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Method for environmental protection of fish from going into water discharge facilities

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ABSTRACT
Spillway structures of hydroelectric power plants, dams, and other large hydroelectric facilities are characterized by high volumes of discharged water. Moreover, the discharge can also go in a volley way - when a large volume of water mass is passed in a short period. At the same time, in a large area in front of the spillway, a powerful current of flowing water arises, which draws in fish and juveniles. Traditional types of fish protection are of little use here, due to the complexity of the conditions. In this regard, we have begun developing a concept for active ecological protection of fish from getting into the spillways of hydroelectric power stations and dams. Its essence lies in the zoned non-physical fencing of the area of the water area in front of the spillway. The transformation of this area into a non-residential zone for fish. To implement this, the principles of active safe displacement of fish and juveniles outside the non-residential zone were formulated. A site dangerous for fish is removed from the ecology of their habitat. This ensures their protection from falling into the spillway. Experiments to test this method of protecting fish and juveniles showed the following. Active acoustic frightening of fish and juveniles makes it possible to effectively displace them from the danger zone. This protects the fish from drifting into the spillways of large waterworks.

Keywords: Echo sounder, Sonar, Fish, Water area, Fish ecology, Fish protection, Spillway, Dam, Fish protection device.
Article type: Research Article.

INTRODUCTION
The spillways of hydroelectric power plants, dams, and other large hydroelectric facilities are characterized by high volumes of discharged water. Moreover, the discharge can also go in a volley way - when a large volume of water mass is passed in a short period. At the same time, in a large area in front of the spillway, a powerful current of flowing water arises, which draws in fish and juveniles. This is dangerous for them due to sudden pressure changes, cavitation, turbulence and mechanical damage (Becker *et al*. 2003). Traditional types of fish protection are of little use here, due to the complexity of the conditions. Kazakhstan has a number of large discharge facilities, for instance, on the dams of the HPP cascade of Irtysh River, Kapshagay HPP, the dams of the reservoirs of the Aktobe Sea, Shardara, UKOOS, etc. All these hydroelectric facilities need effective fish protection that meets regulatory requirements (Build 2009; Requirements 2019). So, we have developed a method and a device for protecting fish in the spillways of large hydroelectric facilities (Kim *et al*. 2014; Isbekov *et al*. 2018). As we progressed in this topic, it became clear that a static fish protection device cannot protect fish and juveniles from entering the spillways of large hydroelectric facilities. A large section of the water area in front of the spillway is dangerous for fish. Installing a static relay around the perimeter of the entire site would be very costly. So, we have begun developing a concept for active ecological protection of fish from getting into the spillways of hydroelectric power stations and dams. The essence of the concept is the active non-physical fencing of a section of the water area in front of the spillway and the transformation of this site into a non-residential zone for fish

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(Tumenov *et al*. 2022). Several methods are known to scare away and expel fish from a dangerous area for it - sound, light, electrical and chemical stimuli, and water flow. Of these, sound has received the most attention as a behaviour modifier. Sound has an advantage over other stimuli in that it is rapidly transmitted over long distances and is independent of water turbidity or time of day (Popper & Carlson 1998). We formulated the principles of active safe displacement of fish and juveniles outside the non-residential zone (Tumenov *et al*. 2022). Thus, a site dangerous for fish is removed from the ecology of their habitat. This ensures their protection from falling into the spillway.

In 2021-2022, experiments were carried out to test a method for the ecological protection of fish and juveniles from falling into discharge facilities. These experimental studies were carried out within the framework of the grant project IPN AP09058066 “Development of an active mobile hydroacoustic fish protection device to protect fish and juveniles from entering the spillways of large hydroelectric dams and reservoirs”, funded by the Ministry of Education and Science of the Republic of Kazakhstan.

The research was carried out in the following areas:

- determination of the boundaries of the threshold, attracting and carrying away current velocities in the water area in front of the spillway;
- calculation of the area of the non-residential (dangerous for fish) zone in front of the spillway;
- a study of the possibility of expelling (frightening away) fish and juveniles from the non-residential danger zone.

