Research into the fish-friendly axial pump

Report: VA2009_19

On behalf of:
FishFlow Innovations

August 2009

by:

Author(s):
F.T. Vriese (VisAdvies).

English translation of Axial pump sections on behalf of Nijhuis Pompen BV

1. Introduction

Various studies have shown that large numbers of fish are injured and/or killed when passing through conventional pumping station pumps. FishFlow Innovations has developed two pump designs where the aim of the design is to allow fish to pass through without injury. The first design relates to a fish-friendly axial pump. FishFlow Innovations developed this axial pump in collaboration with Nijhuis Pompen. *The second design relates to a fish-friendly Archimedean screw pump.*

FishFlow Innovations wished to have the fish-friendliness of the pump designs established independently. This report describes the pump tests. While the pump tests were being conducted an independent observer from VisAdvies BV was present to record and report the results.

The statistical analysis was carried out by Onno Van Tongeren of the Data Analyse Ecologie (DATANECO) service in collaboration with Tim Vriese.

2. Description of the pumps

2.1 Axial pumps

Axial or screw pumps have a rotor comprising a number of blades that are set at an angle on a central shaft. The water is supplied and discharged along the longitudinal direction of the shaft. When the rotor agitates the water a turbulent flow is created in the pump. In order to ensure that the water returns to a laminar (parallel) flow, so-called vanes are placed behind the rotor. In general, axial pumps are characterised by a high speed.

Conventional axial pumps
Research has shown that, of all designs, conventional axial pumps cause most injury and death amongst the fish passing through. This injury and death primarily results from collisions with the rotor blades and/or the vanes.

The FishFlow Innovations / Nijhuis Pompen axial pump
The principle behind the FishFlow Innovations and Nijhuis Pompen axial pump is based on an adjustment to the shape of both the rotor and the vanes. The shape of the fish-friendly impeller is derived from FishFlow Innovations' Archimedean screw pump (see § 2.2) and is therefore based on the same principles. It is notable that the impeller has a larger pump passage than a conventional impeller. That is to say, there is more space between the various rotor blades to allow objects to pass through. The shape of the impeller propels water (and fish) through the middle of the impeller and away from the walls. In addition the edges of the impeller and vanes are rounded to counteract cutting. Figure 2.1 shows the conventional and fish-friendly impeller shapes.

