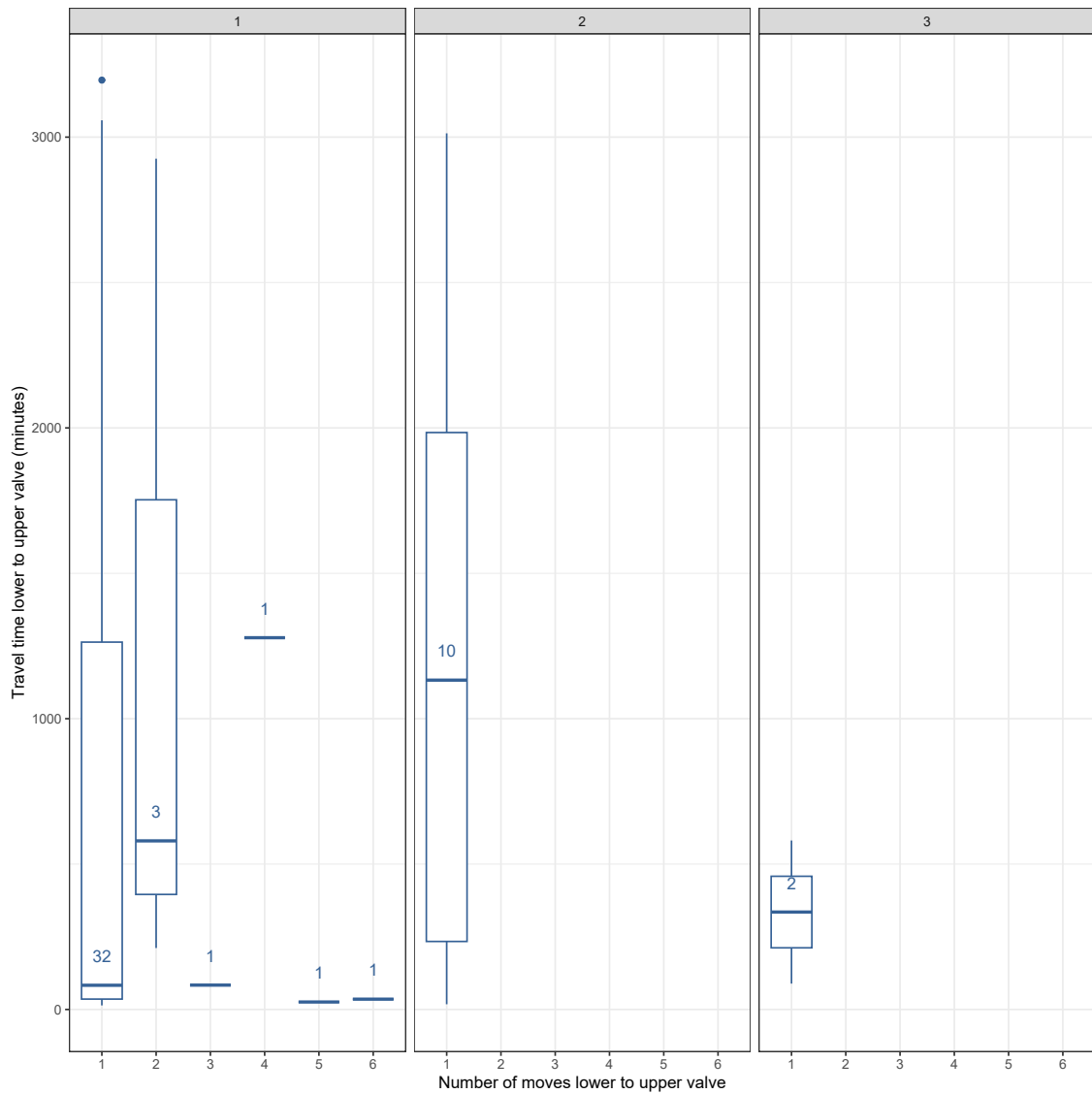


Figure 3.2: Travel time (min) from the lower valve to the upper valve in function of the number of times a fish moved from the lower valve to the upper valve. A distinction is made between fish that have been used once, twice, or three times.

3.2 ENTRANCE EFFICIENCY, PASSAGE EFFICIENCY AND OVERALL EFFICIENCY

Before fish can successfully enter and pass the FSSG they need to be able to find the entrance (i.e., attraction efficiency). Unfortunately, the current experimental set-up does not allow for an assessment of the attraction efficiency as the area in which fish were released was too narrow to be representative for most real-life situations (Triano *et al.*, 2022).

Entrance efficiency is defined as the percentage of attracted fish that enter the fishway (Cooke & Hinch, 2013). In this study the entrance efficiency is considered the proportion of tagged fish able to enter the FSSG (i.e., the lower valve) and swim through it. In practice, this is the proportion of released fish detected on either the lower antenna, upper antenna or recaptured in the upper basin. Since all tagged fish are considered to be attracted to the FSSG due to the narrowness of the lower basin and proximity of the entrance of the FSSG, all tagged fish were considered for the entrance efficiency. **Entrance efficiency was very different between experiments and was highest for exp1 (0.98) and lowest for exp3 (0.70)** (Table 3.3). It should be noted that the calculated metric is **most likely an overestimation from the actual entrance efficiency that was obtained in this lab setting**. This is because fish in the narrow lower basin had no real other options than move towards the entrance and fish that lingered outside the entrance without entering might also have been detected by the lower antenna. Due to the imperfect detection probability of the lower antenna (exp1: 100%, exp2: 83% and exp3: 83%) fish might have passed through the lower antenna without being detected, resulting in an underestimation of the metric. However, this effect is most likely to be less of an issue compared to the former two. Not only because the detection probability of the lower antenna was relatively high, also because of the combined opportunities of detection at both the lower and upper antennas and the opportunity to recapture fish at the upper basin (i.e., fish that were not detected at the lower antenna but detected at the upper antenna and/or recaptured in the upper basin must have entered at some point and were therefore also labelled as such).

Passage efficiency is defined as the percentage of entered fish that successfully pass the FSSG (Cooke & Hinch, 2013). In this study, the passage efficiency is considered the proportion of entered fish that were able to move through the exit of the FSSG. In practice, this is the proportion of fish that are detected on the upper antenna and/or recaptured in the upper basin over the fish that are known to have entered the FSSG (i.e., they were detected on at least one antenna or recaptured in the upper basin). **Passage efficiency was more similar between experiments than the entrance efficiency and was highest for exp2 (0.84) and lowest for exp3 (0.68)** (Table 3.3). Unfortunately, the pit antenna at the upper valve failed to detect numerous fish (as many fish undetected by the upper antenna were recaptured in the upper basin) and for this reason it was important to also look at the number of fish that were recaptured in the upper basin to determine the passage efficiency. Using both the number of recaptured fish and the detections yielded the highest and most representative passage efficiency as some fish that reached the upper basin might have moved back to the lower basin. Without the pit antenna this would not have been recorded. Nevertheless, because of the very low detectability (exp1: 6%, exp2: 28% and exp3: 39%) the issue remains that fish moving to the upper basin and back to the lower basin or the area between the lower and upper valve, might not always have been detected. In addition, since the number of entered fish is most likely to be an overestimation and given that this is the reference for the estimation of the passage efficiency, the latter might be further underestimated. The passage efficiency calculated here, even the one that combines recapture and detections, is therefore **most likely to be an underestimation from the actual passage efficiency that was obtained in this lab setting**.

Table 3.2: Description of the uncertainty of the different estimates of the calculated metrics

Metric	Underestimation	Overestimation	Reliability
Entrance efficiency	Not all fish that entered might have been detected (i.e., imperfect detection probability)	<p>Fish in the narrow lower basin had no real other options than move towards the entrance</p> <p>Fish that lingered outside the entrance without entering might have been detected by the lower antenna</p>	Most likely an overestimation
Passage efficiency	<p>The number of entered fish (denominator of metric) is likely to be overestimated</p> <p>Not all fish that exited might have been detected (i.e., imperfect detection probability)</p>	Fish that lingered before the exit without entering might have been detected by the lower antenna	Most likely an underestimation

Overall efficiency is defined as the percentage of all approaching fish that are attracted to, enter and pass through the exit of the FSSG (Baker *et al.*, 2019). In this study, the overall efficiency is considered the proportion of all tagged fish that were able to move through the FSSG. In practice, this is the proportion of fish that are detected on the upper antenna and or recaptured in the upper basin over the total number of tagged fish. As for the entrance efficiency, **the overall efficiency was very different between experiments and was highest for exp1 (0.79) and lowest for exp3 (0.47).** It should be stressed that in this study all tagged fish were considered attracted fish. If failure to attract would have been accounted for (which was not possible for this study), it is likely that this overall efficiency would be considerably lower.

Table 3.3: Entrance efficiency, passage efficiency and overall efficiency calculated in different ways. The most reliable estimates are marked in red.

calculation	exp1	exp2	exp3
entrance efficiency: recapture and detections	0.98	0.86	0.70
passage efficiency: recapture and detections	0.80	0.84	0.68
passage efficiency: recapture	0.74	0.75	0.58
passage efficiency: detections	0.17	0.36	0.36
overall efficiency: recapture and detections	0.79	0.72	0.47
overall efficiency: recapture	0.72	0.65	0.40
overall efficiency: detections	0.17	0.28	0.24

To assess which factors were determinative for a fish making it up the FSSG or not, a simple logistic model was used with as response whether a fish made it up the FSSG or not and as explanatory variables the length and weight. Model selection via the AIC criterium and a backward approach of adding and removing variables resulted in a model that only retained an intercept. This suggests **there was no effect of length or weight on whether a fish made it up the FSSG or not**. When using only fish that were only used once, the same results were obtained.

To assess which factors were determinative for the opening of the valve (upper and below) through which fish entered, a simple logistic model was used with as response the opening as a percentage (i.e. 0% was fully closed and 100% was fully open) and as explanatory variables the length, weight, and whether it was the upper or lower valve and their interaction. Model selection via the AIC criterium and a backward approach of adding and removing variables resulted in a model that only retained the intercept. This suggests **there was no effect of length, weight, or which valve was involved on the opening through which a fish entered the lower valve or left the upper valve**. When using only fish that were only used once, the same results were obtained.

3.3 STATISTICS OF THE FSSG DURING THE EXPERIMENTS

The duration of one cycle was similar between the upper and lower valve within a certain experiment (Figure 3.3). This makes sense as they need to work synchronized. Between experiments there was however a clear difference in the total duration of a cycle and how it was distributed over the different phases (closed, opening, open, and closing).

Exp1 to exp3 were more or less similar in the total duration of one cycle (though it seemed to be slightly shorter for exp1) and the distribution among the different phases within a valve. While the lower valve was closed most of the time, the upper valve was open most of the time. For exp1 especially, the time the lower valve was open appeared only slightly more than half of that of exp2 and exp3. Also the time the upper valve was open appeared smaller for exp1, but not to the same level as for the lower valve. Important to note is that the temporal resolution of the valve-opening-measurements of exp1 were more than 10 times coarser than for the other experiments (Table 3.4), which might cause the opening and closing seem to start earlier and later respectively and the duration of the open phase to appear smaller. One might therefore argue that the operational settings of exp1, exp2 and exp3 were most likely to be the same and any difference between them would be the result of other conditions (e.g. learning behaviour of fish or weather conditions and related differences in oxygen concentration and temperature).

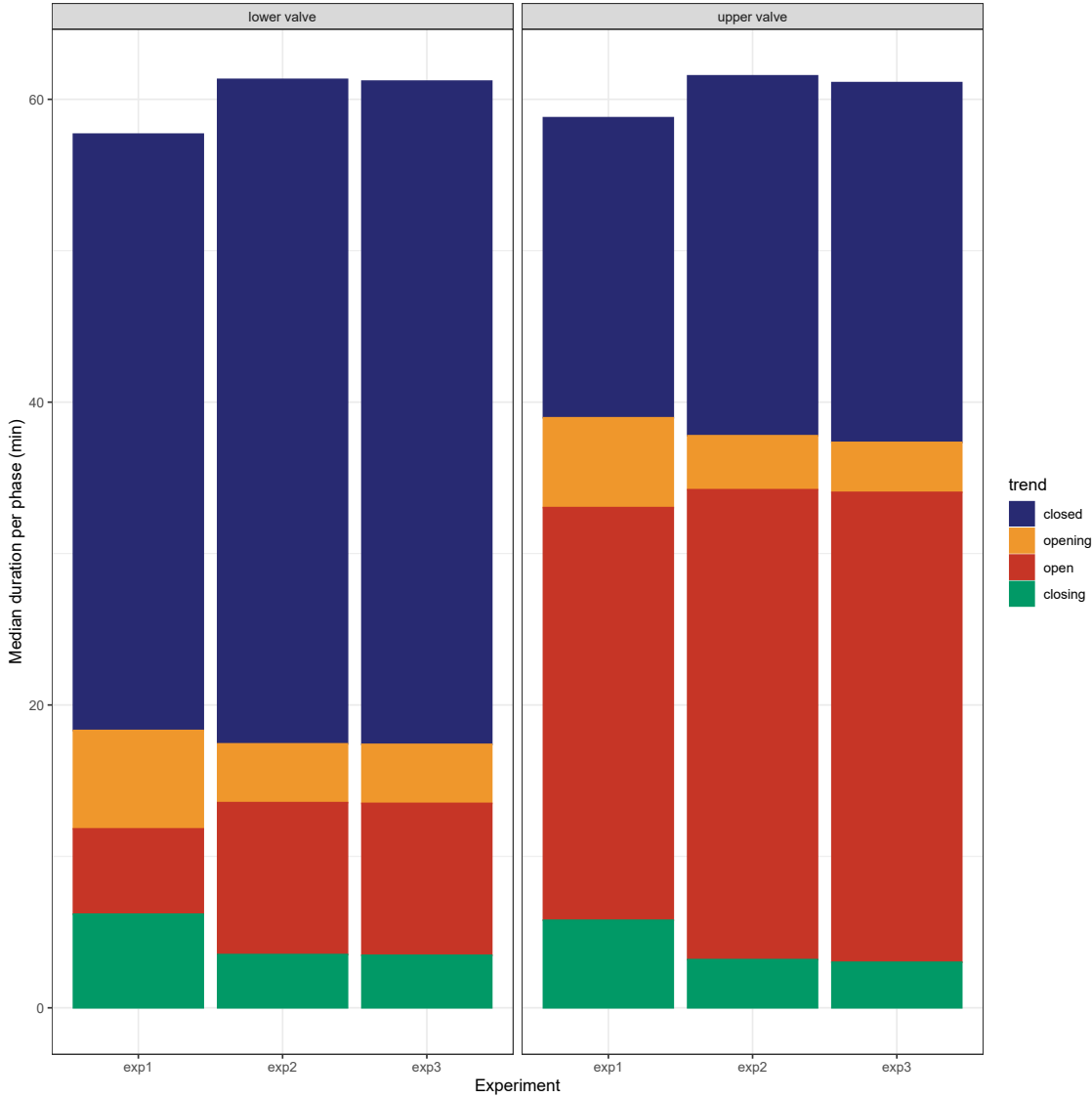


Figure 3.3: median duration (min) of each phase (closed, opening, open and closing) per experiment.

Table 3.4: Temporal resolution (in seconds) of measurements of the valve opening

node	exp.gate	mean	sd
lower valve	exp1	96.8	68.2
lower valve	exp2	8.9	0.3
lower valve	exp3	8.9	0.3
upper valve	exp1	102.3	66.1
upper valve	exp2	8.9	0.3
upper valve	exp3	8.9	0.3

3.4 STATISTICS OF THE FISH MOVEMENT IN THE FSSG

When considering all fish, the **entrance time** (i.e., the travel time from the lower basin (start of the experiment) to the lower valve (i.e. first detection at the lower antenna)) seemed to become lower from exp1 to exp2 to exp3 and was even significantly lower for exp3 than for exp1 and exp2 (Figure 3.4 and Table 3.5). This might be partially the result of some of the fish being re-used. Leaving out these fish resulted in a higher travel time for exp1 and exp2, but as there was no significant effect of using fish a third time, the travel time of exp3 (where many fish were used a third time) stayed more or less the same. **Passage time** (i.e., the travel time of fish moving from the lower valve (i.e. last detection at the lower antenna) to the upper valve (i.e. last detection at the upper antenna)) did not seem to differ between experiments. It should be noted however that though a significant difference was found between experiments for the entrance time and not for the passage time, the number of fish that were detected moving from the lower basin to the lower valve was much higher than the amount of fish that were detected moving from the lower valve to the upper valve. This affects the statistical power and allows for smaller differences in the entrance time to be identified as significant. When comparing the medians and averages, the differences between experiments appear much more pronounced for the passage time.

Travel time from the lower basin to the lower valve was considerably lower than the travel time for the lower to the upper valve (Fig. 3.5). **50% of all tagged fish had an entrance time of less than 100 (exp2) to 200 minutes (exp1 and exp3), while 50% of all entered fish had a passage time of less than 225 (exp1 and exp2) to 1200 minutes (exp3)** (Fig. 3.6). After 24 hours (or 1440 minutes), approximately 85% of the entering fish had entered the FSSG. After 24 hours, approximately 50 to 85% of the passing fish had passed the FSSG.