Large reservoirs have areas dangerous for fish. For instance, water intake facilities, hydroelectric dams, etc. Therefore, there is a need to protect or divert fish from such areas. One way to scare away fish is to use a loud acoustic signal. Most fish have developed hearing, and water is a good conductor of sound (Nikol'skii 1963). Therefore, fish are very sensitive to underwater sounds. Most fish can make sound signals for communication (Parmentier *et al*. 2017). The detection and identification of sounds are used by many fish to avoid predators or find prey, and avoid obstacles (Popper & Platt 1993). Therefore, when using sound exposure, it can be counted on the response of the fish. It is known that the location of fish near a source of high-intensity sound signals can injure them (Hastings & Popper 2005). In our case, it is possible to avoid this due to the mobility of the hydroacoustic module. With its smooth approach to the fish, the volume will gradually increase. This causes the fish to leave before the volume reaches the pain threshold. Intense sound waves by the increased energy density also affect the soft tissues and the swim bladder of fish. Also, acoustic signals affect the sensitive lateral line (Schellart & Wubbels 1998). In response to this increased acoustic impact, the fish leave the area in uncomfortable conditions.

MATERIALS AND METHODS

Experimental studies were carried out on a model reservoir - the Kirov reservoir in the West Kazakhstan region. The species composition of the ichthyofauna was studied in early studies. To determine the background ichthyological data, scientific fishing was carried out in the order of fixed nets with meshes from 22 to 80 mm. A total of 10 scientific catches were carried out. A sampling of juveniles was carried out using a fry circle designed by Russ and fry drags. In species identification of fish and juveniles, we were guided by well-known manuals (Koblitskaya 1981; Maitland & Linsell 2006; Makeeva *et al*. 2011). Ichthyological studies were carried out according to the generally accepted methodological guidelines (Pravdin 1966). A total of 320 fish specimens were taken to determine the species, age, and size-weight composition of the ichthyofauna. The study of fish concentration was carried out using the echo-sounding method (Kim 2018). To determine the concentration, migrations, and downstream of juvenile fish, samples were taken with a Russ circle and a fry seine 15 m long, with meshes of 2 mm. The fishing gear of our design was also used to sample juveniles. This is a fry trap with a vertical lift (Kim & Choi 2015).

RESULTS

The Kirov reservoir has an area of 3000 hectares. The source of water supply is Ural River. The reservoir has a retaining dam with a spillway. The stability of the water regime with periodic discharges of water, the presence of a capital-regulated hydroelectric complex, and a diverse ichthyofauna create conditions for working out the issues of designing fish protection devices suitable for this type of water bodies. This made it possible to choose the reservoir as a model reservoir for the implementation of the grant project IPN AP09058066 “Development of an active mobile hydroacoustic fish protection device to protect fish and juveniles from entering the spillways of large hydroelectric dams and reservoirs" (Tumenov *et al*. 2021). The species composition of the ichthyofauna of the Kirovsky farm was studied in early studies. The list of fish living here includes pike, bream, silver carp, roach, and perch. The fish productivity of the reservoir can be assessed as average. The study of the number of fish by the method of echo sounding showed a concentration of 285 specimens per 1 hectare of water area. The concentration of juvenile fish in the reservoir is also quite high and amounts to approximately 15,000 ind./ha. The indicators of fish fatness and other biological characteristics correspond to the average values for the water bodies of the region. Thus, the background ichthyological indicators of the study area can be assessed as typical for this kind of water body. The purpose of the first experiment was to study the current velocities at different distances from the dam spillway in spring and summer. In spring, the maximum amount of water enters the reservoir. Accordingly, water discharges have the highest rates. At the time of research in May, around-the-clock discharge of about 50 m^3 of water per second was carried out. This is the maximum figure for the seasons of the year. Initially, the depths were measured in the area in front of the spillway. The echo sounder Garmin Striker v 9 sv was used. The depth in the channel part of the spawning ground averaged 3.5 m. Next, the current velocity was measured with a hydrometric current meter HMCM-1 (Fig. 1). Measurements of the current velocity were carried out along the transverse sections, at a distance of 5 to 250 m from the spillway of the dam. Spatial orientation by sampling stations was carried out using the built-in Garmin satellite navigator and the Google Earth Pro computer program.