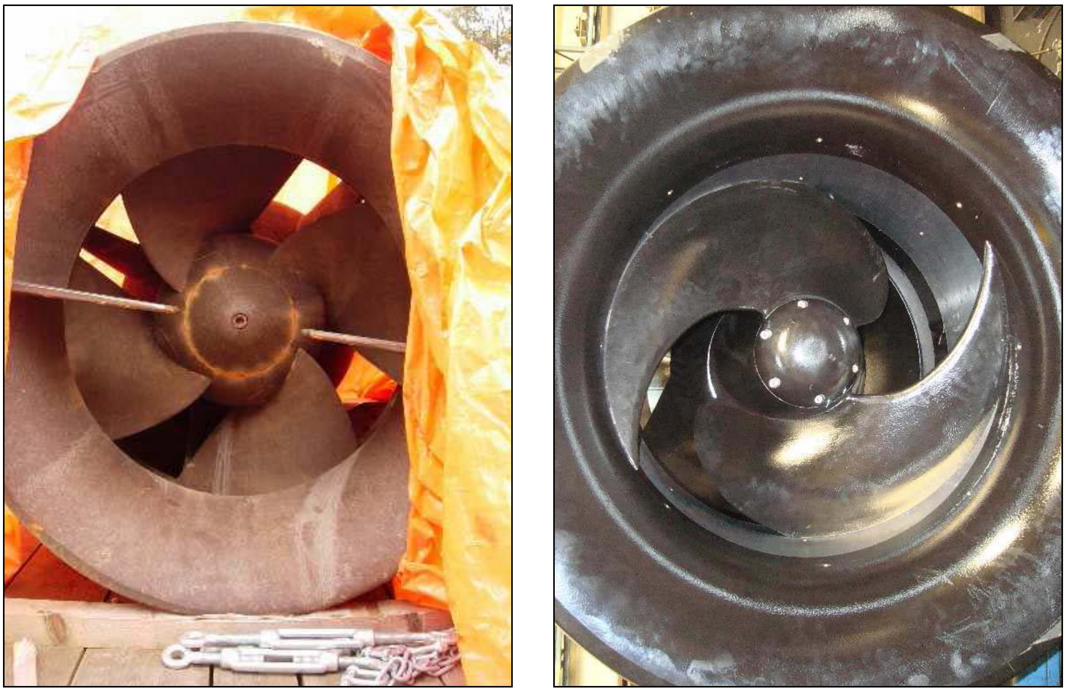

Figure 2.1 - Conventional impeller shape (left) and FFI impeller shape (right).

3 Method used in the practical tests

3.1 Test animals

Coarse fish and eels were used when conducting the tests.

The coarse fish were caught in Medemblik harbour during seine net fishing. The fish caught were then loaded into the hold of a holding-tank ship using a crane. During fishing it appeared there were too few fish present. The catch therefore comprised a relatively small number of fish of various types and lengths.

The eels were procured from a professional fisherman. These eels were stored in an aerated tank.

Permission to use the test animals was obtained from the Dierexperimenten-commissie (DEC) of the Central Veterinary Institute in Wageningen UR (letter dated 29 May 2009, see Appendix II). The animal testing was carried by *ir.* F.T. Vriese of Visadvies BV (authorized officer in accordance with Article 9 WOD {Dutch Experiments on Animals Act}) supervised by *drs.* P.S. Kroon of the Central Veterinary Institute (authorized officer in accordance with Article 14 WOD) in the presence of *dr.* G. Kruitwagen of FishFlow Innovations (likewise authorized officer in accordance with Article 9 WOD).

3.2 Set up

Axial pump
A pump with an open impeller, a capacity of 81.1 m3/m and a diameter of 800 mm was used in conducting the test. The pump was fitted with a frequency regulator and ran at 333 revolutions per minute during the test. The lift was 1 metre.

The test was carried out in a dock on the Jongert te Wieringerwerf marina.

Two steel beam were placed across the width of the dock for the test. The axial pump was placed on the beams by a truck crane, where the suction mouth was directly down into the water. A bend-piece as fitted to the outlet, which led the pumped-out water back to water surface. The pump was set up in the longitudinal direction of the dock as a result of which the water was pumped out into the wider outer harbour.

A metal cage with a length and width of 1 metre and a height of 1.5 metres was positioned below the suction mouth. The gauze on the metal cage had a mesh width of 28 x 28 mm intact mesh. The cage was fitted with floats which kept the edges of the cage on the surface of the water.

A net with a mesh size of 22 mm intact mesh was placed around the pump outlet. Lines were used to string the net across the width of the outer harbour so that there was sufficient space to avoid contact with the fish as far as possible. Figure 3.1 shows an image of the axial pump in the test set up. Figure 3.2 shows the cage for supplying the fish. Figure 3.3 is a view of the axial pump in the supply cage.

Figure 3.1 - Axial pump in the test set up

Figure 3.2 - Cage for supplying the fish

Figure 3.3 - View of the pump in the cage

Prior to starting the actual test there was a test-run of the pump without fish being present in the supply cage. When this was done a large amount of sediment was stirred up, from which it could be deduced that it was relatively shallow underneath the pump outlet opening. The jet of water blew away the local sediment so that the conditions for conducting the test improved.

3.3 Conduct of the tests

The practical tests with the axial pump and Archimedean screw pump were conducted on 15 June 2009.

Axial pump
Before the start of the test with the axial pump a dip net was used to remove a number of coarse fish from the hold of the holding-tank ship and place them in a barrel of water. The content of the barrel was then placed in the cage below the suction mouth of the axial pump. After the coarse fish were placed in the cage a number of eels were transferred from the storage tank to the cage using a net.