Table 3.5: Median statistics for different experiments and trajectories. Travel time represents the time (in minutes) from the last detection in one site to the first detection in another, with the exception of the trajectory from the lower valve (i.e. lower antenna) to the upper valve (i.e. upper antenna) where for both the last detection was used. The opening of the valve at which the first (in the case of the lower valve) or the last (in the case of the upper valve) is given in cm. The time of entrance (in the case of the lower valve) or escape (in the case of the upper valve) since the valve started to open is given in minutes.

metric	exp	travel_time	opening	since_open
entrance time	exp1	198.3	27.3	11.9
entrance time	exp2	189.4	28.8	8.6
entrance time	exp3	121.6	29.0	6.6
passage time	exp1	214.2	29.1	23.2
passage time	exp2	1705.9	29.1	18.2
passage time	exp3	210.9	29.0	19.8

This decreasing trend in travel time from the lower basin to the lower valve for later experiments is also apparent from the **number of cycles before fish enter the lower valve** (Figure 3.7). For both exp2 and exp3 most fish found the lower valve during the second cycle and some fish were even able to find it during the

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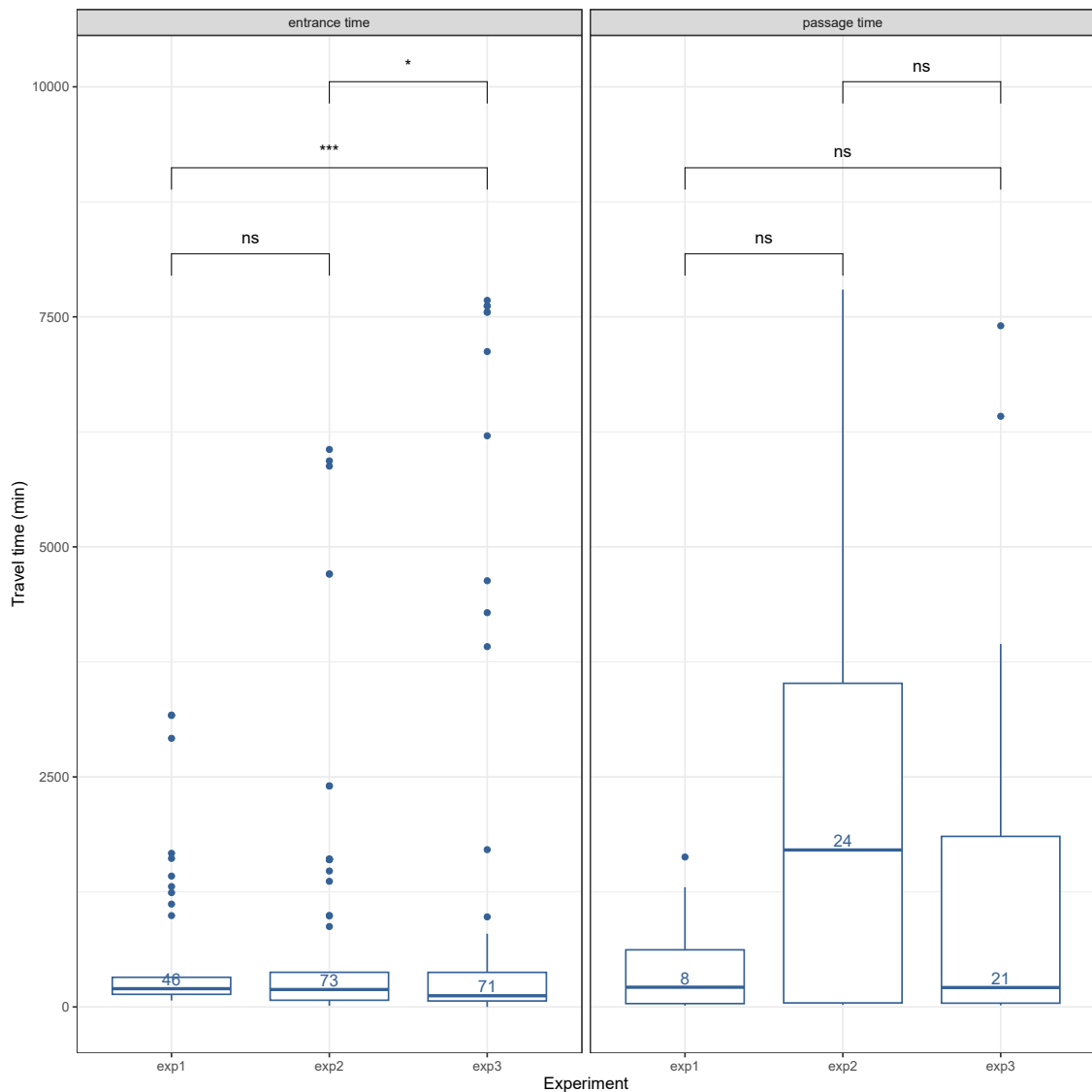


Figure 3.4: Travel time (min) from the lower basin to the lower valve and from the lower valve to the upper valve per experiment. Pairwise wilcoxon ranks sum tests with Bonferroni correction were applied. p-values were classified as ns (>0.05), * ($0.05-0.01$), ** ($0.01-0.001$), *** ($0.001-0.0001$), **** ($0.0001-0$).

first cycle. For exp1 on the other hand, most fish found the lower valve after only the fourth cycle and none were able to find it after the first cycle. Omitting re-used fish did not affect these results much. Therefore re-used fish were also used. Results without the re-used fish are given in appendix A2.

For all experiments there were also fish that took a very long time to move to the lower valve. Indeed, many fish only found the lower valve after more than 20 cycles.

For exp2 and exp3, fish seem to wait until the lower valve is completely open before entering, but some fish also seem to enter when the valve is opening and closing (Figure 3.8). The time the lower valve was entered since the valve last started to open decreased significantly from exp1 to exp2 and exp3 (Figure 3.10). Especially for exp1 the time since the valve opened was much higher than for exp2 and exp3. This is somewhat to be expected as fish seem to mainly wait for the valve to be fully opened before entering and the time it takes for the valve to open and close seemed much larger for exp1 than for exp2 and exp3 (although, as mentioned earlier, this might be the result of the much lower temporal resolution of the valve-opening-measurements of exp1). However, when accounting for the different durations of the different phases the open phase still seems most important for exp2 and exp3, unlike for exp1 where now not only the opening phase seems to be more important than the open phase, but also the closing phase

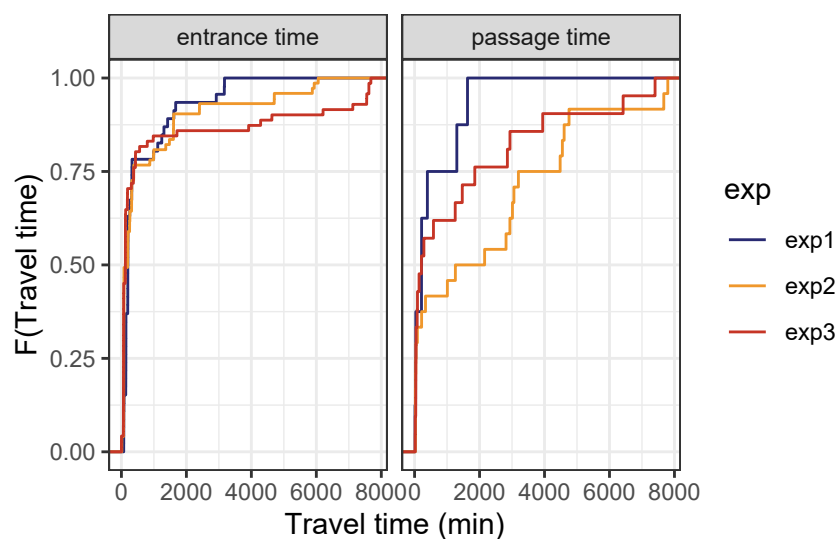


Figure 3.5: Cumulative distribution function of the travel time from the lower basin to the lower valve, and from the lower valve to the upper valve. The y-axis depicts the proportion of fish that after a certain amount of time (x-axis) have completed the trajectory.

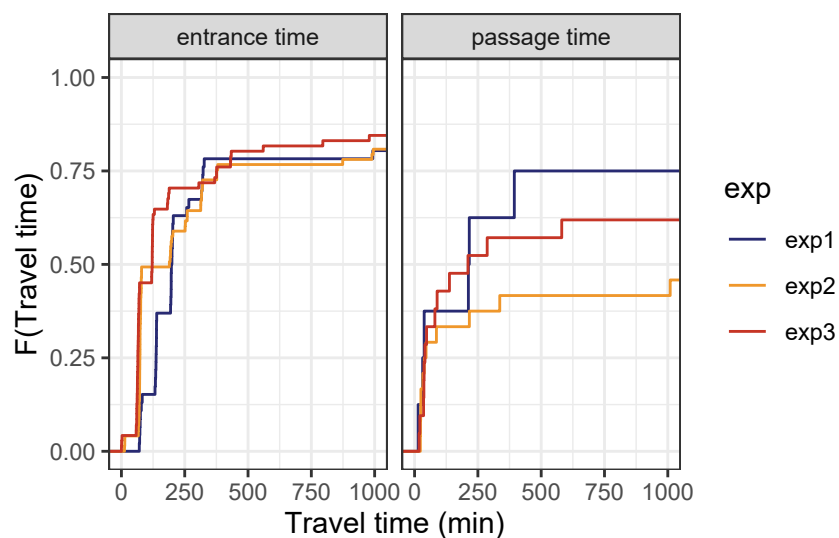


Figure 3.6: Zoomed in (until 1000 minutes) cumulative distribution function of the travel time from the lower basin to the lower valve, and from the lower valve to the upper valve. The y-axis depicts the proportion of fish that after a certain amount of time (x-axis) have completed the trajectory.

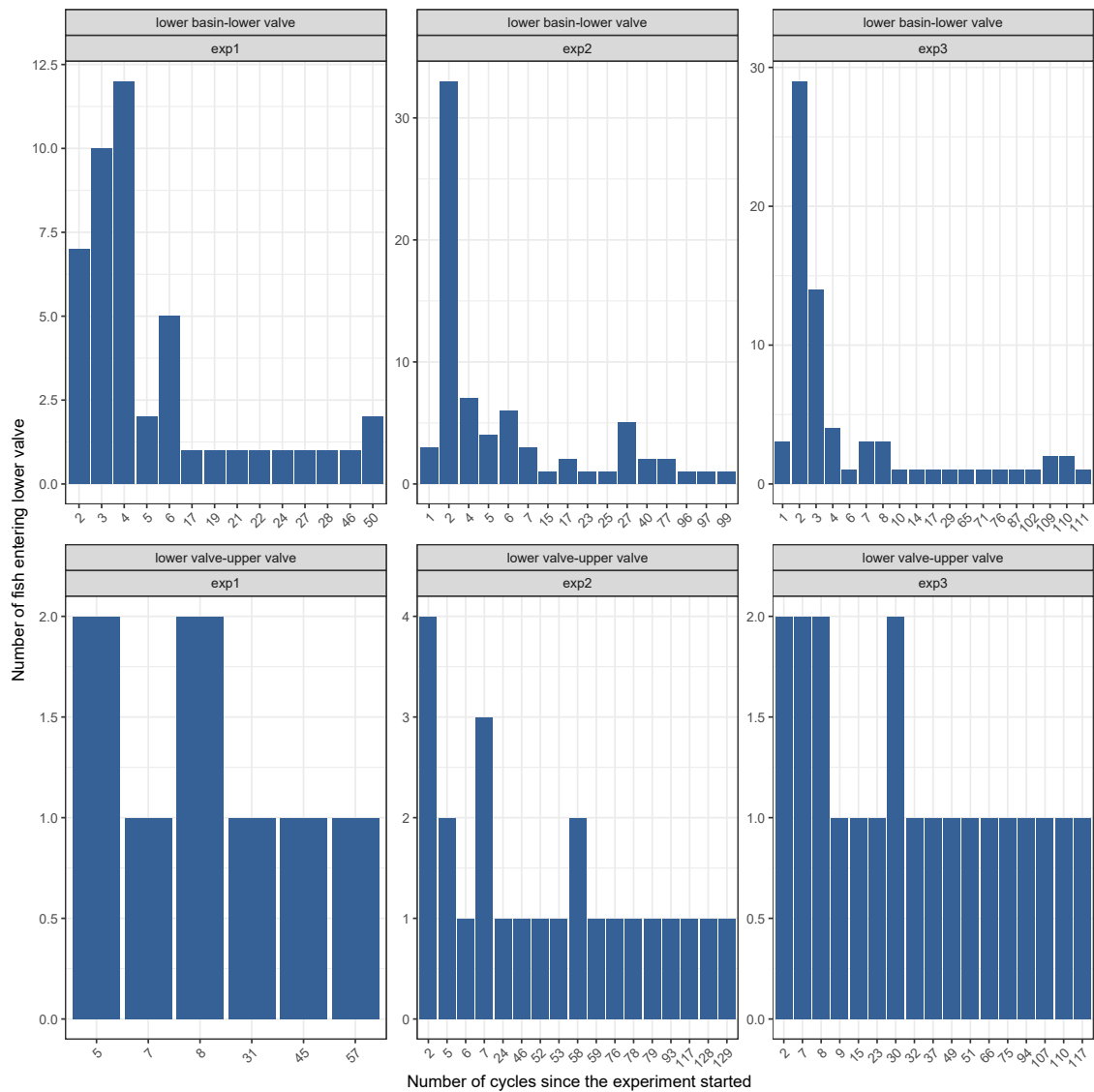


Figure 3.7: Number of cycles before fish entering the lower valve (lower basin to lower valve) and leaving the upper valve (lower valve to upper valve) per experiment.

seems to be relatively important (Figure 3.9). Since the opening and closing phase are most important for exp1 it is to be expected that the opening of the valve at which they seem to enter the lower valve will be smaller than for exp2 and exp3. Indeed the opening at which fish enter seems to decrease significantly from exp1 to exp2 and exp3 (Figure 3.11).

Regarding the upper valve, fish also seem to mainly wait until it is completely open (Figure 3.8), but compared to the lower valve, a relatively large number seem also to leave when the valve is opening or closing. It is striking how some fish seem to pass the upper valve when it is closed. This might be the result of the detection range of the antenna being too large (detecting animals outside the FSSG) or too low (not being able to detect animals at the moment they leave). Given the low observed detectability of the upper antenna, it is most likely that the detection range is too low.

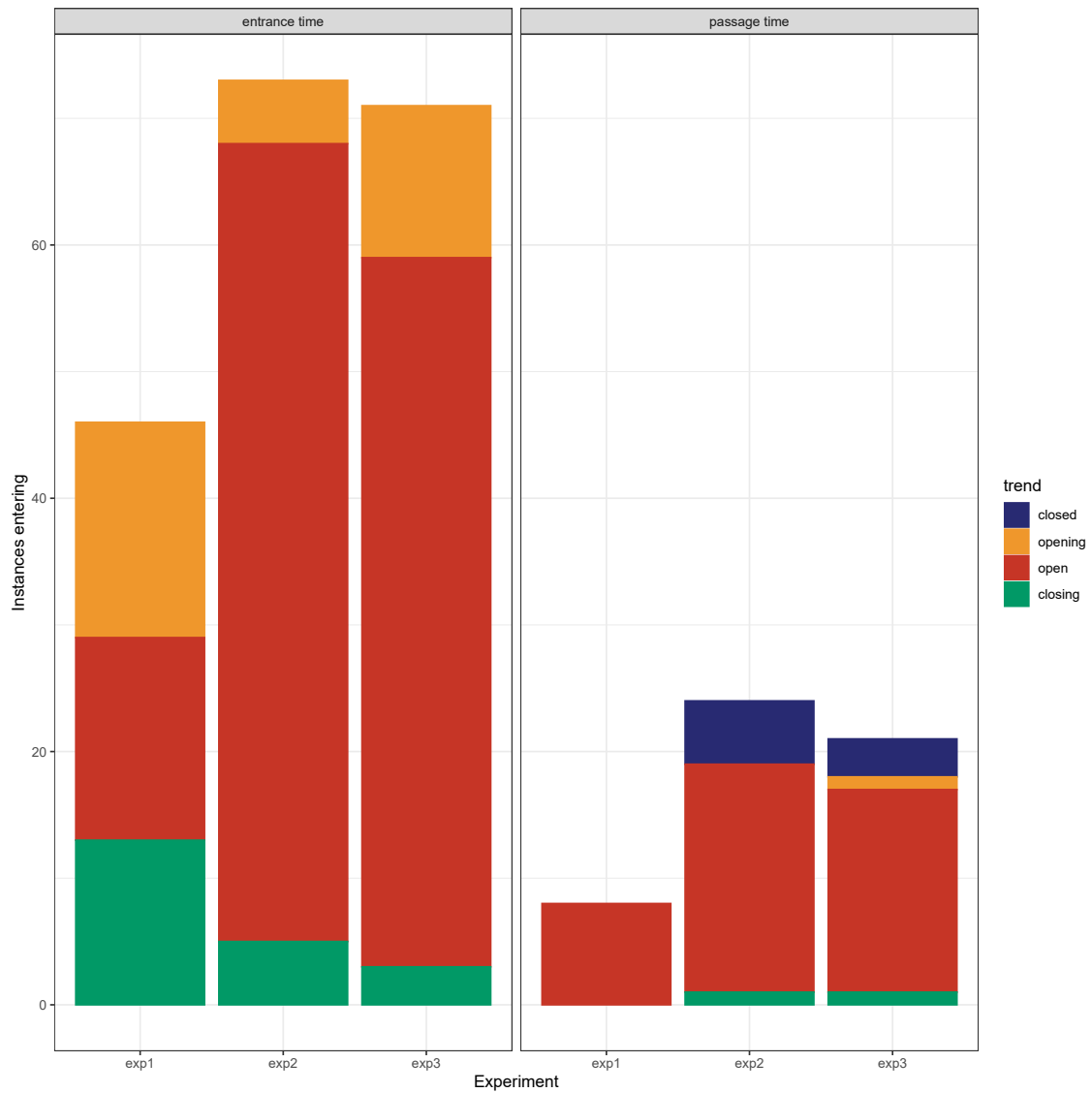


Figure 3.8: Number of fish entering the lower valve or leaving the upper valve per phase and per experiment.