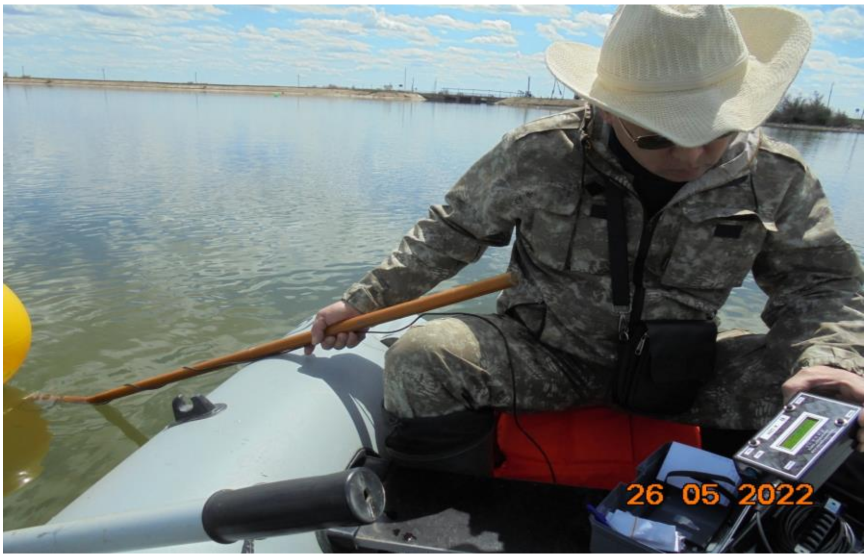

Fig. 1. Measurements of the current velocity by the HMCM-1 device.

In spring, about 50 $m^3 s^{-1}$ is discharged through the spillway. The current velocity is highest at the spillway gate valve. At a distance from the spillway, the current velocity decreases. Table 1 depicts the current velocity indicators in the upper pool, in the spring. The analysis of Table 1 shows that in spring the current velocities contribute to the passage of fish and juveniles into the spillway of the dam. Several gradations of the current velocity can be given, which affect the escape of fish and juveniles to the spillway. Firstly, this is a threshold speed of 0.15-0.20 m s^{-1}. Using this, semi-anadromous fish react to the flow of water, tending to migrate with the flow. Attracting velocity of 0.5 – 0.8 m s^{-1} already directly encourages them to move with the flow. The demolition velocity of 0.90-1.20 m s^{-1} causes their forced demolition. For juvenile fish, only a carrying speed of 0.15-0.25 m s^{-1} is indicated. Based on Table 1, we can conclude the following: In spring, the demolition current velocity is observed only in the immediate vicinity of the spillway gate valve. The attracting current velocity was noted at a distance of 25 m, and the threshold velocity at a distance of 150 m from the spillway gate valve. For juvenile fish, the demolition current velocity is observed at a distance of up to 150 m. Therefore, in spring, the entire area of the water in front of the spillway, at a distance of up to 150 m from the gate valve, can be considered dangerous for fish and juveniles (Fig. 2). In summer, about 30 $m^3 s^{-1}$ is discharged through the spillway. The current velocity is somewhat reduced. Table 2 below shows the current velocity indicators in the upper pool, in the summer period. The analysis of Table 2 shows that in summer the demolition current velocity is also observed only in the immediate vicinity of the spillway gate valve. The attracting current velocity is observed at a distance of 25 m, and the threshold velocity is observed at a distance of 100 m from the spillway gate valve.

Table 1. Indicators of the current velocity in the upper pool in front of the spillway of the Kirov reservoir dam, in the spring of 2022.