The pump was started shortly after the fish were placed in the cage. After the set speed was achieved pumping was carried out for 5 minutes. The pump was then switched off. The net behind the pump outlet was then hauled onto a barge where the fish in the net were transferred to a plastic barrel containing water. The fish were taken from the barrel one by one after which the total length per individual was determined and whether or not there were any injuries and/or death as a result of passing through the pump was ascertained. After the inspection the fish were placed in a second barrel of water. After all the fish had been measured and examined the fish were released into the water of the harbour.

4 Results

4.1 Axial pump

During the test with the axial pump all 91 fish survived the passage of the pump (see Table 4.1). There were 25 eels amongst these fish. All of these eels passed through uninjured. Of the coarse fish, 2 bream displayed injuries which were the result of contact with the impeller and/or the vanes. In addition 20 of the coarse fish displayed damage to their scales. This damage very probably has no relationship to the actual pump passage, but is presumably the result of contact with the net. As a large amount of bottom material was blown away during the test run, it is plausible that the scale damage occurred because the force of the outlet flow pressed the small fish against the netting. This hypothesis is supported by the fact that various fish were partially de-scaled on both flanks, as a result of 'rolling' over the netting.

Table 4.1 - Fish passed through the axial pump and injuries

Fish type	Length (cm)	No injuries	Scale damage		Total number
			by pump	by netting	
Roach	13-23	16		16	32
Bream	14-50	23	2	3	28
White bream	14-24	3		1	4
Perch	17-18	2			2
Eel	55-82	25			25
Total		69	2	20	91

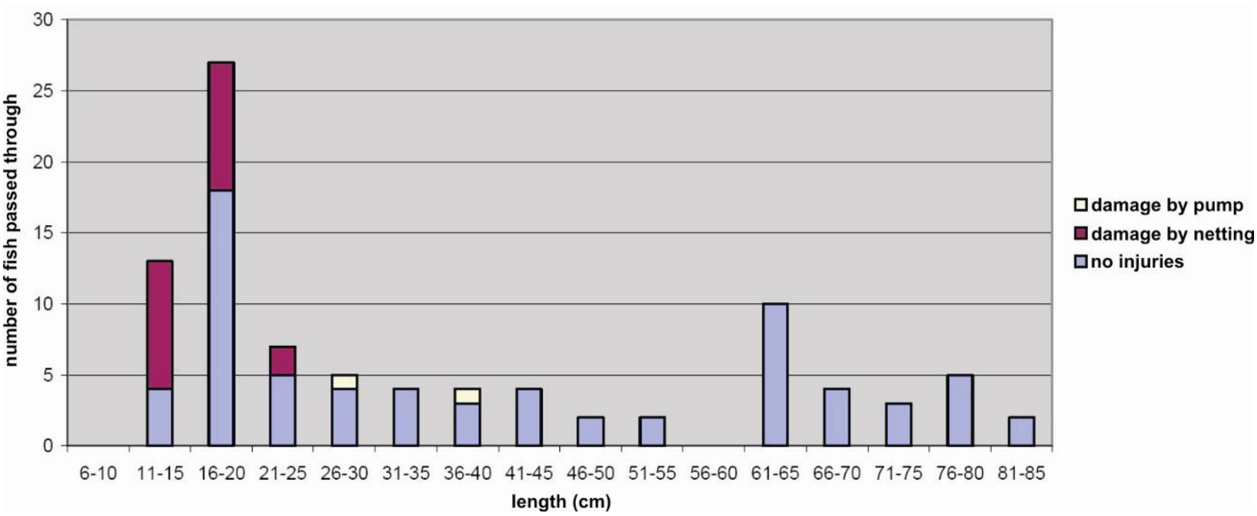

Figure 4.1 Fish passed through the axial pump by length and injuries

5 Statistical evaluation

5.1 Methods

On the one hand the results of the experiment with the two fish-friendly pumps can be regarded as simple observations, from which one can derive the probability of fish injury when such pumps are used under comparable conditions, and on the other hand it is possible to compare the results of this experiment with observations at pumping stations. In the latter case, providing the conditions relating to comparability (lift, capacity, pump diameter etc.) are met, then statistical methods can be used to conclude whether or not the fish-friendly pumps actually do result in fewer injuries.