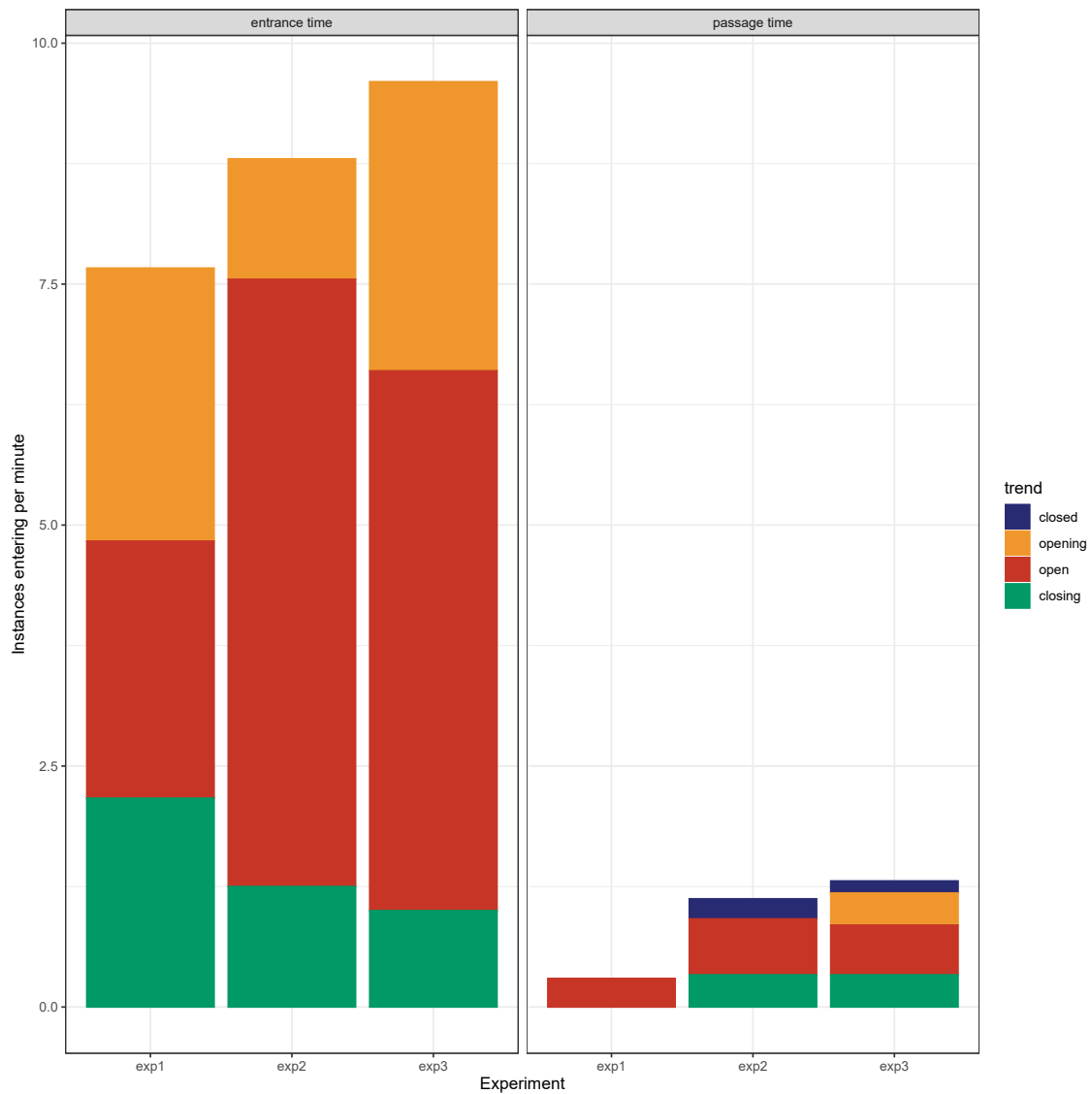


Figure 3.9: Number of fish entering the lower valve or leaving the upper valve per phase and per experiment. To account for the different durations of each phase, the number was normalized against the duration of each phase (i.e. one fish being assigned to a short phase had more impact in the barplot than one fish assigned to a long phase).

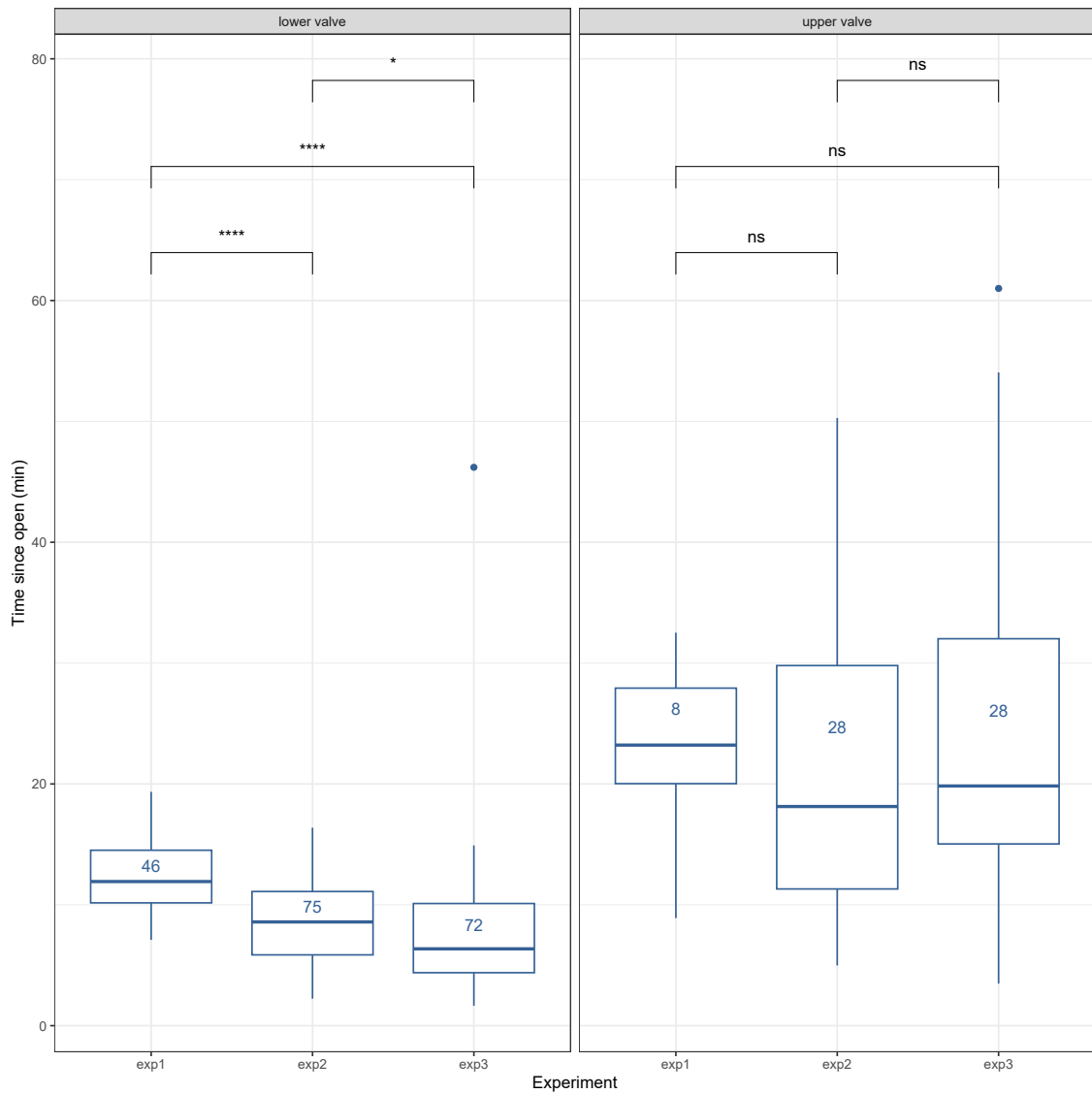


Figure 3.10: Time since opening (min) at which fish enter or leave the lower and upper valve respectively per experiment.

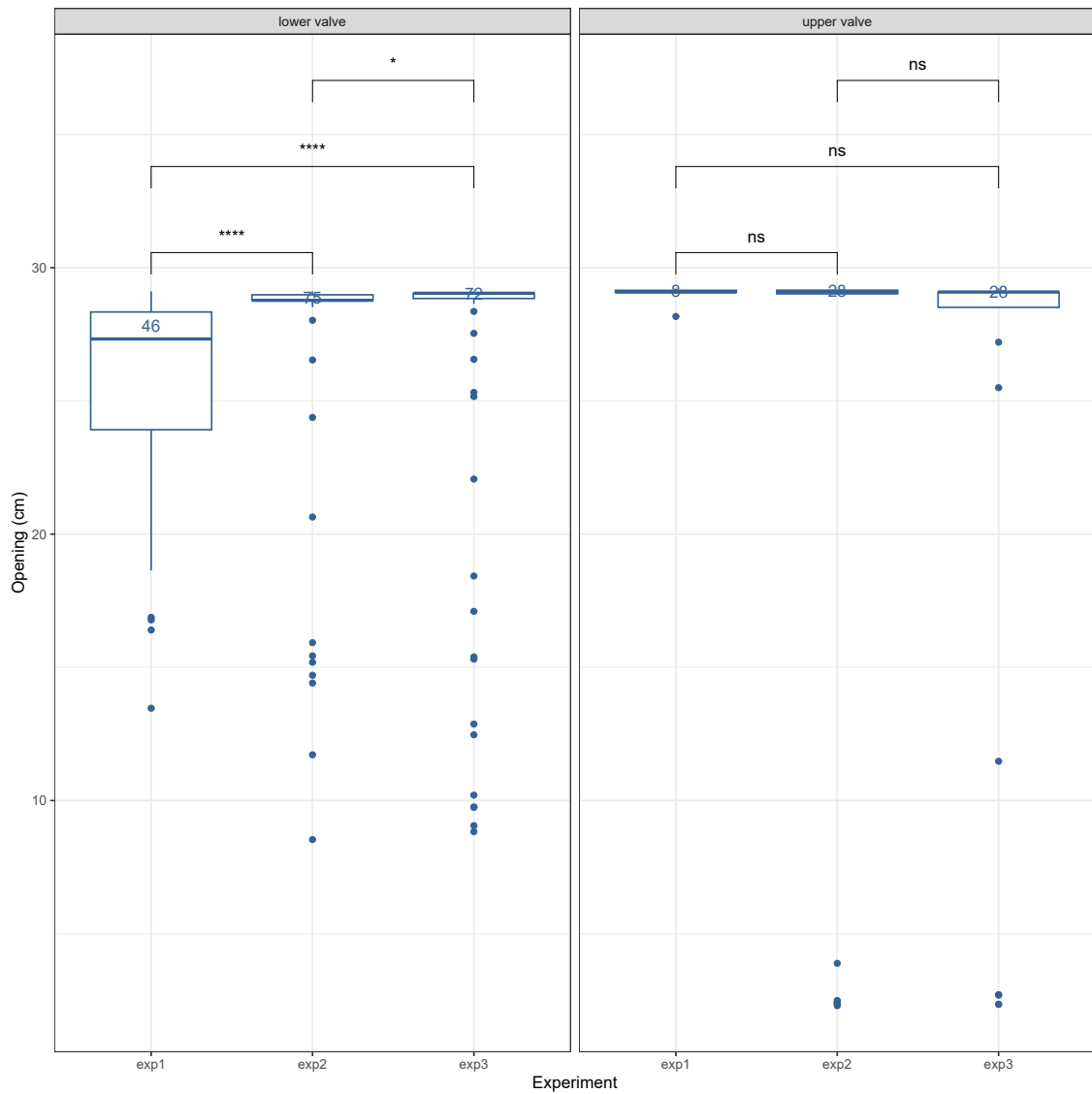


Figure 3.11: Opening (cm) at which fish enter or leave the lower and upper valve respectively per experiment.

3.5 GRAPHS VALVE OPENING

In the following graphs the working of the lower and upper valve are depicted. The cycle duration and phase distribution of exp1 (Figure 3.12 and Figure 3.13), exp2 (Figure 3.14 and Figure 3.15) and exp3 (Figure 3.16 and Figure 3.17) are very similar. The slight difference in cycle duration and phase distribution of exp1 versus exp2 and exp3 is most likely the result of the much lower temporal resolution of the valve-measurement-data of the former. The pressure at the entrance ranged from 0.05 to 0.40 kPa (Figures A.17, A.19 and A.21), while at the exit it ranged from -0.30 to 0.05 kPa (Figures A.18, A.20 and A.22).

3.5.1 Graphs valve opening exp1 (may 2024)

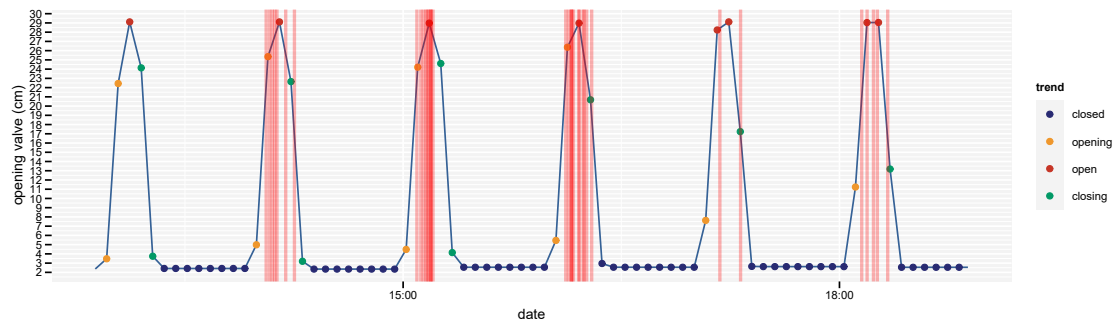


Figure 3.12: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish. The different phases are depicted in different colors.

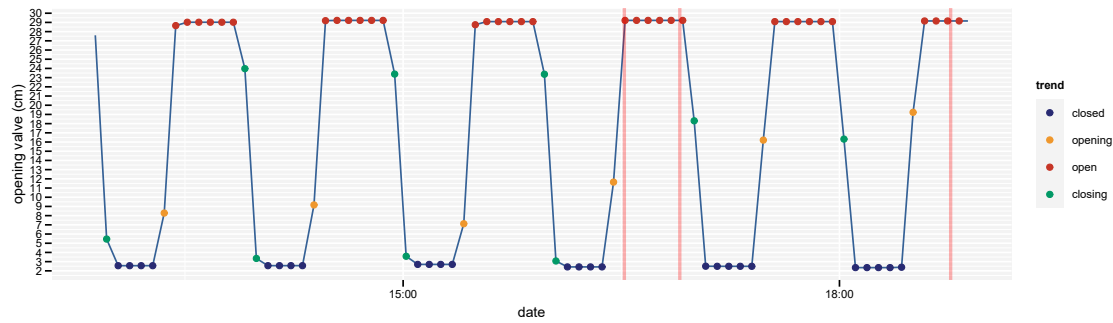


Figure 3.13: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish. The different phases are depicted in different colors.

3.5.2 Graphs valve opening exp2 (may 2024)

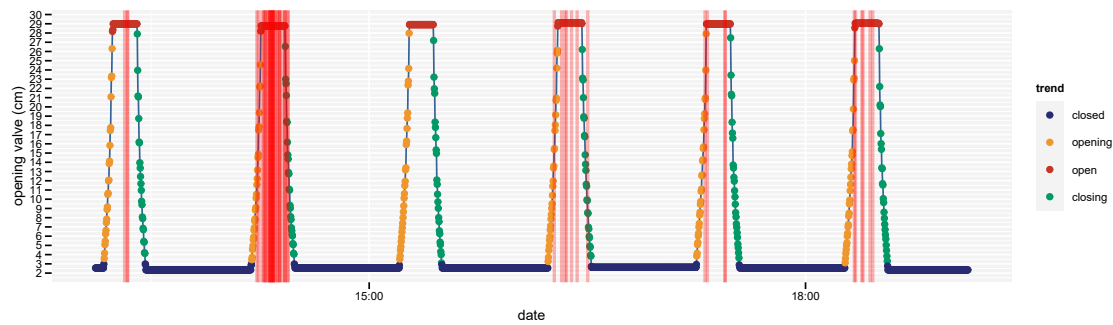


Figure 3.14: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish. The different phases are depicted in different colors.