Section number (distance from the dam spillway)	Current velocity at the section points (m s^{-1})					Average value
	right end	middle right	central	middle left	left end	
1 (25 m from spillway)	0.48	0.49	0.50	0.48	0.47	**0.49**
2 (50 m from spillway)	0.22	0.23	0.24	0.23	0.22	**0.23**
3 (75 m from spillway)	0.21	0.21	0.22	0.21	0.21	**0.21**
4 (100 m from spillway)	0.20	0.20	0.21	0.20	0.20	**0.20**
5 (125 m from spillway)	0.18	0.18	0.19	0.18	0.17	**0.18**
6 (150 m from spillway)	0.16	0.17	0.18	0.17	0.16	**0.17**
7 (175 m from spillway)	0.12	0.12	0.12	0.12	0.11	**0.12**
8 (200 m from spillway)	0.10	0.10	0.11	0.10	0.10	**0.10**
9 (225 m from spillway)	0.09	0.09	0.09	0.09	0.08	**0.09**
10 (250 m from spillway)	0.07	0.07	0.08	0.08	0.07	**0.07**

Fig. 2. Section of the water area in front of the spillway, at a distance of 150 m from the gate valve, dangerous for fish and juveniles (1 - dam spillway; 2 - section of the water area dangerous for fish and juveniles; 3 - direction of flow).

For juvenile fish, the demolition current velocity is observed at a distance of 100 m. Therefore, in summer, the entire section of the water area in front of the spillway, at a distance of up to 100 m from the gate valve, can be considered dangerous for fish and juveniles. This experiment was carried out in spring (May). Its purpose was to study the possibility of expelling (frightening away) fish and juveniles from the non-residential danger zone in spring. In this season, fish migrations take place, so it is more persistent and active. As experiment 1 showed, in spring the entire section of the water area in front of the spillway, at a distance of 150 m from the gate valve, can be considered dangerous for fish and juveniles. Based on this, the sizes of the sites for the experiment were chosen: 150 × 150 m. In spring, the experiment was carried out on two sites, i.e., coastal and deep. This is due to the fact that in spring fish migrations pass through the deep channel part of the reservoir. In the coastal part, the fish rest or feed. The water depth in the deep section averaged 3.5 m, while in the coastal area 2.2 m. First, the corners of the plots with dimensions of 150 × 150 m and an area of 2.25 ha each were marked with buoys. Further, the displacement (frightening away) of fish and juveniles from the plots was carried out. A boat with an underwater acoustic speaker DRS-8-003/SA430 Mod 2 passed straight routes between two opposite sides of the site (Fig. 3). It is known that fish become accustomed to prolonged sound exposure (Radford *et al*. 2016). To overcome the habituation factor, acoustic signals were used with a loudness of up to 95 dB, with a fast frequency change from 580 to 4078 Hz. Sounds up to 95 dB are considered loud for the air environment. With a low sound background underwater, they sound deafening. The rapid change of frequencies brings its sharpness. This does not allow the fish to get used to. The average distance between routes is 7 m. The speed of passing 1 route is 1.5 min. On 1 complete passage of the site, an average of 30 min was spent. After the completion of the next cycle, the next one was immediately carried out. The concentration of fish in the area was determined by the echo sounder Garmin

Striker v 9 sv. Monitoring the abundance of migratory fish by the hydroacoustic method is quite effective (Martignac *et al*. 2014). The concentration of juveniles was measured by catches of fry traps.

Table 2. Indicators of the current velocity in the upper pool in front of the spillway of the Kirov reservoir dam, in the summer of 2022**.**

Section number (distance from the dam spillway)	Current velocity at the section points (m s^{-1})					Average value
	Right end	Middle right	Central	Middle left	Left end	
1 (25 m from spillway)	0.42	0.42	0.43	0.42	0.42	**0.42**
2 (50 m from spillway)	0.17	0.17	0.18	0.17	0.16	**0.17**
3 (75 m from spillway)	0.16	0.16	0.17	0.16	0.15	**0.16**
4 (100 m from spillway)	0.15	0.15	0.16	0.15	0.14	**0.15**
5 (125 m from spillway)	0.12	0.12	0.13	0.12	0.12	**0.12**
6 (150 m from spillway)	0.10	0.11	0.11	0.11	0.10	**0.11**
7 (175 m from spillway)	0.08	0.08	0.09	0.09	0.08	**0.08**
8 (200 m from spillway)	0.05	0.06	0.05	0.05	0.05	**0.05**
9 (225 m from spillway)	0.03	0.04	0.04	0.03	0.03	**0.03**
10 (250 m from spillway)	0.02	0.02	0.03	0.02	0.02	**0.02**

Fig. 3. Repelling fish with an underwater speaker.