From the results it is not only possible to make an estimate of the probability of fish being injured, but it is also possible to estimate the limits between which this probability lies, the so-called confidence interval. The estimated probability of a certain type of injury is equal to the number of injured fish divided by the total number of fish that passed through the pump. The variance in the number of injured fish is then estimated with:

$$s^2(n) = N\hat{p}(1-\hat{p})$$

where $s^2(n)$ is the estimated variance in the number of injured fish, n and $N\hat{p}$ the number of injured fish, N is the total number of fish and $\hat{p}$ the estimated probability of injury.

A rough estimate of the 95% confidence interval for the number of injured fish is given by n ± 2s(n). Dividing these values by the number of observations gives us the confidence interval of the probability.

The confidence interval can be determined more accurately, where the most conservative result is achieved with the so-called exact method, which makes direct use of the properties of the binomial distribution (Wikipedia). The confidence intervals in the results section are calculated using a confidence interval calculator on the Internet: (http://statpages.org/confint.html#Binomial)

Comparisons between various pumping stations and the fish-friendly pumps have been made using the Chi-squared test for r*k tables. The value of Chi-squared is calculated from the observed and the expected values for the number of fish injured or killed. The null hypothesis is that there is no difference between the various pump types. The expected number of fish killed or injured for every type of pump is thus equal to the total number of fish killed or injured (calculated across all pumps) divided by the total number of fish that passed through the pumps and then multiplied by the number of fish that passed through the pump concerned. Chi-squared is then calculated as the sum of the squared differences between observed numbers and expected numbers divided by the expected numbers. The larger the found value for Chi-squared the smaller the probability that there is no difference between the pumps. This probability is found by evaluating the found Chi-squared against the number of degrees of freedom (in this case the number of pumps or pump types minus 1)

5.2 Results

Table 5.1 below shows a summary of the evaluations from previous reports about fish injury in pumping stations that are more or less comparable with the lift works used for this experiment (Kunst *et al.*, 2008). Here, two comments bear making. The pumping stations concerned with which the comparison was made relate to conventional pumping stations, i.e. pumping stations that were not designed from the starting point of fish-friendliness. In addition, the tests mentioned related partly to natural migration of fish through pumping stations and partly to the forced exposure of fish to lift works. Also, the method of characterizing the fish injuries that occurred in the tests was different, where various injury categories were used (superficial injury, incisions, decapitation etc.). For the comparison in this research the data about injuries to the fish were divided into injuries that would eventually lead to the death of the fish and superficial injuries which the fish would probably survive.

Table 5.1 Fish injuries in a selection of pumping stations

		Name	Cap. (m^3/h)	Head (m)	Fish type	Length (cm)	N	N-n alive	n dead	% dead
	AXIAL PUMPS									
4	Germonpré et al., 1994	Stenensluisvaart	60	2.7	Div. cyprinids	?	20	0	20	100
					Eels	?	4	0	4	100
5	Riemersma & Wintermans, 2005	Den Deel	67	0.6	Div. cyprinids	?	126	0	126	100
					Eels	25-83	101	63	38	38
6	Lange & Merkx, 2005	Haanwijk	20	2.4	Div. coarse fish	3-26	430	374	56	13

Table 5.2 below shows that there was no mortality with fish-friendly pumps, only scale damage which was then primarily the result of contact with the catch net.