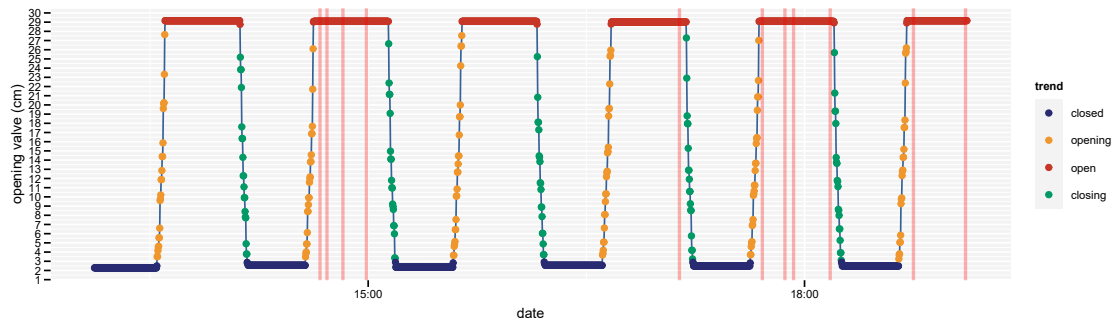


Figure 3.15: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish. The different phases are depicted in different colors.

3.5.3 Graphs valve opening exp3 (may 2024)

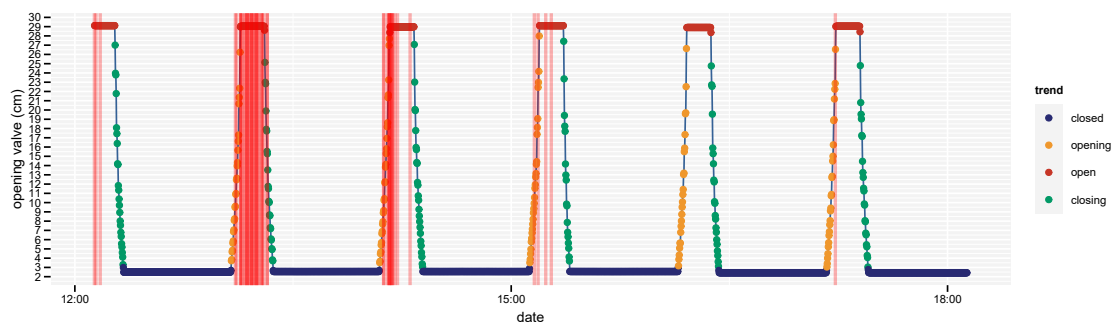


Figure 3.16: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish. The different phases are depicted in different colors.

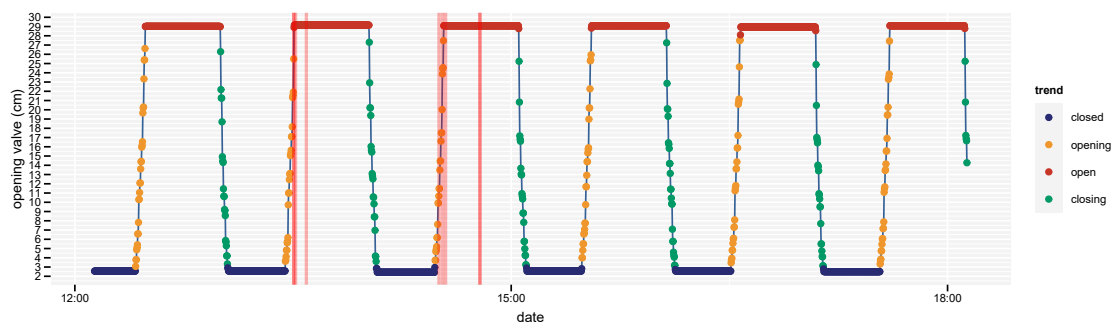


Figure 3.17: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish. The different phases are depicted in different colors.

4 DISCUSSION

For the experiments exp1 to exp3, the cycle duration and phase distribution can be considered the same, though this was not apparent from the data because of the too low temporal resolution of the exp1 valve-opening data. The lower valve was closed most of the time, while the upper valve was open most of the time. Fish generally **wait until the valves are completely open before entering and leaving the FSSG**, though for the upper valve a relatively large amount of fish also seem to leave the FSSG when the valve is opening or closing.

Despite operational settings of the FSSG throughout the experiments of 2024 being fixed, **entrance efficiency and passage efficiency varied substantially** as they ranged **from 0.70 to 0.98, and from 0.68 to 0.84, respectively**. It is very difficult to determine the underlying cause behind this difference as these values are not exact (especially the entrance efficiency might have been overestimated due to the experimental design and detection range reaching outside the entrance) and local, potentially interfering, conditions might have been present but were only sporadically measured (e.g. water quality) ([Bunt *et al.*, 2012](#)). In addition, though the available results did not indicate any effect, the familiarity with the FSSG of fish that were re-used for the different experiments might have had an effect. **The length and weight did however not seem to have any effect on whether fish were able to successfully use the FSSG, nor did it have an effect on the time it took fish to move up the FSSG**. Only a limited number of fish went through the FSSG multiple times. Some preliminary tests with other species indicated there was no clear difference between species in the passage success or passage timing.

When assessing fish passage four different aspects should be assessed: attraction efficiency (the proportion of approaching fish that locate the fishway entrance), entrance efficiency (proportion of attracted fish that enter the fishway), passage efficiency (proportion of entered fish that successfully pass the fishway) and overall efficiency (proportion of approach fish that are attracted to, enter, and successfully pass the fishway) (Baker *et al.*, 2019).

Regarding the attraction efficiency, it should be noted that fish were forced into the narrow lower basin with no-where else to go than towards the lower valve. It is reasonable to assume that all fish within this lower basin where in the attraction zone of the FSSG and could all be classified as attracted to the FSSG. Whether the provided attraction flow would be strong enough to direct upstream-migrating riverine fish towards the inlet of the FSSG (i.e., What would be the attraction efficiency?) in a real-life situation, could not be assessed under these fixed laboratory settings and would require field tests on sites that resemble the locations the FSSG is intended for or experiments with larger approach zones. **The FSSG therefore has the potential to aid fish in their migration, but placement and sound operational settings will most likely be key.** Though the relatively low amount of water that passes through the FSSG is beneficial for water managers that want to prevent too much water to flow from one side of a sluice or hydropower installation to the other, it is not ideal to attract fish and make them move through the system. Both the unnatural low amount and the discontinuous, interrupted supply of water via the single inlet (which could be remediated by the use of all three canals in combination with an additional attraction flow (not tested here)) are likely to limit the ability for fish to find the FSSG entrance (i.e., attraction efficiency), enter it (i.e., entrance efficiency) and move successfully through it (i.e., passage efficiency)(Bunt *et al.*, 2012). **Assessments of attraction efficiency in real-life situations are strongly advised.**

Despite its high variability, **the entrance efficiency in this study was relatively high (0.70 to 0.98)**. It is however key to mention here that the calculated entrance efficiency is **most likely an overestimation from the actual entrance efficiency that was obtained in this lab setting**. Few studies have assessed entrance efficiency before but the few studies available describe mainly lower values. More specifically,

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5 CONCLUSION

This study demonstrates that the Fish Spiral Sluice Gate (FSSG) holds strong potential as an effective fish passage system. The FSSG achieved a relatively high entrance efficiency (0.70–0.98) and passage efficiency (0.68–0.84), performing comparably to nature-like fishways without being significantly influenced by fish length, weight, or species.

However, critical limitations inherent to the laboratory setting frame these findings:

- **Efficiency metric uncertainties:** Entrance efficiency was likely overestimated due to detection range boundaries extending outside the entrance, whereas passage efficiency was likely underestimated.
- **Uncertain attraction efficiency:** Forced entry conditions in the lower basin prevented a true evaluation of attraction flow, which remains a key concern given the system's low, discontinuous water supply.
- **Delayed passage timing:** Entry and transit durations were noticeably high as fish had to wait for valves to open.

While these preliminary results confirm the core functionality of the FSSG, lab performance cannot fully predict behavior under dynamic river conditions. Field evaluations in real-world settings are strongly advised to assess attraction efficiency, evaluate operational configurations, and validate passage success in natural fish communities before widespread deployment.

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A APPENDIX

A.1 ADDITIONAL GRAPHS AND TABLES WITH ALL FISH USED

A.1.1 Gate statistics

Table A.1: Median duration of different phases (min) per experiment

node	exp.gate	closed	opening	open	closing
lower valve	exp1	39	6	6	6
lower valve	exp2	44	4	10	4
lower valve	exp3	44	4	10	3
upper valve	exp1	20	6	27	6
upper valve	exp2	24	4	31	3
upper valve	exp3	24	3	31	3

A.1.2 Number of individuals (unique tags) at the different nodes

Table A.2: Number of individuals (unique tags) at different nodes

node	exp1	exp2	exp3
lower basin	47	99	115
lower valve	46	75	72
upper valve	8	28	28
upper basin	34	64	46

A.1.3 Statistics concerning the trajectory from the lower basin to the lower valve

Table A.3: Travel time (min) to move up the fish spiral calculated as the time difference between the last detection at the lower antenna and the first at the upper antenna. The time since the upper valve opened and the first detection at the upper antenna are given. The opening (cm) at which the first detection at the upper antenna is noted is also given. Some fish went up and down several times. Subsequent trajectories are numbered under loop.

exp	travel_time	min_det	max_det	since_open	opening	trend	loop
exp1	3168 mins	2024-05-17 17:40:31	2024-05-18 13:02:29	11	29.11	open	1
exp1	138 mins	2024-05-15 15:11:27	2024-05-15 16:14:57	13	28.35	open	1
exp1	316 mins	2024-05-15 18:09:11	2024-05-15 18:09:12	7	20.92	opening	1
exp1	201 mins	2024-05-15 16:14:17	2024-05-15 16:16:15	15	25.95	closing	1
exp1	1670 mins	2024-05-16 16:43:09	2024-05-16 16:43:09	13	29.11	open	1
exp1	3173 mins	2024-05-17 17:45:32	2024-05-17 17:45:33	16	22.05	closing	1
exp1	258 mins	2024-05-15 17:10:40	2024-05-18 12:03:21	10	28.44	open	1
exp1	137 mins	2024-05-15 15:09:53	2024-05-17 11:34:06	12	28.09	open	1
exp1	70 mins	2024-05-15 14:03:30	2024-05-16 18:49:48	8	22.22	opening	1

exp1	993 mins	2024-05-16 05:25:38	2024-05-16 08:39:56	9	27.69	opening	1
exp1	321 mins	2024-05-15 18:14:01	2024-05-15 18:14:01	12	29.04	open	1
exp1	1309 mins	2024-05-16 10:41:49	2024-05-16 15:44:27	17	18.63	closing	1
exp1	318 mins	2024-05-15 18:11:24	2024-05-19 11:32:49	9	29.04	open	1
exp1	133 mins	2024-05-15 15:05:41	2024-05-15 18:11:43	8	22.83	opening	1
exp1	1118 mins	2024-05-16 07:30:51	2024-05-16 07:35:00	12	28.27	open	1
exp1	327 mins	2024-05-15 18:19:54	2024-05-17 12:41:29	18	16.40	closing	1
exp1	73 mins	2024-05-15 14:06:01	2024-05-15 18:09:42	10	26.76	opening	1
exp1	2920 mins	2024-05-17 13:32:31	2024-05-17 14:34:18	8	26.58	opening	1
exp1	139 mins	2024-05-15 15:11:36	2024-05-18 04:53:38	14	28.21	open	1
exp1	205 mins	2024-05-15 16:17:47	2024-05-15 16:17:52	19	18.88	closing	1
exp1	75 mins	2024-05-15 14:07:58	2024-05-15 19:10:51	12	28.31	open	1
exp1	195 mins	2024-05-15 16:08:13	2024-05-15 19:10:39	9	26.61	opening	1
exp1	323 mins	2024-05-15 18:15:38	2024-05-15 19:19:00	14	29.05	open	1
exp1	200 mins	2024-05-15 16:12:45	2024-05-15 16:12:46	14	28.63	open	1
exp1	194 mins	2024-05-15 16:07:05	2024-05-15 16:18:08	8	23.29	opening	1
exp1	82 mins	2024-05-15 14:15:10	2024-05-15 16:14:34	19	16.78	closing	1
exp1	79 mins	2024-05-15 14:11:34	2024-05-15 18:09:51	16	25.60	closing	1
exp1	138 mins	2024-05-15 15:11:13	2024-05-18 06:04:07	13	28.57	open	1
exp1	72 mins	2024-05-15 14:04:55	2024-05-16 15:44:40	9	25.89	opening	1
exp1	199 mins	2024-05-15 16:12:22	2024-05-15 16:15:52	13	28.88	open	1
exp1	1242 mins	2024-05-16 09:35:09	2024-05-17 18:40:25	15	27.33	closing	1
exp1	197 mins	2024-05-15 16:10:17	2024-05-18 15:06:48	11	27.74	opening	1
exp1	74 mins	2024-05-15 14:07:04	2024-05-15 18:11:39	11	27.59	opening	1
exp1	197 mins	2024-05-15 16:09:35	2024-05-15 16:15:21	11	27.35	opening	1
exp1	203 mins	2024-05-15 16:15:43	2024-05-18 04:58:48	17	23.45	closing	1
exp1	134 mins	2024-05-15 15:07:18	2024-05-15 17:12:22	9	25.50	opening	1
exp1	139 mins	2024-05-15 15:12:20	2024-05-16 14:36:49	14	27.54	closing	1
exp1	136 mins	2024-05-15 15:09:25	2024-05-17 04:51:10	11	27.62	opening	1
exp1	266 mins	2024-05-15 17:19:12	2024-05-15 19:13:20	19	16.88	closing	1
exp1	1614 mins	2024-05-16 15:47:08	2024-05-19 14:31:01	16	13.46	closing	1
exp1	202 mins	2024-05-15 16:14:38	2024-05-15 16:17:15	16	25.34	closing	1
exp1	137 mins	2024-05-15 15:10:28	2024-05-16 22:45:52	12	28.68	open	1
exp1	197 mins	2024-05-15 16:09:31	2024-05-18 10:03:21	10	27.32	opening	1
exp1	135 mins	2024-05-15 15:08:20	2024-05-16 16:46:10	10	26.54	opening	1
exp1	1422 mins	2024-05-16 12:35:01	2024-05-17 10:30:52	7	28.91	open	1
exp1	196 mins	2024-05-15 16:09:16	2024-05-15 19:22:10	10	27.18	opening	1
exp2	5877 mins	2024-05-26 15:04:09	2024-05-28 06:35:31	13	29.04	open	1
exp2	194 mins	2024-05-22 16:21:24	2024-05-22 16:26:09	8	29.11	open	1
exp2	13 mins	2024-05-22 13:20:25	2024-05-22 16:20:46	10	28.98	open	1
exp2	69 mins	2024-05-22 14:15:44	2024-05-24 05:16:01	4	28.78	open	1
exp2	72 mins	2024-05-22 14:18:55	2024-05-22 14:27:34	7	28.78	open	1
exp2	76 mins	2024-05-22 14:23:09	2024-05-22 14:23:09	12	28.78	open	1
exp2	2403 mins	2024-05-24 05:09:57	2024-05-25 19:30:56	6	28.99	open	1
exp2	2401 mins	2024-05-24 05:07:51	2024-05-25 17:35:39	4	28.99	open	1
exp2	313 mins	2024-05-22 18:20:08	2024-05-23 15:52:41	4	24.38	opening	1
exp2	1365 mins	2024-05-23 11:52:11	2024-05-27 01:12:22	15	15.93	closing	1
exp2	76 mins	2024-05-22 14:23:00	2024-05-22 14:23:00	12	28.78	open	1
exp2	6059 mins	2024-05-26 18:05:40	2024-05-26 18:07:26	10	29.11	open	1