Observations by the camera of the underwater drone Giadius mini S showed a high sensitivity of fish to intense sound exposure (Fig. 4). Fig. 4 shows that before the loud sound is turned on, the fish feel at ease. After turning on the sound signal, they quickly swim away. This suggests that loud and intense sound causes fear and discomfort in them. Table 3 shows the results of displacement (frightening away) of fish from a conditionally non-residential danger zone in the spring. According to Table 3, at the coastal experimental site, fish scaring was quite successful. After 1 hour of frightening away, about 25% of the fish were driven out; after 2 hours up to 32%. The results of 3 and 4 hours of scaring were more significant: 48 and 62%. After 5 hours, 74% of the fish were expelled. In the deep section, the results were more modest. Fish migration took place here, and therefore it was more persistent. After 1 hour of scaring away, about 16% of the fish were driven out; after 2 hours about 25%; and after 3 and 4 hours 39 and 54%. After just 5 hours, 65% of the fish were driven out. Fig. 5 shows echo sounder scans before and after acoustic repelling. Table 4 shows the results of the displacement (frightening away) of juveniles from the conditionally non-residential danger zone in the spring. Based on Table 4, at the coastal experimental area, the frightening away of juveniles was quite noticeable. After 1 hour of scaring, about 18% of juveniles were driven out; after 2 hours about 29%; and after 3 and 4 hours 45 and 58%. After 5 hours, 69% of juveniles were expelled. In the deep section, the results were lower. The migration of juveniles took place here, and therefore it was more active. After 1 hour of scaring, about 14% of juveniles were driven out; after 2 hours about 22% and after 3 and 4 hours 35 and 52%. After just 5 hours, 63% of juveniles were displaced. After the completion of the five-hour frightening away, an observation boat went out to the experimental sites. Using the Garmin Striker v 9 sv fish finder and Giadius mini S underwater drone, we tracked the dynamics of the return of fish and juveniles. Observations showed that the fish began to return after 32 min. After 75 min, the concentration of fish in the area was the same as before scaring. The juveniles began to return after 37 min. After 82 min, the concentration of juveniles in the area was the same as before scaring away.

Fig. 4. Behaviour of fish before and after turning on an intense loud sound signal.

Table 3. The results of the spring experiment on the displacement (frightening away) of fish from the conditionally non-residential danger zone**.**

Experiment indicators	**Time ranges**					
	Before frightening away	**After 1 hour of frightening away**	**After 2 hours of frightening away**	**After 3 hours of frightening away**	**After 4 hours of frightening away**	**After 5 hours of frightening away**
Concentration of fish in the coastal area (ind.)	528 (100%)	396 (75%)	359 (68%)	275 (52%)	201 (38%)	137 (26%)
Concentration of fish in the deep area (ind.)	816 (100%)	685 (84%)	612 (75%)	498 (61%)	375 (46%)	286 (35%)