Table 5.2 Fish injuries in the FishFlow Innovations pumps

	Name	Cap. (m^3/h)	Head (m)	Fish type	Length (cm)	N	Scale damage pump	Scale damage netting	% injury
1	Axial pump Wieringerwerf	81	1	coarse fish		64	2	20	50
				Eels		25	0	0	0

Comparison between the fish injuries in pumping stations and fish injuries in the fish-friendly pumps in this experiment is only possible on the basis of mortality figures because of the absence of detailed information about injuries in the pumping stations. Many mutual comparisons are theoretically possible, but based on the numbers of observations of a few types of fish statistically reliable statements are only possible for a few (combinations of) fish types and pumping stations. Tables 5.3 and 5.4 show that in all cases the fish-friendly pumps perform better statistically in terms of limiting fish mortality as a result of passing through a pump. Apart from the results of the testing using the Chi-squared test the calculated confidence intervals of individual mortalities was tested also.

In the Archimedean screw pumping stations (Table 5.3) the mortalities vary between 14 and 42% for cyprinids while the upper limit of the 95% confidence interval for the Archimedean screw pump is only 5% mortality. The occurrence of injury was measured at 0 for both coarse fish and eels.

The conventional screw pumps (Table 5.4) show a comparable image, but the mortality is much higher (0.3 - 1.0) except in the case of the fish-friendly axial pump. Here 2 seriously injured fish were not counted as injured but were counted as dead because they probably would have died as a result of passing through the pump. The upper limit of the confidence interval for the axial pump is 11% for cyprinids and the upper limit of the confidence interval for eels is 14%. The occurrence of injury in cyprinids is very small, while it was 0 for eels.

Table 5.4 Screw-pump pumping stations compared with the axial pump. a. cyprinids per pumping station; b. cyprinids total; c. eels per pumping station; d. eels total.

Cyprinids	***Alive***	***Dead***	***Total***	***Mortality***	***95% confidence interval***		
Stenensluisvaart	0	20	20	1.00	0.83	-	1
Den Deel	0	126	126	1.00	0.97	-	1
Haanwijk	374	56	430	0.13	0.1	-	0.17
Axial pump	62	2	64	0.03	0.004	-	0.11
Chi-squared	406.7749	Freedom degr.	3	p	<0.00001		

Cyprinids	***Alive***	***Dead***	***Total***	***Mortality***	***95% confidence interval***		
Totaal gemalen	374	202	576	0.35	0.31	-	0.39
Axial pump	62	2	64	0.03	0.004	-	0.11
Chi-squared	27.06802	Freedom degr.	1	p	<0.00001		

Eels	***Alive***	***Dead***	***Total***	***Mortality***	***95% confidence interval***		
Stenensluisvaart	0	4	4	1.00	0.4	-	1
Den Deel	63	38	101	0.38	0.28	-	0.48
Axial pump	25	0	25	0.00	0	-	0.14
Chi-squared	21.61791	Freedom degr.	3	p	0.00002		

Eels	***Alive***	***Dead***	***Total***	***Mortality***	***95% confidence interval***		
Totaal gemalen	63	42	105	0.40	0.31	-	0.5
Axial pump	25	0	25	0.00	0	-	0.14
Chi-squared	14.77273	Freedom degr.	1	p	0.00001		

In view of the fact that the data for these comparisons were not collected in a single experiment the result of the statistical analysis must be interpreted with the necessary caution. It is recommended that conditions are better standardized in a subsequent experiment and the fish-friendly pumps as set up such that lift and capacity are the same as those of the pumps they are being compared with.

6 Discussion and conclusions

The original test set up as was discussed with FFI differed in a number of aspects from the experiment now carried out. A choice was made for the forced passage of 50 specimens of eel in the length class 50-60 cm and 50 specimens of bream in the length class 20-30 cm. Because fewer coarse fish were available, the experiment was finally conducted with an assortment of coarse fish of various lengths where smaller numbers passed through the pump also. As far as the eels that passed through are concerned there was a misunderstanding about the number of animals available and as a result fewer animals were exposed to the pump than was originally intended. Although all of this has consequences for the calculated confidence intervals, it can, nevertheless, be concluded that the Archimedean screw pump and the axial pump perform considerably better in the fish-injury aspect than conventional Archimedean screw pumps and axial pumps.