exp1	32 mins	2024-05-15 18:45:52	2024-05-15 18:45:52	20	29.16	open	1
exp1	216 mins	2024-05-15 19:53:51	2024-05-15 19:53:51	26	29.09	open	1
exp1	1499 mins	2024-05-16 17:14:02	2024-05-16 19:23:56	27	29.09	open	1
exp1	1301 mins	2024-05-17 12:17:37	2024-05-17 12:17:37	33	29.15	open	1
exp1	14 mins	2024-05-15 16:31:16	2024-05-15 16:31:16	9	28.17	open	1
exp2	1256 mins	2024-05-23 13:21:56	2024-05-23 13:21:56	21	29.02	open	1
exp2	3013 mins	2024-05-24 18:33:43	2024-05-24 18:33:45	50	2.35	closed	1
exp2	959 mins	2024-05-24 21:15:30	2024-05-27 12:30:28	50	2.49	closed	1
exp2	2156 mins	2024-05-25 01:40:34	2024-05-25 01:40:34	48	2.41	closed	1
exp2	216 mins	2024-05-22 17:55:29	2024-05-22 17:55:29	18	29.09	open	1
exp2	291 mins	2024-05-22 18:10:35	2024-05-24 12:14:39	40	2.30	closed	1
exp2	4481 mins	2024-05-25 19:03:57	2024-05-25 19:03:57	16	29.02	open	1
exp2	1009 mins	2024-05-26 12:26:46	2024-05-26 12:26:46	18	29.02	open	1
exp2	168 mins	2024-05-22 17:08:24	2024-05-28 00:15:41	16	29.02	open	1
exp2	38 mins	2024-05-22 19:58:44	2024-05-22 19:58:44	18	29.16	open	1
exp2	23 mins	2024-05-22 14:43:00	2024-05-22 14:43:00	9	29.09	open	1
exp2	25 mins	2024-05-22 14:49:35	2024-05-22 14:49:35	15	29.09	open	1
exp2	43 mins	2024-05-22 19:06:25	2024-05-24 19:18:23	34	29.16	open	1
exp2	2926 mins	2024-05-27 00:29:12	2024-05-27 00:29:12	4	29.02	open	2
exp2	24 mins	2024-05-22 18:44:56	2024-05-22 18:44:57	6	29.16	open	1
exp2	45 mins	2024-05-22 20:08:20	2024-05-22 20:08:20	28	29.16	open	1
exp2	1359 mins	2024-05-23 15:57:52	2024-05-25 21:08:30	17	29.16	open	1
exp2	2924 mins	2024-05-24 18:03:37	2024-05-25 22:03:29	11	29.02	open	1
exp2	86 mins	2024-05-22 17:42:36	2024-05-22 17:42:36	5	29.09	open	1
exp2	3196 mins	2024-05-24 23:39:16	2024-05-24 23:39:16	49	2.41	closed	1
exp2	33 mins	2024-05-22 14:59:17	2024-05-22 14:59:17	25	29.09	open	1
exp2	3058 mins	2024-05-25 00:28:46	2024-05-25 00:28:46	38	3.89	closing	1
exp2	23 mins	2024-05-22 14:40:08	2024-05-22 14:40:09	6	29.09	open	1
exp2	205 mins	2024-05-22 17:51:55	2024-05-22 20:02:57	23	29.16	open	1
exp2	7495 mins	2024-05-27 22:21:44	2024-05-28 01:18:31	16	29.09	open	1
exp3	270 mins	2024-05-29 19:44:50	2024-05-31 16:10:32	48	2.69	closed	1
exp3	37 mins	2024-05-30 18:15:26	2024-05-30 18:15:27	18	29.16	open	1
exp3	21 mins	2024-05-29 13:35:30	2024-05-29 13:35:30	9	29.16	open	1
exp3	41 mins	2024-06-01 16:23:55	2024-06-01 16:23:55	28	29.02	open	1
exp3	47 mins	2024-05-29 20:09:08	2024-05-29 20:09:08	34	29.09	open	1
exp3	15 mins	2024-05-29 14:32:56	2024-05-30 11:09:09	19	29.22	open	1
exp3	211 mins	2024-06-01 08:02:35	2024-06-01 08:03:13	18	28.95	open	2
exp3	75 mins	2024-06-01 12:55:33	2024-06-01 13:04:47	13	29.09	open	3
exp3	1104 mins	2024-06-02 10:06:41	2024-06-02 13:01:15	21	29.02	open	4
exp3	26 mins	2024-06-03 18:29:29	2024-06-03 18:29:29	15	29.02	open	5
exp3	36 mins	2024-06-05 05:19:11	2024-06-05 05:19:11	21	29.02	open	6
exp3	38 mins	2024-05-29 18:53:31	2024-05-29 18:53:32	20	29.09	open	1
exp3	80 mins	2024-06-03 20:16:33	2024-06-03 20:16:33	61	2.35	closed	1
exp3	138 mins	2024-05-29 20:43:05	2024-05-29 20:43:06	7	28.95	open	1
exp3	211 mins	2024-05-30 20:17:43	2024-05-30 20:17:43	18	29.22	open	1
exp3	16 mins	2024-05-29 13:31:02	2024-06-01 06:59:50	17	29.02	open	1
exp3	12 mins	2024-05-29 14:31:38	2024-05-31 13:56:29	36	11.47	closing	1
exp3	580 mins	2024-06-04 04:37:40	2024-06-04 04:37:41	10	29.22	open	2
exp3	1854 mins	2024-05-31 01:18:24	2024-05-31 01:18:24	14	29.09	open	1

exp3	17 mins	2024-05-29 14:30:12	2024-06-03 17:36:00	22	28.95	open	1
exp3	581 mins	2024-06-04 03:41:16	2024-06-04 03:41:17	15	28.95	open	1
exp3	89 mins	2024-05-30 02:58:10	2024-05-30 02:58:10	17	29.02	open	1
exp3	4062 mins	2024-06-01 13:01:54	2024-06-03 04:18:59	21	29.09	open	1
exp3	18 mins	2024-05-29 13:30:15	2024-05-29 13:30:16	3	25.50	opening	1
exp3	36 mins	2024-05-29 19:55:00	2024-05-29 19:55:00	20	29.09	open	1
exp3	1468 mins	2024-05-30 18:51:53	2024-05-30 18:51:53	54	2.35	closed	1
exp3	29 mins	2024-05-29 14:47:07	2024-05-29 19:04:55	31	29.09	open	1
exp3	165 mins	2024-05-30 03:08:36	2024-06-04 03:28:41	3	19.39	opening	2

A.1.5 Arrival time at different antennas

Table A.5: Time of first detection per fish on the lower and upper antenna

tag_code	lower valve	upper valve	upper basin
900209000086149_exp1	2024-05-17 17:40:31	0	2024-05-21 18:00:00
900209000086150_exp1	2024-05-15 15:11:27	2024-05-15 19:47:25	2024-05-21 18:00:00
900209000086156_exp1	2024-05-15 18:09:11	0	2024-05-21 18:00:00
900209000086157_exp1	2024-05-15 16:14:17	2024-05-15 16:54:08	0
900209000086158_exp1	2024-05-16 16:43:09	0	2024-05-21 18:00:00
900209000086161_exp1	2024-05-17 17:45:32	2024-05-18 00:19:25	0
900209000086162_exp1	2024-05-15 17:10:40	0	2024-05-21 18:00:00
900209000086164_exp1	2024-05-15 15:09:53	0	0
900209000086168_exp1	2024-05-15 14:03:30	0	0
900209000086169_exp1	2024-05-16 05:25:38	0	2024-05-21 18:00:00
900209000086174_exp1	2024-05-15 18:14:01	2024-05-15 18:45:52	2024-05-21 18:00:00
900209000086175_exp1	2024-05-16 10:41:49	0	0
900209000086177_exp1	2024-05-15 18:11:24	0	0
900209000086178_exp1	2024-05-15 15:05:41	0	2024-05-21 18:00:00
900209000086179_exp1	2024-05-16 07:30:51	0	2024-05-21 18:00:00
900209000086180_exp1	0	0	0
900209000086182_exp1	2024-05-15 18:19:54	0	2024-05-21 18:00:00
900209000086183_exp1	2024-05-15 14:06:01	0	2024-05-21 18:00:00
900209000086186_exp1	2024-05-17 13:32:31	0	0
900209000086187_exp1	2024-05-15 15:11:36	0	2024-05-21 18:00:00
900209000086188_exp1	2024-05-15 16:17:47	2024-05-15 19:53:51	2024-05-21 18:00:00
900209000086194_exp1	2024-05-15 14:07:58	0	2024-05-21 18:00:00
900209000086196_exp1	2024-05-15 16:08:13	0	2024-05-21 18:00:00
900209000086197_exp1	2024-05-15 18:15:38	0	2024-05-21 18:00:00
900209000086199_exp1	2024-05-15 16:12:45	0	2024-05-21 18:00:00
900209000086200_exp1	2024-05-15 16:07:05	0	2024-05-21 18:00:00
900209000086203_exp1	2024-05-15 14:15:10	2024-05-16 17:14:02	2024-05-21 18:00:00
900209000086204_exp1	2024-05-15 14:11:34	0	2024-05-21 18:00:00
900209000086206_exp1	2024-05-15 15:11:13	0	0
900209000086212_exp1	2024-05-15 14:04:55	0	2024-05-21 18:00:00
900209000086216_exp1	2024-05-15 16:12:22	0	2024-05-21 18:00:00
900209000086219_exp1	2024-05-16 09:35:09	0	0
900209000086220_exp1	2024-05-15 16:10:17	0	0
900209000086222_exp1	2024-05-15 14:07:04	0	2024-05-21 18:00:00

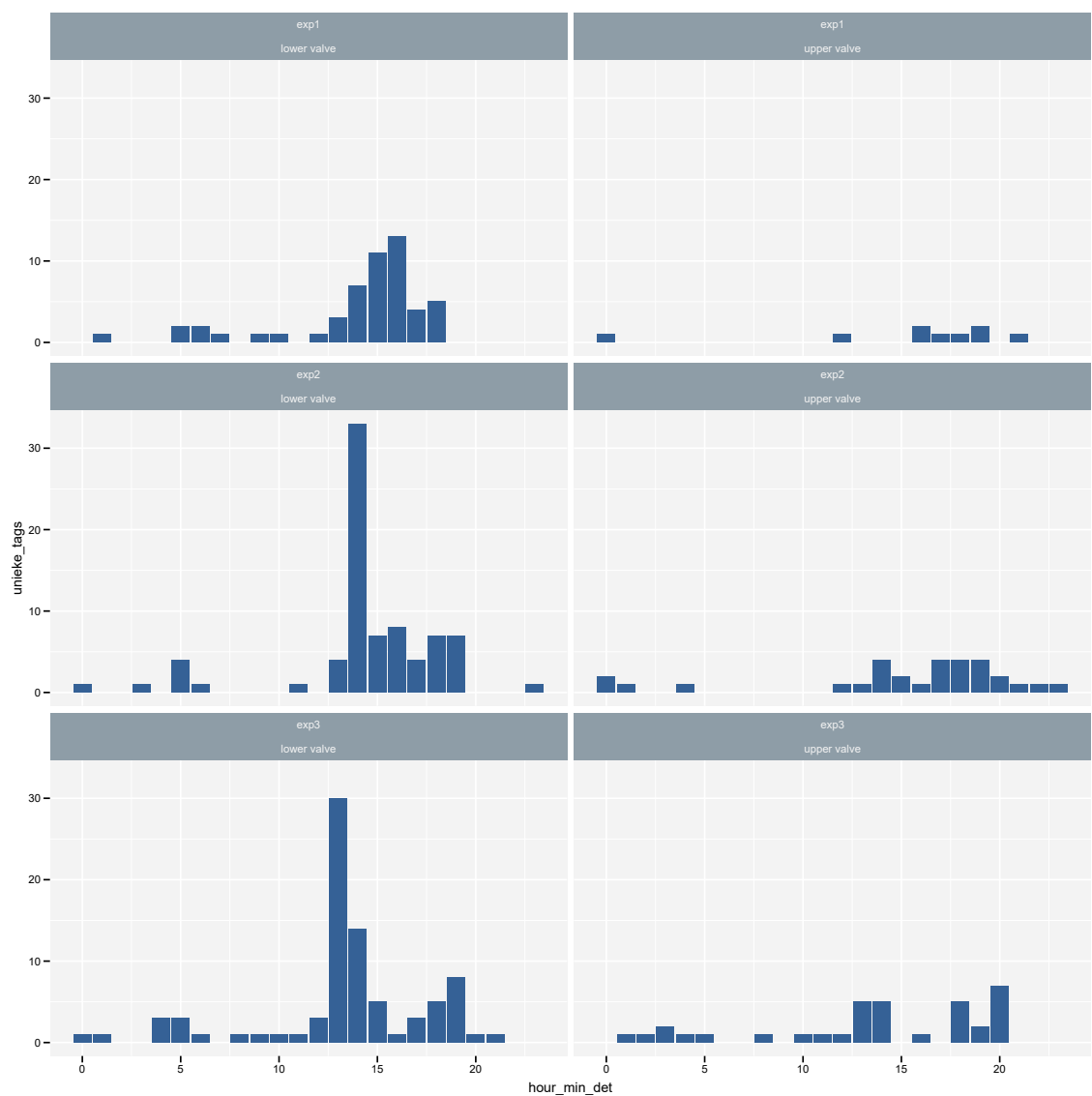
900209000086573_exp3	0	0	0
900209000086577_exp3	2024-05-29 13:11:11	0	2024-06-05 18:00:00
900209000086581_exp3	2024-06-03 19:06:05	0	2024-06-05 18:00:00
900209000086582_exp3	0	0	0
900209000086586_exp3	2024-05-29 15:11:05	0	0
900209000086587_exp3	2024-05-29 14:07:28	0	0
900209000086588_exp3	2024-05-29 13:19:21	0	2024-06-05 18:00:00
900209000086589_exp3	2024-05-29 13:12:14	2024-05-29 13:30:15	2024-06-05 18:00:00
900209000086590_exp3	2024-05-29 13:16:52	0	0
900209000086591_exp3	2024-05-29 19:19:27	2024-05-29 19:55:00	2024-06-05 18:00:00
900209000086593_exp3	2024-06-01 17:20:07	0	0
900209000086594_exp3	2024-05-29 13:15:38	0	2024-06-05 18:00:00
900209000086596_exp3	2024-05-29 13:06:13	0	2024-06-05 18:00:00
900209000086597_exp3	0	0	0
900209000086599_exp3	0	0	0
900209000086601_exp3	2024-05-29 14:09:44	0	2024-06-05 18:00:00
900209000086602_exp3	0	0	0
900209000086605_exp3	0	0	0
900209000086606_exp3	2024-05-29 18:23:31	2024-05-30 18:51:53	0
900209000086612_exp3	2024-06-02 19:35:05	0	2024-06-05 18:00:00
900209000086621_exp3	2024-06-04 13:18:58	2024-05-29 18:59:24	0
900209000086623_exp3	0	0	0
900209000086624_exp3	2024-05-29 18:16:24	0	2024-06-05 18:00:00
900209000086627_exp3	2024-05-29 13:08:15	0	2024-06-05 18:00:00
900209000086632_exp3	2024-05-29 13:11:35	0	0
900209000086635_exp3	0	0	0
900209000086638_exp3	2024-05-29 13:12:46	0	2024-06-05 18:00:00
900209000086642_exp3	2024-05-29 18:24:04	0	2024-06-05 18:00:00
900209000086643_exp3	2024-05-29 13:10:53	0	0
900209000086645_exp3	2024-05-29 13:14:02	2024-05-29 14:47:07	2024-06-05 18:00:00
900209000086648_exp3	0	0	0

A.1.6 Number of unique tags per sequence

Table A.6: Number of individuals (unique tags) per sequence

last_sequence	exp1	exp2	exp3
NA-lower basin	47	99	114
lower basin-lower valve	46	73	71
lower valve-lower basin	11	15	31
lower valve-upper valve	8	24	21
upper valve-lower valve	5	5	7
upper valve-lower basin	1	6	3
upper valve-upper basin	2	18	18
lower valve-upper basin	32	39	26
lower basin-upper valve	0	5	7
lower basin-upper basin	0	7	2
NA-lower valve	0	0	1