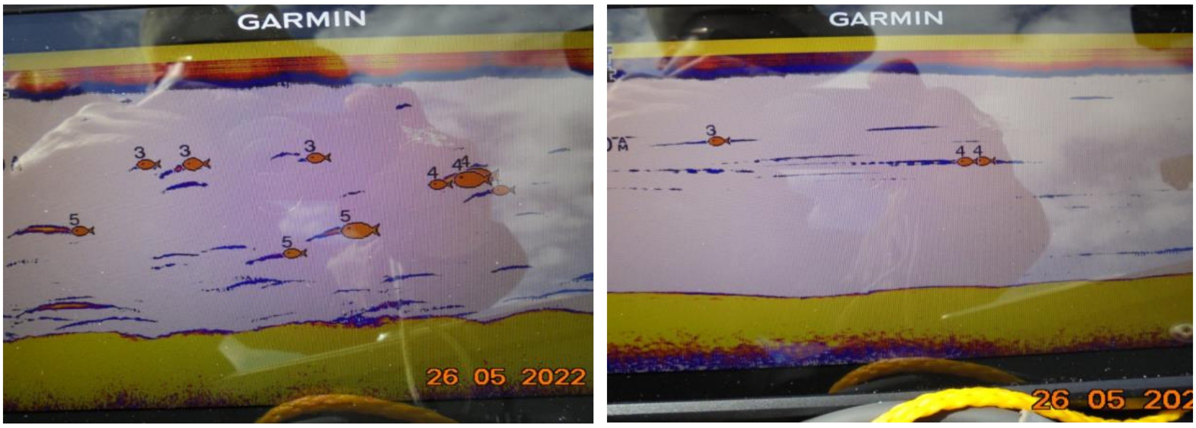

Fig. 5. Photographs of echo sounder scanning before (left) and after (right) acoustic fish frightening away.

Table 4. Results of the spring experiment on the displacement (frightening away) of juveniles from the conditionally non-residential danger zone.

Experiment indicators	**Time ranges**					
	Before frightening away	**After 1 hour of frightening away**	**After 2 hours of frightening away**	**After 3 hours of frightening away**	**After 4 hours of frightening away**	**After 5 hours of frightening away**
Concentration of juveniles in the coastal area (ind.)	8642 (100%)	7086 (82%)	6135 (71%)	4753 (55%)	3630 (42%)	2679 (31%)
Concentration of juveniles in the deep area (ind.)	9511 (100%)	8180 (86%)	7418 (78%)	6182 (65%)	4565 (48%)	3519 (37%)

This experiment was carried out in summer (June). Its purpose was to study the possibility of expelling (frightening away) fish and juveniles from the non-residential danger zone in the summer. As experiment 1 showed, in summer the entire section of the water area in front of the spillway, at a distance of 100 m from the gate valve, can be considered dangerous for fish and juveniles. Based on this, the sizes of the sites for the experiment were chosen: 100 × 100 m. In the summer, the experiment was also carried out on two sites - coastal and deep. The water depth in the deep section averaged 2.8 m, while in the coastal area 1.7 m. The corners of the plots with dimensions of 100 × 100 m and an area of 1 ha each were marked with buoys. Further, the displacement (frightening away) of fish and juveniles from the plots was carried out. A boat with an underwater acoustic speaker DRS-8-003/SA430 Mod 2, passed direct routes between two opposite sides of the site. Acoustic signal loudness up to 95 dB, with fast frequency change from 580 to 4078 Hz was used. The average distance between routes was 7 m. The speed of passing 1 route was 1 minute. On average, one complete passage of the site took about 20 minutes. After the completion of the next cycle, the next one was immediately carried out. The concentration of fish in the area was determined by an echo sounder, the concentration of juveniles was determined by fry traps. Table 5 shows the results of displacement (frightening away) of fish from a conditionally non-residential danger zone in the summer period. From Table 5 it can be seen that in the coastal experimental area, fish repelling was quite successful. After 1 hour of frightening away, about 29% of the fish were driven out; after 2 hours up to 35%. The results of 3 and 4 hours of scaring were 52 and 65%. After 5 hours, 76% of the fish were expelled. In the deep section, the results were higher than in spring, because the time for migrations had passed. After 1 hour of scaring away, about 21% of the fish were driven out; after 2 hours about 28% and after 3 and 4 hours 43 and 58%. After just 5 hours, 69% of the fish were driven out.

Table 5. The results of the summer experiment on the displacement (frightening away) of fish from the conditionally non-residential danger zone.