Although on the basis of previous experiences it has already been observed that it was important to choose a large catch net (certainly for the axial pump due to the relatively large capacity) it appeared that while the experiment was being carried out scale damage still occurred in small roach and to a lesser degree in small bream as a result of contact with the net. Additionally this was probably not to blame on the size of the net but more that at the outlet from the axial pump the high delivery still 'blew' the fish along the netting. This is an important point for attention in future experiments with forced exposure of fish to lift works with a high capacity. There was no scale damage in the experiment with the Archimedean screw pump. Because of the lower delivery the fish landed in the catch net relatively 'calmly' without making contact with the netting.

In the experiment with the axial pump a cage structure was used where the fish were deposited prior to passage through the pump. With the Archimedean screw pump a net structure was used and the fish were led from this to the Archimedean screw. In an ideal situation the choice would have been to have the fish pass through the pump one by one, partly because this better resembles the natural passage through a lift works. Because it is possible that large numbers of fish were sucked into the pump simultaneously it is probable that there was maximization of injuries in the current experiment. Nevertheless, in practice there appeared to practically negligible injury in the axial pump and 0 in the Archimedean screw

Axial pump
During the test with the axial pump 91 fish in wide range of lengths passed through the pump. Of these, only 2 of the 66 coarse fish that passed through showed injuries that probably occurred during the passage through the pump. All 25 eels were uninjured.

For statistical evaluation it was decided to include the roach, bream and white bream types in the various cyprinids category. Any injury to these fish, given their relationship, is better comparable than injuries occurring in percids such as perch for example. The two perch that passed through were then not included in the analysis either. From the cyprinid group a total of 64 specimens passed through the pump, where 2 specimens suffered a possibly fatal injury. The calculated injury to cyprinids then comes to 3%. The confidence interval runs from 0 - 11%. In total 25 eels passed through the axial pump without any form of injury. The injuries were therefore determined to be 0%. The confidence interval runs from 0 - 14%. If more eels had passed through the pump (the expectation being without injury to eels) the upper limit of the confidence interval would have been even lower.

For both eels and cyprinids it can be noted that the axial pump performed significantly better in the fish-injury aspect than the conventional screw pumps against which they were compared (for cyprinids $p < 0.00001$ and for eels $p < 0.0001$).

Archimedean screw pump

In the test with the Archimedean screw pump all 99 fish passed through the pump without injury. The group of various cyprinids here comprised 71 specimens. All of these fish passed through without injury, and as a result the injuries were determined to be 0%. The confidence interval runs from 0 - 5%. Of the eel fish type 23 specimens passed through the Archimedean screw pump without any form of injury. As a result the injuries were determined to be 0%. The confidence interval runs from 0 - 15%. The same applies here too, if more eels had passed through the Archimedean screw pump, without injury as expected, the upper limit of the confidence interval would have been even lower.

For both eels and cyprinids it can be noted that the Archimedean screw pump performed significantly better in the fish-injury aspect than the conventional Archimedean screw pumps against which they were compared (for cyprinids $p < 0.00001$ and for eels $p < 0.0074$).

Closing remarks

The experiment did not examine delayed mortality in the fish that passed through. No founded statements can be made in this respect. The experiment observers did gain the impression that the 'condition' in which the fish left the lifting works was so good that no delayed mortality could be expected to occur.

An important comment on the results obtained is that the findings apply to the pumps used in the situations tested. Deviations from the specific conditions (different speeds or lifts for example) could lead to a different result.

It seems advisable that this kind of experiment is not carried out in the summer, but in the spring or autumn. In those periods the natural passage through lifting works is at its peak. In summer the fish are more vulnerable due to relatively higher temperatures and less oxygen.