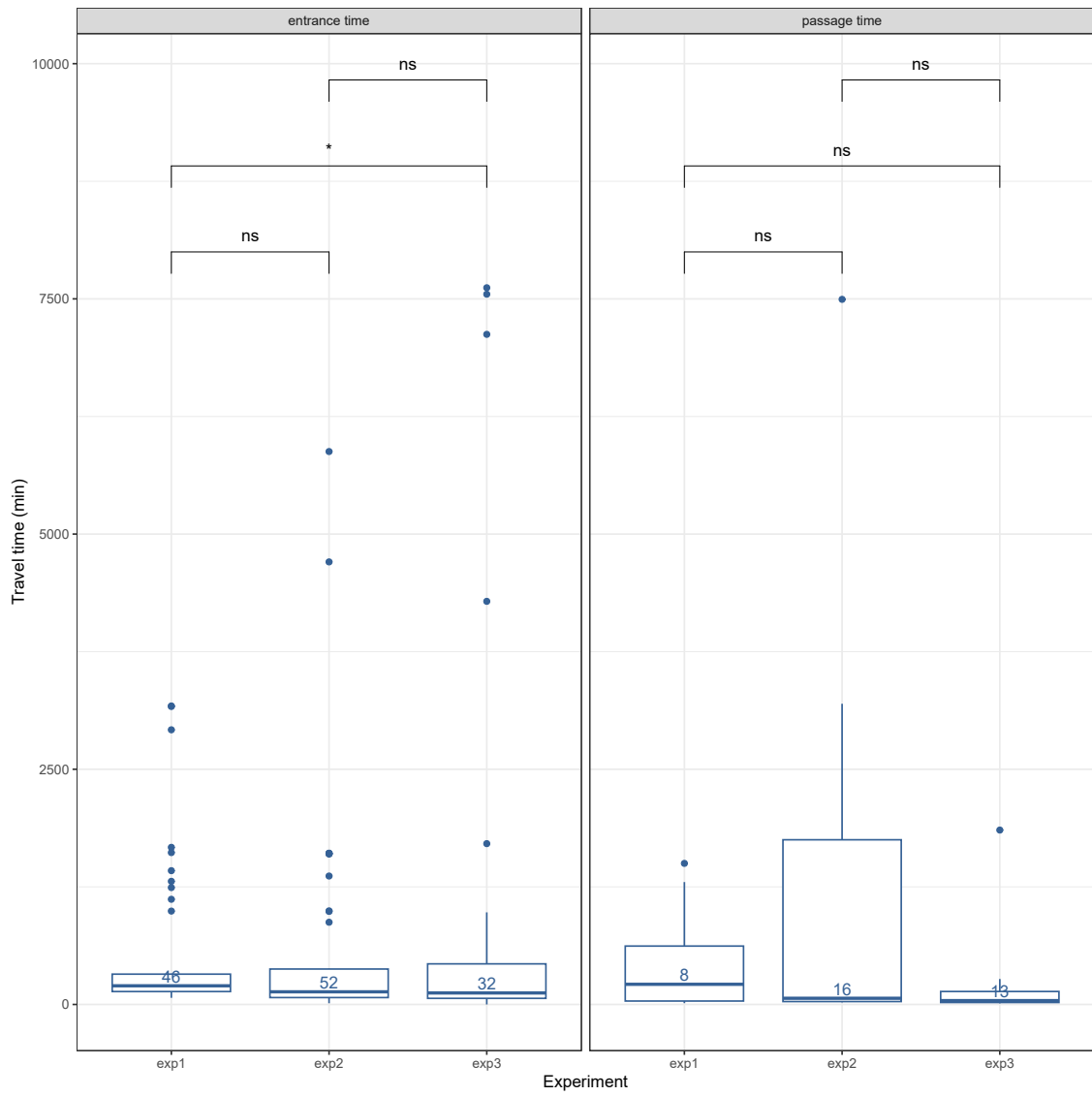
A.1.7 **Arrival time at the different antennas during the day**

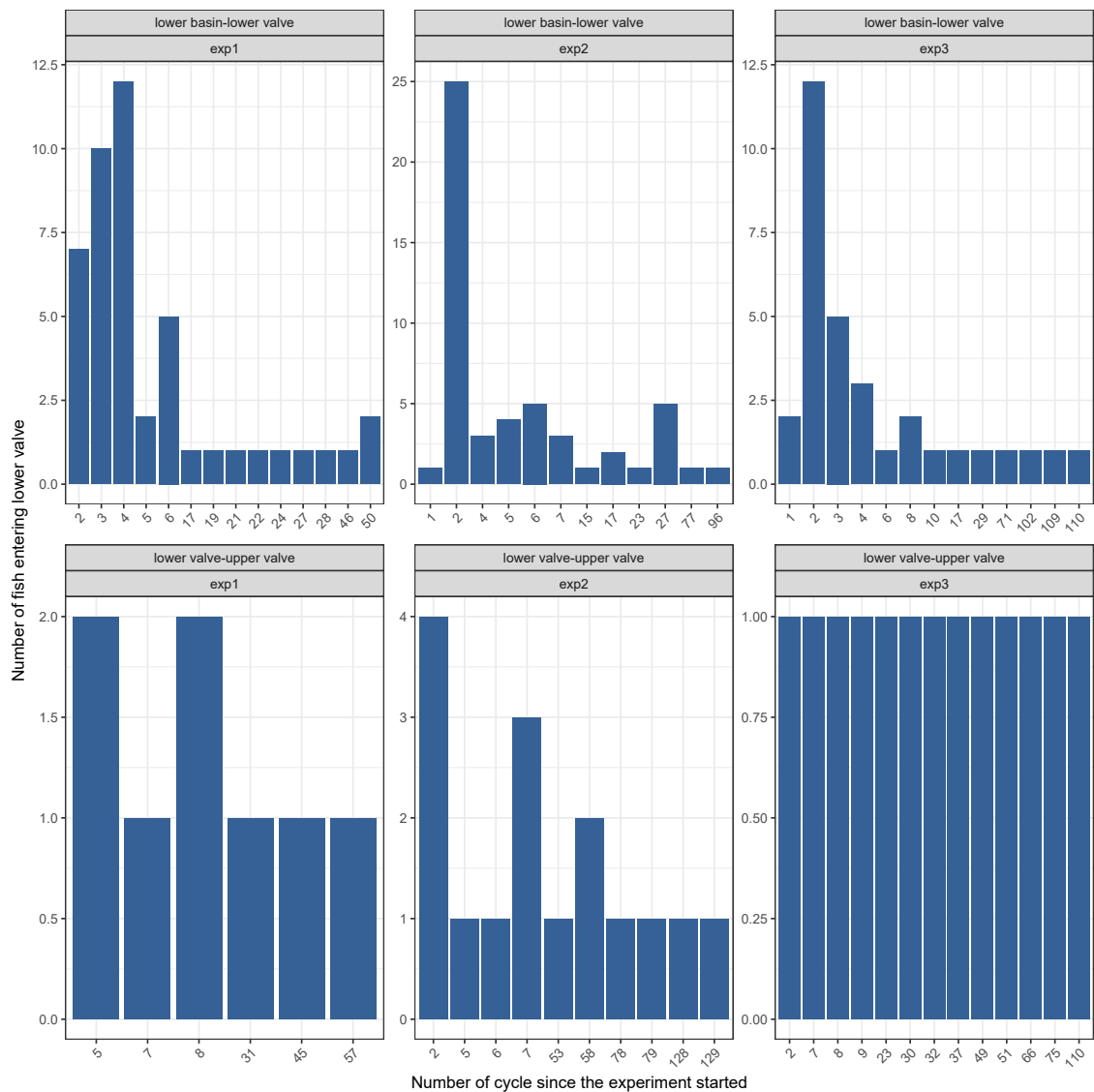


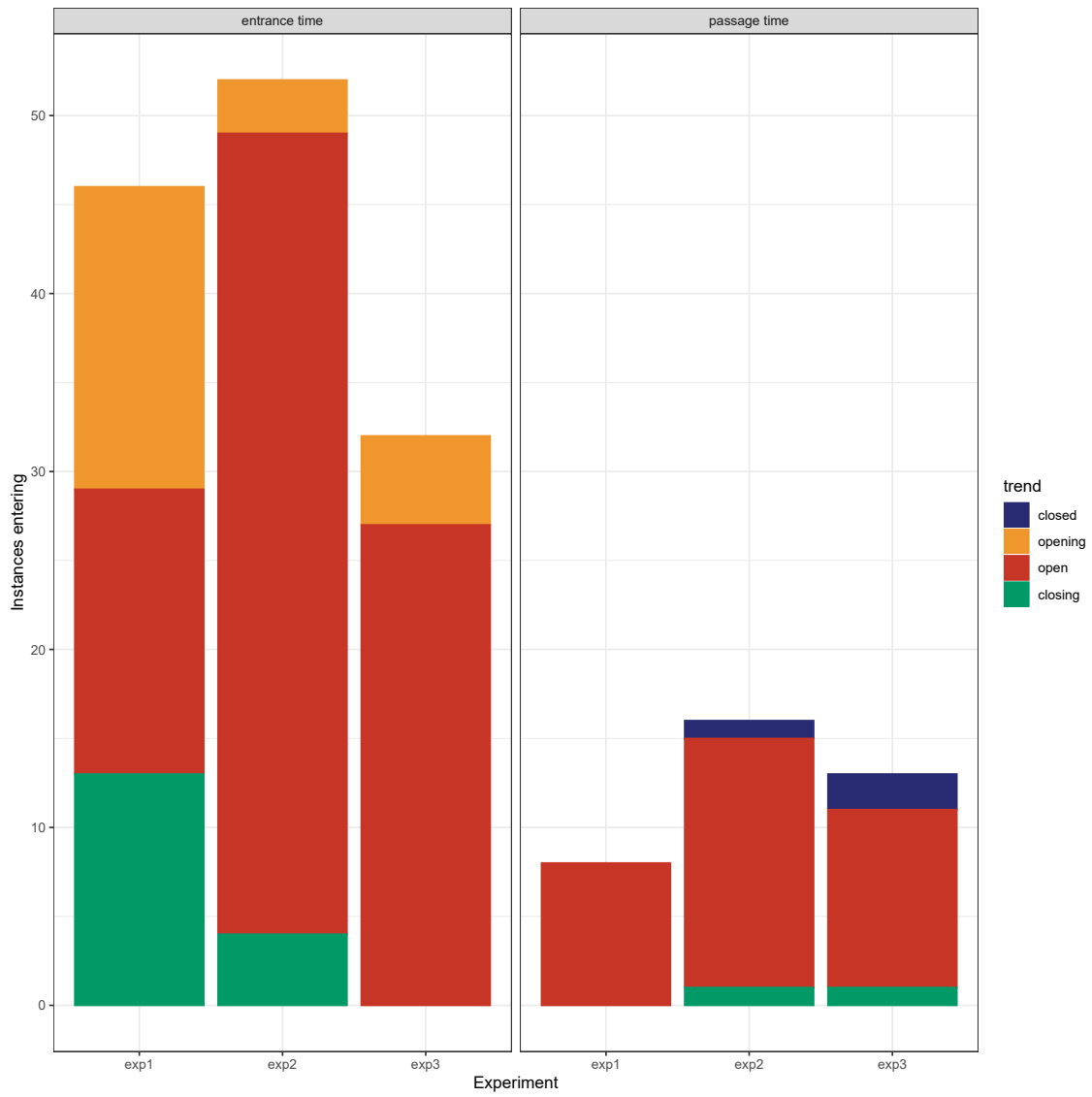
A.2 **REPLICATE GRAPHS AND TABLES BUT WITHOUT THE
RE-USED FISH**

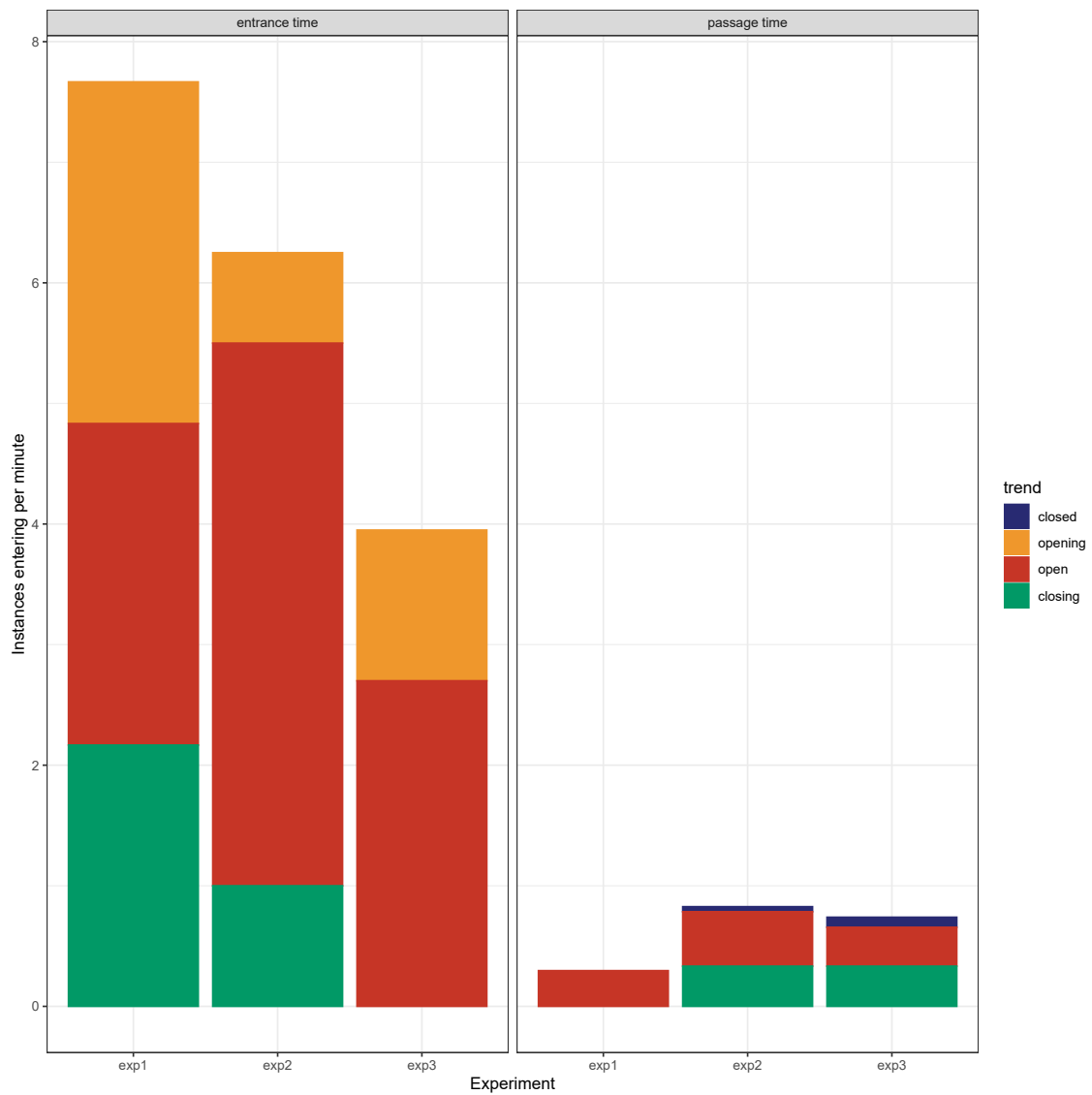
Table A.7: Entrance efficiency, passage efficiency and overall efficiency calculated in different ways. As there was no recapture data available for the experiments of 2023, the estimates were not provided here but in the appendix (as it comes with an amount of unquantifiable uncertainty).

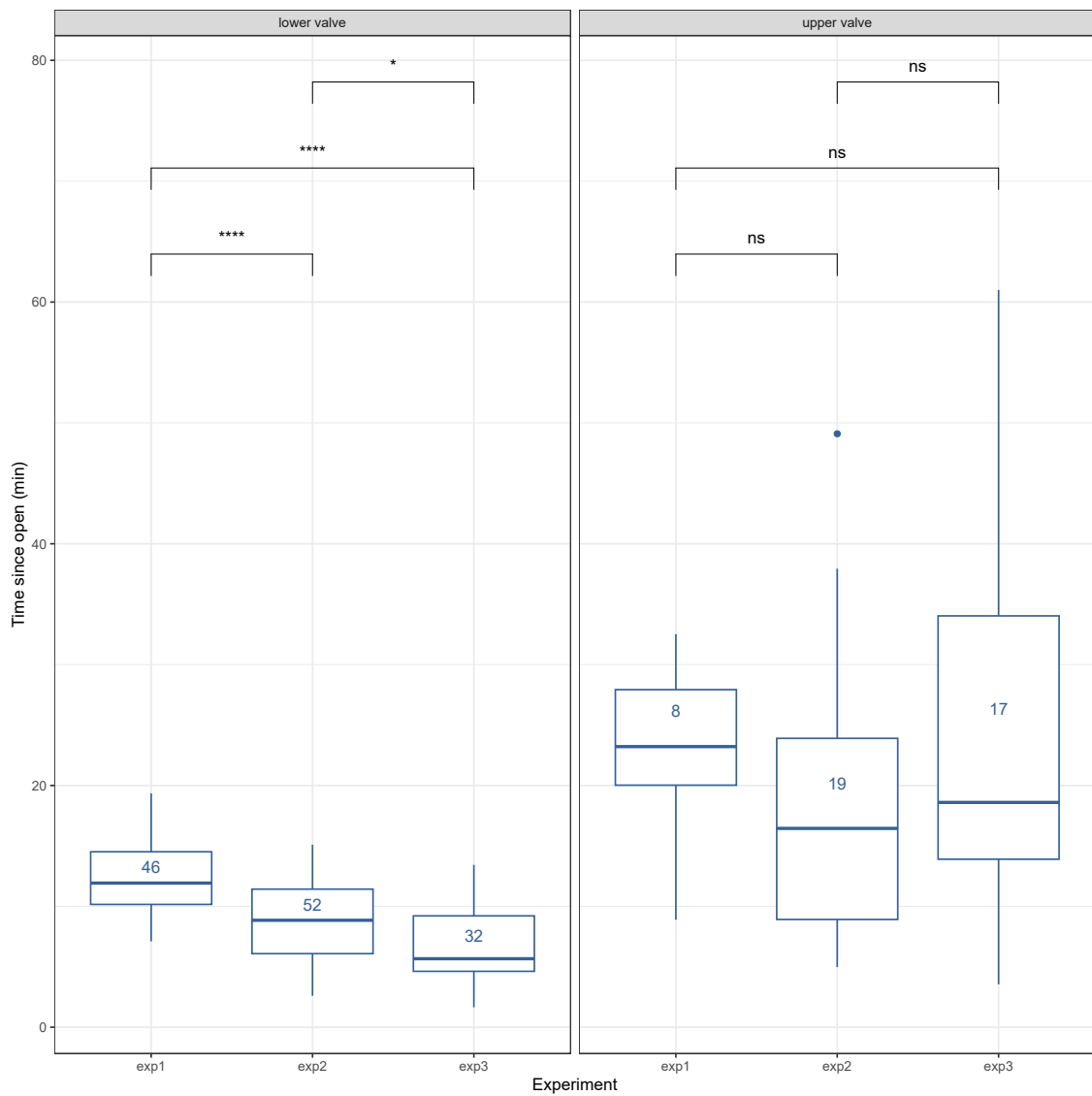
calculation	exp1	exp2	exp3
entrance efficiency: recapture and detections	0.98	0.88	0.69
passage efficiency: recapture and detections	0.80	0.82	0.69
passage efficiency: recapture	0.74	0.77	0.60
passage efficiency: detections	0.17	0.35	0.47
overall efficiency: recapture and detections	0.79	0.72	0.48
overall efficiency: recapture	0.72	0.67	0.40
overall efficiency: detections	0.17	0.30	0.33