Experiment indicators	**Time ranges**					
	Before frightening away	**After 1 hour of frightening away**	**After 2 hours of frightening away**	**After 3 hours of frightening away**	**After 4 hours of frightening away**	**After 5 hours of frightening away**
Concentration of fish in the coastal area, ind.	181 (100%)	129 (71%)	118 (65%)	87 (48%)	63 (35%)	43 (24%)
Concentration of fish in the deep area, ind.	193 (100%)	152 (79%)	139 (72%)	110 (57%)	81 (42%)	60 (31%)

Table 6 shows the results of displacement (frightening away) of juveniles from the conditionally non-residential danger zone in the summer period. From Table 6 it can be seen that in the coastal experimental area, the repelling of juveniles was quite noticeable. After 1 hour of scaring, about 22% of juveniles were driven out; after 2 hours about 33% and after 3 and 4 hours 49 and 64%. After 5 hours, 72% of juveniles were expelled. In the deep section, the results were better than in spring. After 1 hour of scaring, about 19% of juveniles were driven out; after 2 hours about 26% and after 3 and 4 hours 41 and 57%. After just 5 hours, 69% of juveniles were displaced. After the completion of the five-hour scaring away, an observation boat entered the experimental site. Using the Garmin Striker v 9 sv fish finder and Giadius mini S underwater drone, we tracked the dynamics of the return of fish and juveniles. Observations showed that the fish began to return after 42 minutes. After 95 minutes, the concentration of fish in the area was the same as before scaring. The juveniles began to return after 39 minutes. After 110 minutes, the concentration of juveniles in the area was the same as before frightening away.

Table 6. The results of the summer experiment on the displacement (frightening away) of juveniles from the conditionally non-residential danger zone.

Experiment indicators	**Time ranges**					
	Before frightening away	**After 1 hour of frightening away**	**After 2 hours of frightening away**	**After 3 hours of frightening away**	**After 4 hours of frightening away**	**After 5 hours of frightening away**
Concentration of juveniles in the coastal area, ind.	3122 (100%)	2435 (78%)	2092 (67%)	1592 (51%)	1124 (36%)	874 (28%)
Concentration of juveniles in the deep area, ind.	1885 (100%)	1527 (81%)	1395 (74%)	1112 (59%)	811 (43%)	584 (31%)

CONCLUSION

In spring, the threshold current velocity for fish was observed at a distance of up to 150 m from the spillway gate valve. For juvenile fish, the carrying current velocity in spring was also observed at a distance of up to 150 m from the spillway. Therefore, in spring, the entire section of the water area in front of the spillway, at a distance of up to 150 m from the spillway gate valve, can be considered dangerous for fish and juveniles. In summer, the current speed decreased. For fish and juveniles, a section of the water area at a distance of up to 100 m from the spillway gate valve is dangerous. Experiments on expelling (frightening away) fish and juveniles from the zone that is conditionally dangerous for them showed the effectiveness of increased acoustic exposure. In the spring, 65 to 74% of the fish were forced out of the areas for 5 hours of scaring away; and Juveniles from 63 to 69%. In summer, 69 to 76% of the fish were forced out of the areas for 5 hours of scaring away; and Juveniles from 69 to 72%. After the completion of the five-hour repelling, the fish began to return after 32-42 minutes (spring-summer). After 75-95 minutes, the concentration of fish in the areas was restored to background values. Juveniles began to return after 37-39 minutes. After 82-110 minutes, the concentration of juveniles was the same as before scaring away. Observations showed that the fish began to return after 42 minutes. After 95 minutes, the concentration of fish in the area was the same as before scaring. The juveniles began to return after 39 minutes. After 110 minutes, the concentration of juveniles in the area was the same as before frightening away. Intense active acoustic impact can force fish and juveniles out of a dangerous part of the reservoir. It takes at least 5 hours to achieve acceptable results. However, when the acoustic impact stops, the fish quickly returns. Therefore, scaring away fish should not be carried out continuously, or with short breaks, no more than 30 minutes. An active mobile hydroacoustic fish protection device is effective enough to protect fish and juveniles from falling into spillways. This requires modern underwater acoustic equipment and a significant amount of effort. During the period of fish migration, fish protection efficiency is somewhat lower. At this time, it is necessary to increase the intensity and duration of frightening the fish.

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