7 Literature *(Dutch)*

Denayer B. & C. Belpaire, 1992. Onderzoek naar de effecten van een vijzelgemaal op vispopulaties. Instituut voor Bosbouw en Wildbeheer van het Ministerie van de Vlaamse Gemeenschap.

Germonpré, E., B. Denayer, C. Belpaire, F. Ollivier, 1994. Inventarisatie van pompgemalen in het Vlaamse gewest en preliminair onderzoek naar de schade van diverse pomptypes op vissen na gedwongen blootstelling. Onderzoek door AMINAL en de Katholieke Universiteit Leuven.

Kunst, J.M., B. Spaargaren, F.T. Vriese, M.J. Kroes, C. Rutjes, E. van der Pouw Kraan & R.R. Jonker, 2008. Gemalen of vermalen worden. Onderzoek naar de visvriendelijkheid van gemalen. Grontmij Nederland bv, De Bilt, VisAdvies, Nieuwegein. Ref.nr. I&M-99065369-MK.

Lange, M.C. de & J.C.A. Merkx, 2005. Experimentele inventarisatie van visschade bij gemalen. VisAdvies BV, Utrecht. VA2005_01 18 pag.

Riemersma, P. & G.J.M. Wintermans, 2005. Optimalisatie vismigratie Den Deel, najaarsonderzoek. Onderzoek naar mogelijkheden inzet scheepvaartsluis ter bevordering van vismigratie bij gemaal Den Deel. Grontmij Noord BV en Wintermans Ecologenbureau.

Appendix I

Individual lengths of fish that passed through

Black figures indicate uninjured fish, red figures indicate injury as a result of passing through the pump and blue figures indicate fish with injuries as a result of the netting.

Fish passed through the axial pump (length and injury)	
Fish Type	**Length and injury**
Roach	13, 13, 14, 14, 14, 15, 15, 15, 15, 15, 16, 16, 16, 16, 16, 17, 17, 18, 18, 18, 18, 18, 19, 19, 20, 20, 20, 20, 21, 21, 21, 23
Bream	14, 14, 16, 17, 20, 20, 20, 21, 21, 26, 27, 28, 30, 30, 32, 33, 34, 34, 36, 37, 40, 40, 42, 42, 44, 45, 46, 50
White bream	14, 16, 17, 24
Perch	17, 18
Eel	25 pieces (length range 55-82 cm) all uninjured.

Appendix II

CENTRAAL VETERINAIR INSTITUUT

WAGENINGEN UR

VISADVIES B.V.
Twentehaven 5
3433 PT Nieuwegein

DATUM
29 mei 2009

ONDERWERP
beoordeling proefplan FFI1-1

BEHANDELD DOOR
P.S. Kroon

DOORKIESNUMMER
(0320) 23 85 61

E-MAIL
paul.kroon@wur.nl

BEZOEKADRES

TELEFOON

FAX

INTERNET

Betreft proefplan FFI1-1
Titel Evaluatie van twee gemaalpompconcepten die ontwikkeld zijn om de visveiligheid van pompen te vergroten
Aantal dieren 1500
Risico van ongerief matig (3)
Status Nieuw pp~~/ Herhaling van eerder pp/ continuering van eerder pp/ wijziging van eerder pp~~
Artikel 9 functionaris: Ir. F.T. Vriese
Periode 27 april tot 31 mei

De Dierexperimentencommissie heeft uw antwoord op de gestelde vragen in de brief dd. 29 april met instemming behandeld. Zij was van oordeel dat het antwoord zeer verhelderend was en dankt u voor de achtergrondinformatie.

Advies
Positief advies

Voorwaarden/ opmerkingen
De indiener dient iedere wijziging van het proefplan ten opzichte van dit advies alsmede onverwachte gebeurtenissen, onverwijld te melden aan de proefdierdeskundige

Met vriendelijke groet,
Namens de DEC
Drs P.S Kroon, Art 14