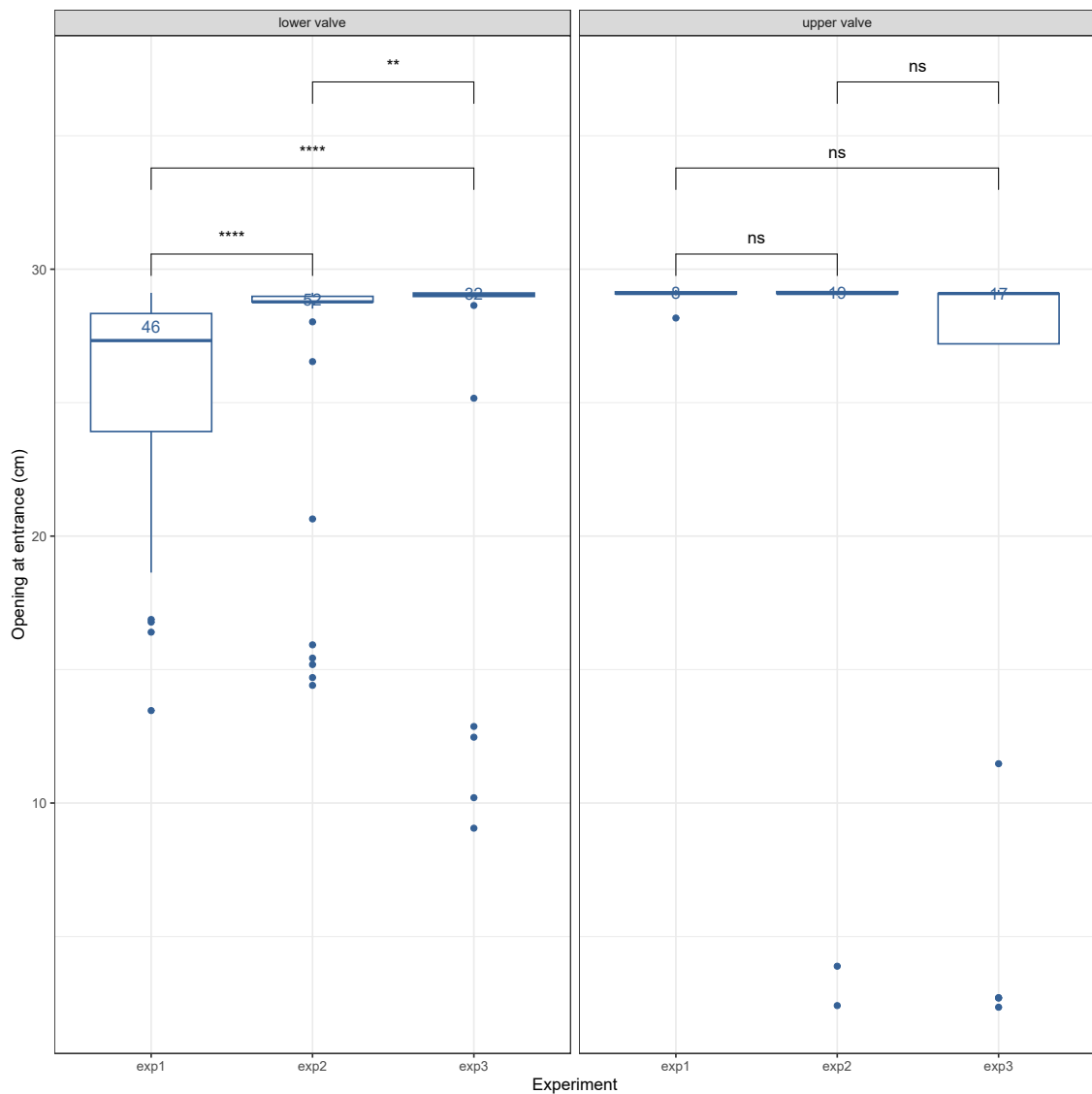












A.3 GRAPHS VALVE OPENING

A.3.1 Graphs valve opening exp1 (mei 2024)

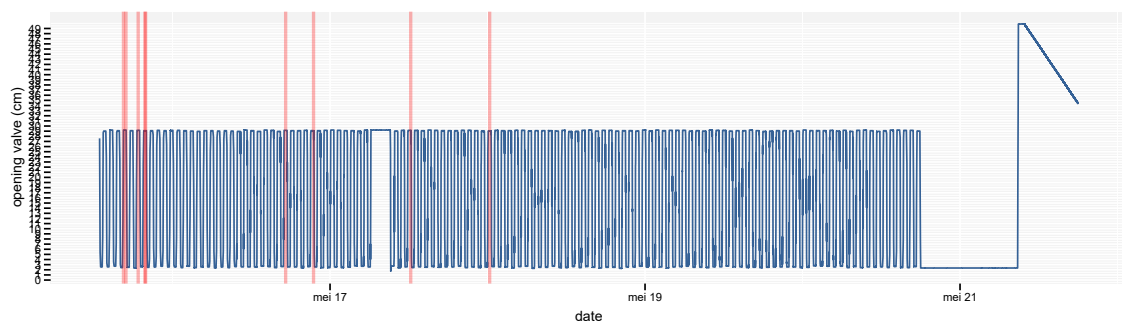
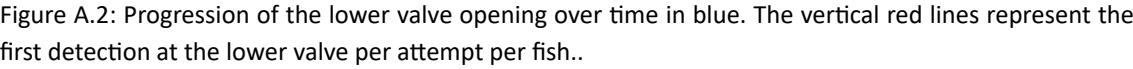
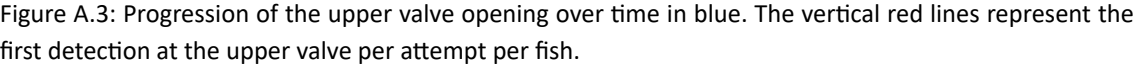
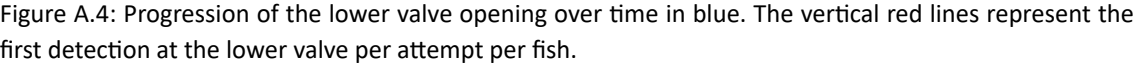


Figure A.1: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish.



A.3.2 Graphs valve opening exp2 (mei 2024)

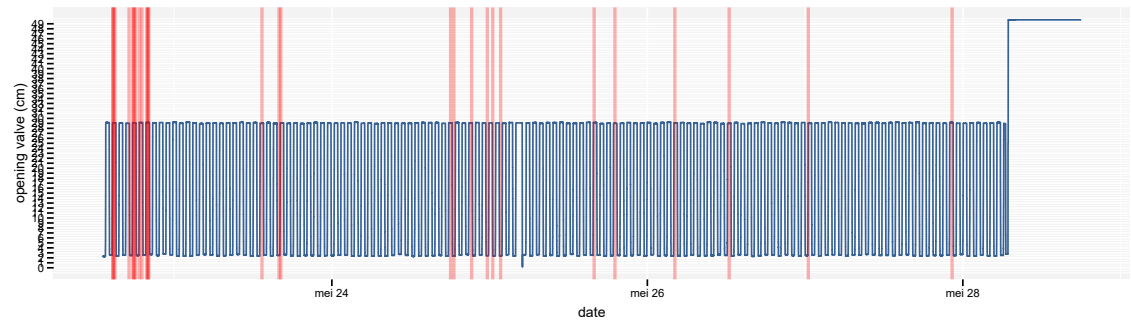


Figure A.5: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish.

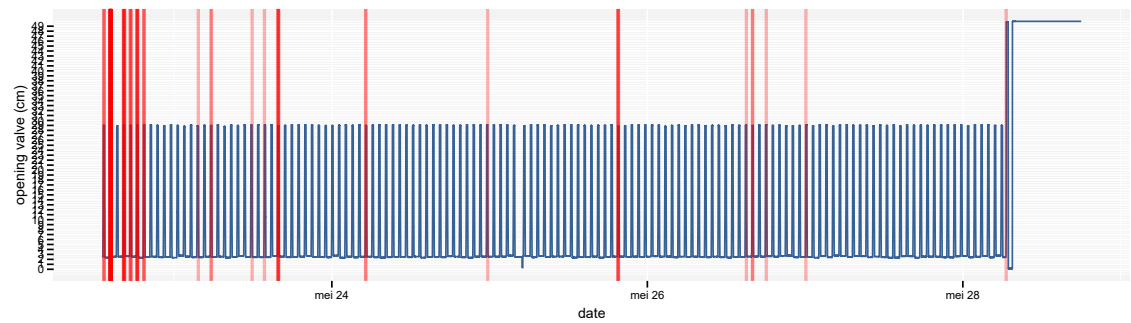


Figure A.6: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish.

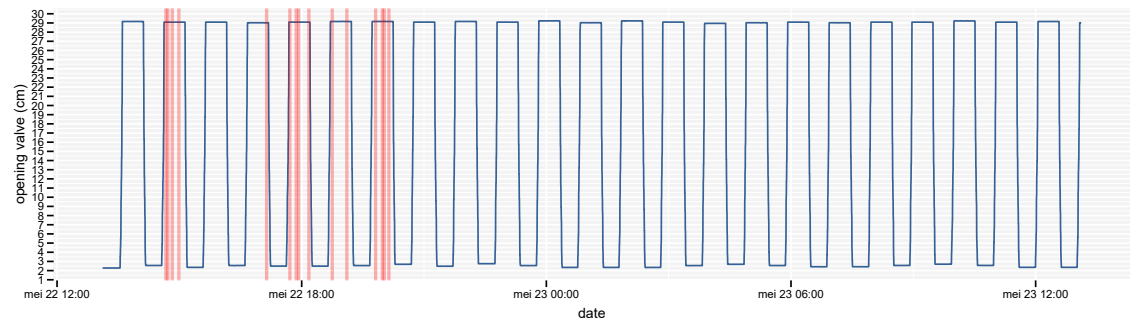


Figure A.7: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish.

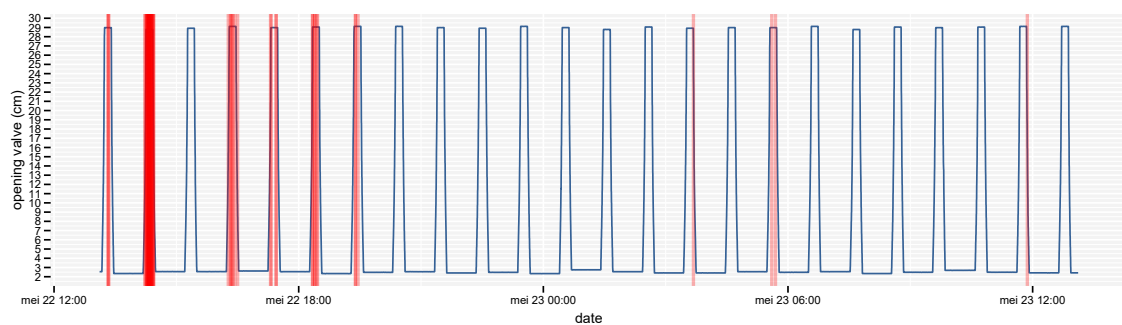


Figure A.8: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish.

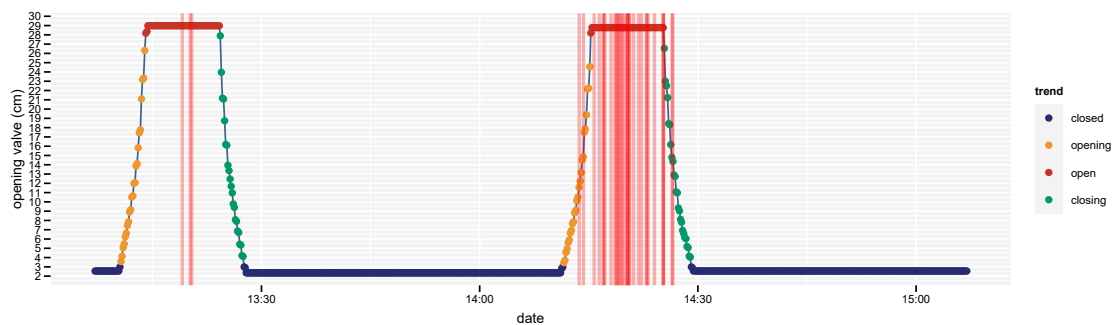


Figure A.9: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish.

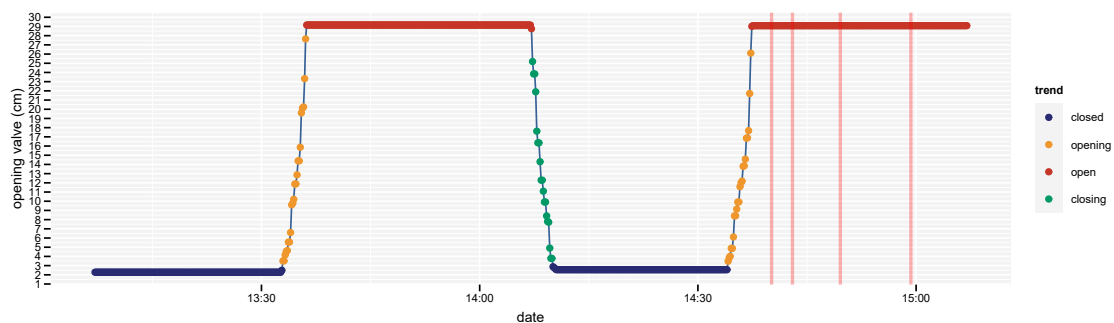


Figure A.10: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish.

A.3.3 Graphs valve opening exp3 (mei 2024)

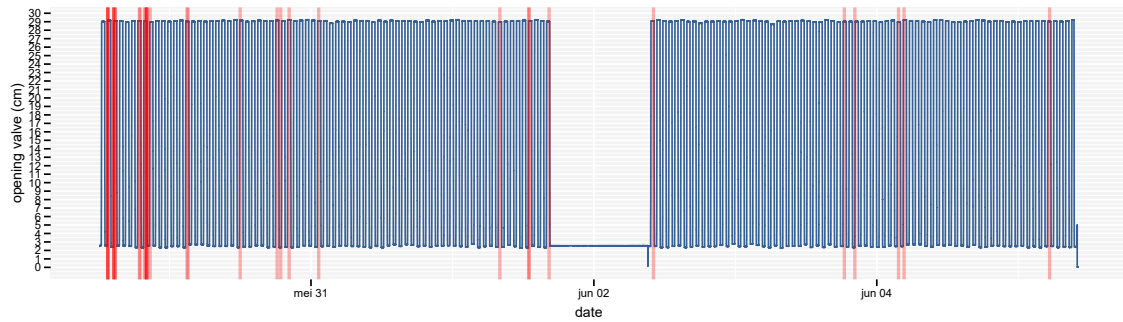


Figure A.11: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish.

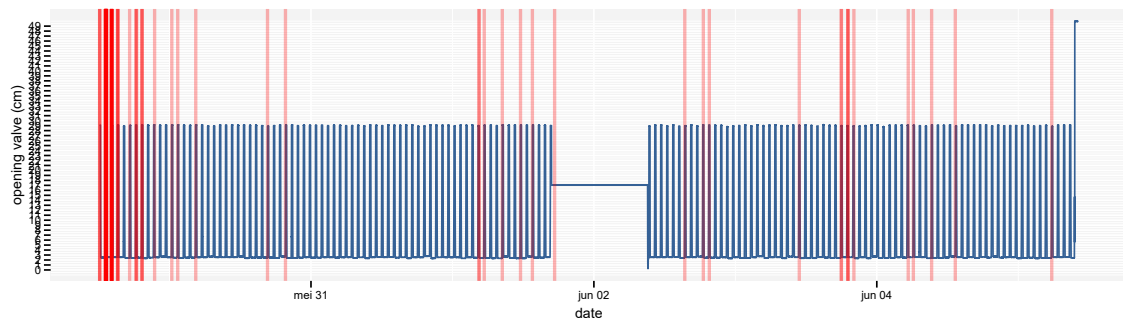


Figure A.12: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish.

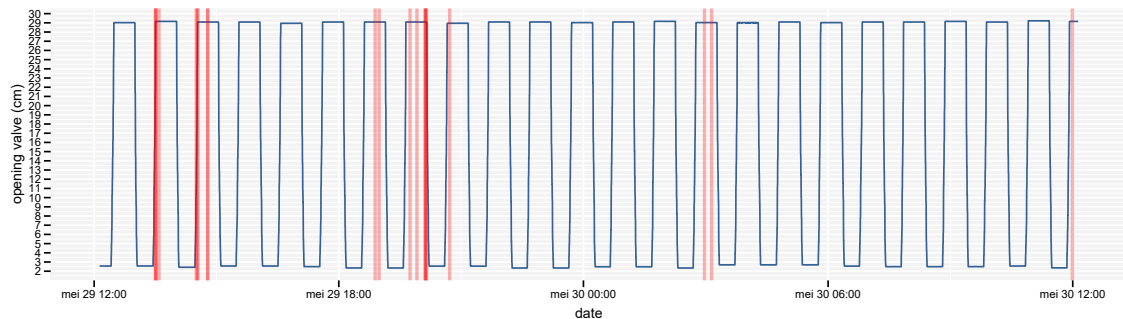


Figure A.13: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish.

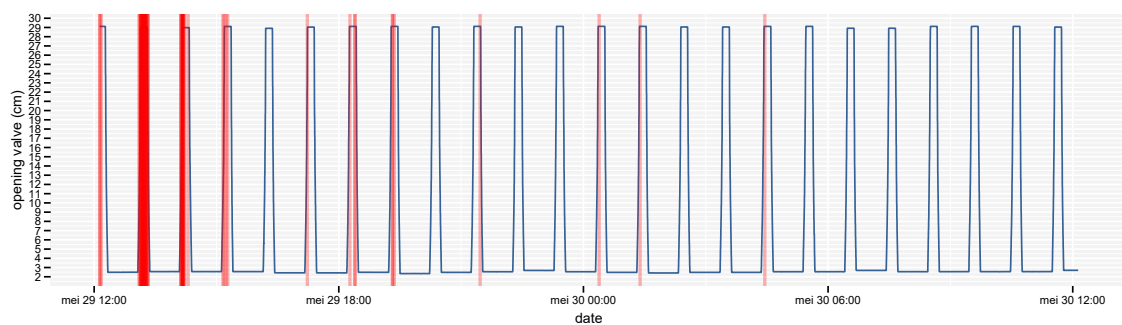


Figure A.14: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish.

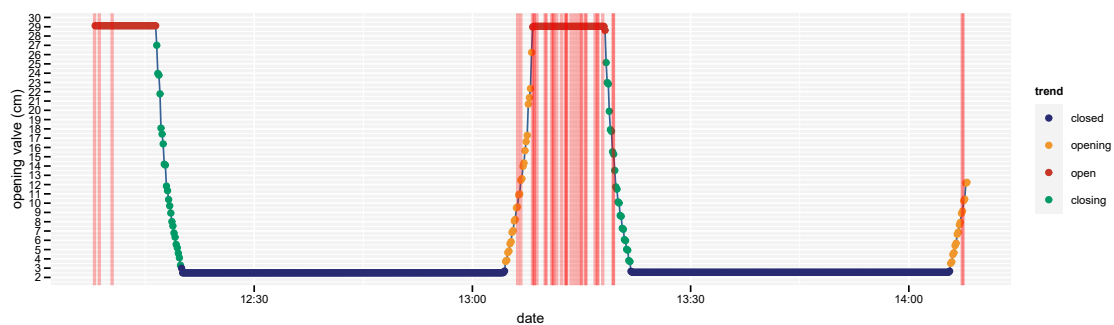


Figure A.15: Progression of the lower valve opening over time in blue. The vertical red lines represent the first detection at the lower valve per attempt per fish.

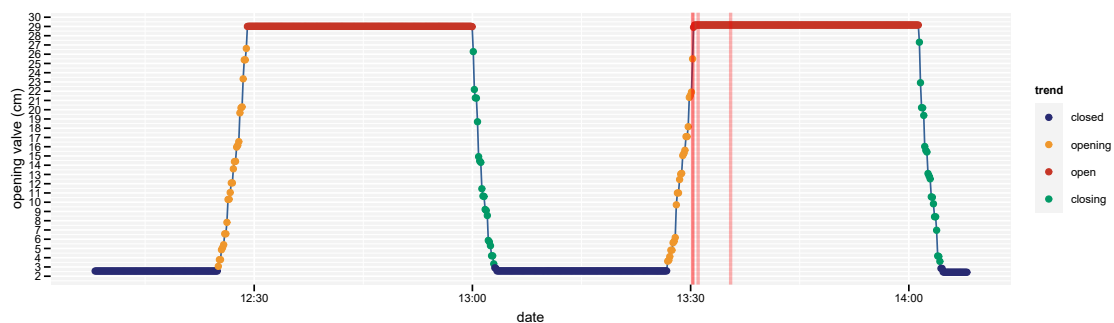


Figure A.16: Progression of the upper valve opening over time in blue. The vertical red lines represent the first detection at the upper valve per attempt per fish.

A.4 GRAPHS PRESSURE

A.4.1 Graphs pressure lower basin exp1

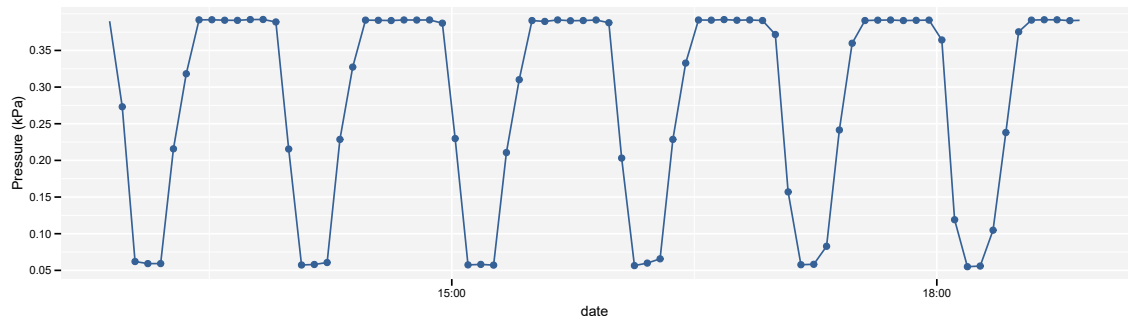


Figure A.17: Progression of the pressure in the lower basin over time.

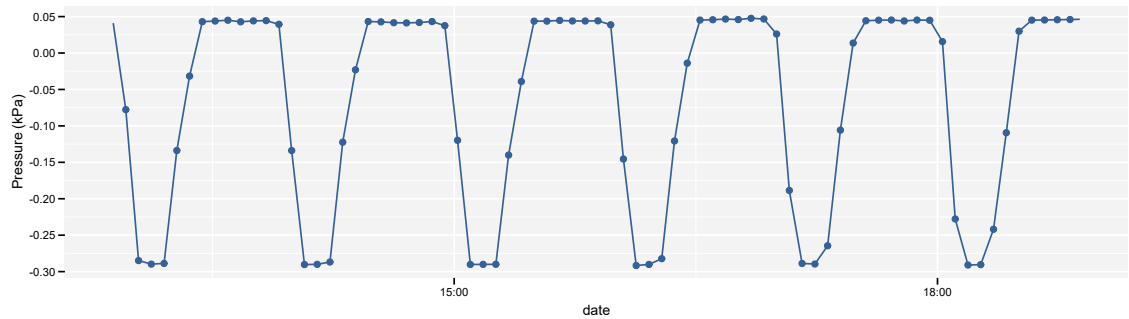


Figure A.18: Progression of the pressure in the upper basin over time.

A.4.2 Graphs pressure lower basin exp2

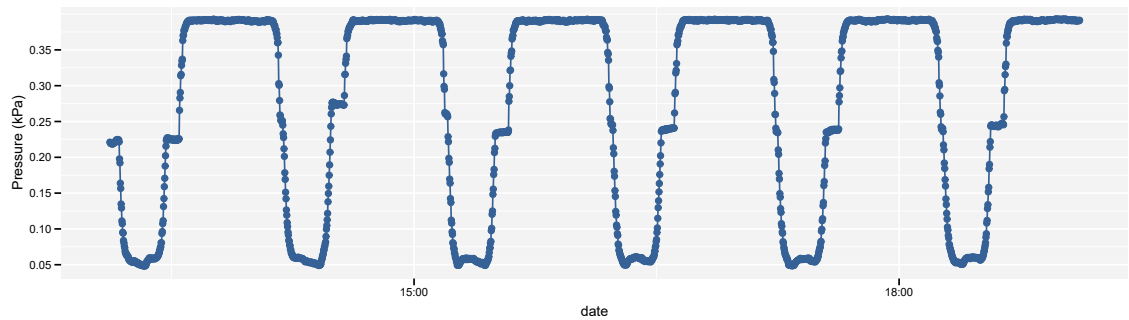


Figure A.19: Progression of the pressure in the lower basin over time.

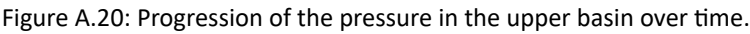
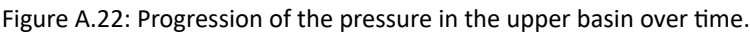


Figure A.21: Progression of the pressure in the lower basin over time.



A.5 NETWORK ANALYSIS

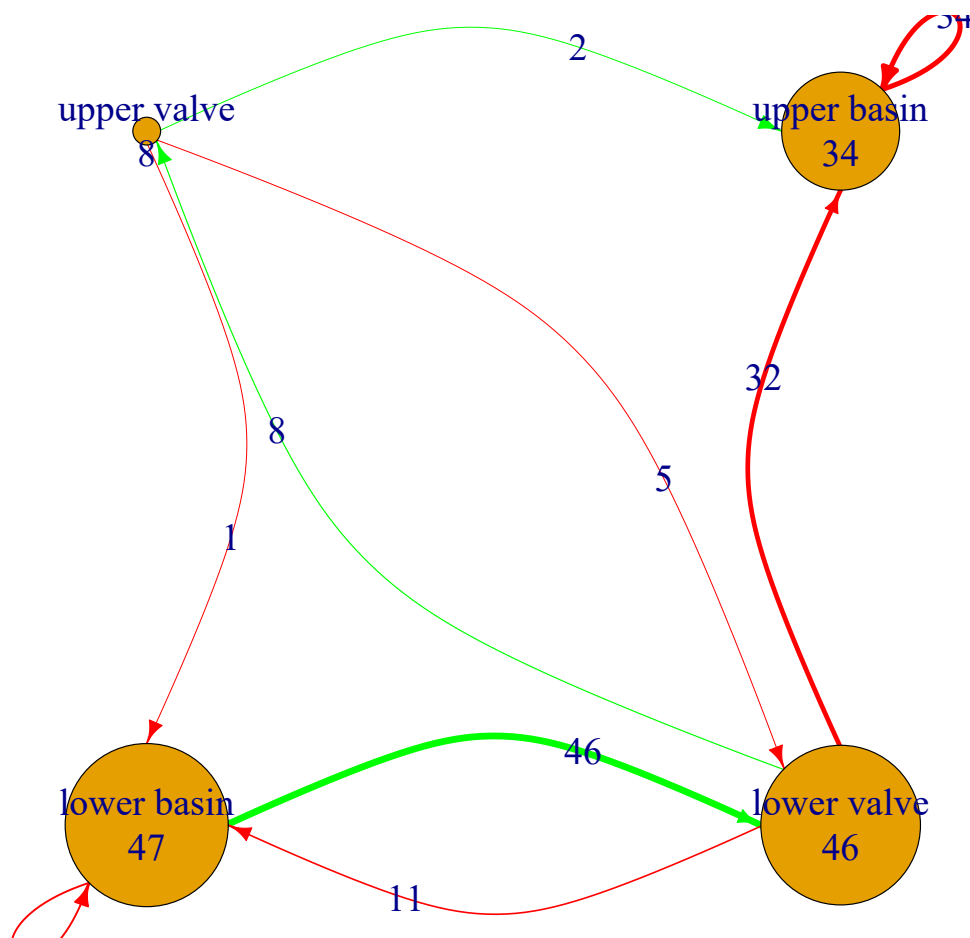


Figure A.23: Network analysis for exp1.

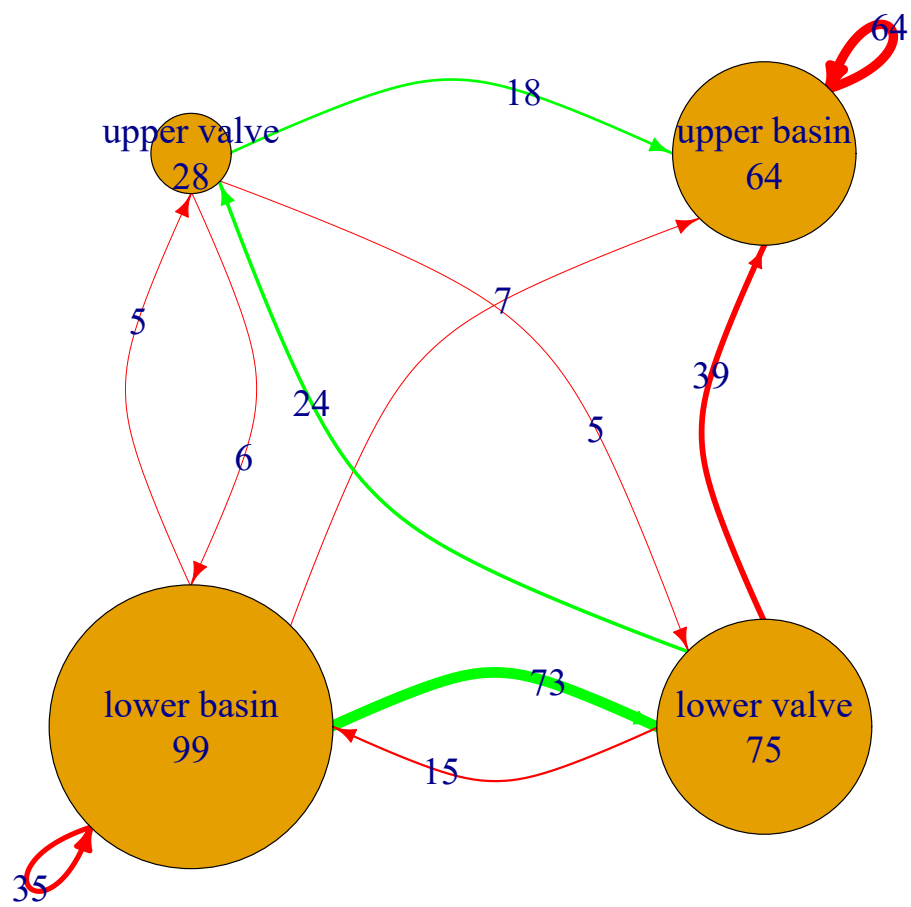


Figure A.24: Network analysis for exp2.

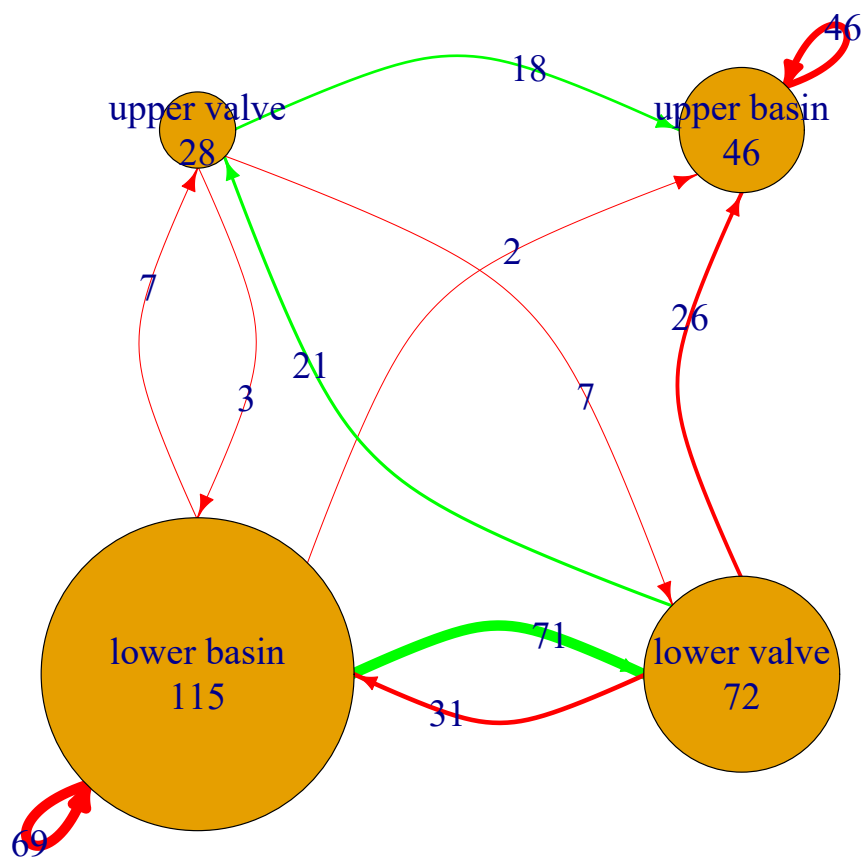


Figure A.25: Network analysis for exp3.