The current state of Atlantic salmon reproduction in the Keret River, White Sea basin, and how it can be increased

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Abstract. The Keret River is one of large salmon rivers in the White Sea basin. The estimated abundance of Atlantic salmon in the river began to decrease in 1991, reaching a maximum in 1997 due to the abruptly increased illegal fishing level and the invasion of juvenile Atlantic salmon by the monogeny of Gyrodactylus salaris. The studies conducted have shown that the salmon population in the Keret River is depressed and that the average distribution density of juveniles aged 1+ and older is 1.6 fish /100 m². Atlantic salmon reproduction on fish hatcheries is important for maintaining the population abundance (farm individuals make up over 50% of the population). Artificial Atlantic salmon reproduction in the Republic of Karelia’s rivers is carried out by the Karelian Branch of Glavrybvod FGBU at the Kem and Vyg fish hatcheries. The fish hatcheries could achieve better results by updating the juvenile breeding technology. An example of a new high-intensity biotechnology is the use of physical factors controlling the vital activity of fish in the various periods of ontogenesis. The study of the effect of low-intensity laser radiation in the early stages of ontogenesis has shown that red light over a certain dose range enhances the adaptability of fish by decreasing mortality and accelerating growth, thus decreasing the loss of fish products in fish hatcheries.

1. Introduction
Propects in the management of aquatic biological resources are related not only to the natural production potential of water bodies but also to the impact of human activities on ecosystems [1], [2].

The fish fauna dynamics of Russia’s water bodies has long been exhibiting a decline in the abundance and catches of valuable fish species. Atlantic salmon from rivers on the White Sea shore of Karelia, where its abundance has catastrophically decreased due to hydraulic power engineering, timber rafting, poorly organized fishery and poaching, are no exception. As a result, the rivers had lost their value by the late 20th century, the total abundance of Atlantic salmon is estimated and part of its producers is caught for hatchery rearing only in some of the rivers, e.g. the Keret. Available data show that in this river the maximum abundance of the salmon which migrates for spawning was 4660 fish in 1983 [3]. I.L. Shchursov [4] noted that the abundance of the spawning stock for the optimum filling of the feeding and growing grounds of the river (persisting reserves) is 1700 fish. The estimated abundance of Atlantic salmon in the Keret River began to decline in 1991, reaching a maximum of 180 fish in 1997. The decline was provoked by the abruptly increased illegal fishing level and the invasion of juvenile Atlantic salmon by the monogeny of Gyrodactylus salaris. Studies [5] have shown
that the Atlantic salmon population in this river was badly affected by Gyrodactylus salaris due to the
invasion of the monogyne of G. salaris. The parasite, first found in the Keret River in 1992, has
inflicted a great damage to the salmon stock (the distribution density of fingerlings in the reference
stretch of the river decreased from 62 fish/100 m² in 1990 to 0.2 fish/100 m² in 1996 and that of parr
(1+) actually dropped to zero). The parasite is assumed to enter the river as the result of fish
management. It took less than five years for the parasite to spread along the entire river. The increase
in the infestation of juvenile salmon by G. salaris was paralleled by fish mortality. As a result, the
adult Atlantic salmon stock has decreased by more than 25 times [5], the present reproductive
potential of the Atlantic salmon population from this river is extremely low and the current state of
Atlantic salmon reproduction is unsatisfactory.

Diminishing populations are restored by artificial breeding all over the world [6]. The hatchery
rearing of Atlantic salmon in the Keret River has been carried out for decades, but its effectiveness is
extremely low. Therefore, problems in the management and rearing technology of this valuable fish
species should be approached in other ways.

An example of the recent application of a new high-intensity biotechnology in fish culture is the
use of physical factors controlling the vital activity of fish in the different periods of ontogenesis. One
way of increasing the commercial quality of the eggs, larvae and juveniles of various ages is to use
methods for quantum biology in aquaculture. The healing effect of low-intensity laser radiation with a
wavelength in the red region has been clinically proven in medicine. Helium-neon laser radiation is
commonly used for this purpose [2]. The effect of laser radiation on living biological organisms is
highly diverse and is controlled mainly by radiation intensity and exposure time, as well as wavelength
and power density. With respect to modern quantum biology, of special interest is the study of the
effect of low-intensity laser radiation on biological targets. In our experiments we used Atlantic
salmon eggs.

2. Materials and methods
Our studies were conducted using 2012-2019 data on the density of juvenile Atlantic salmon from the
Keret River, long-term fishery and biological data from counting fence areas and the results of 2019-
2020 experiments carried out at Vyng hatchery to estimate the influence of low-intensity laser radiation
on Atlantic salmon eggs.

The Keret River is one of the largest rivers on the White Sea shore of Karelia. It flows from Lake
Petrijärvi into Keret Bay of the White Sea. It is a 110 km long river with a ratio of lake surface to
drainage area of 17.5% and a catchment area of 3393 km² (Table 1). The spawning, feeding and
growing grounds (SFGG), including those in the Louksa River, one of major spawning tributaries (4.1
ha), cover an area of 71.7 ha. The main SFGGs are located in the 45 km long stretch of the river from
Sukhoy Rapids to the river mouth.

Table 1. Hydrological parameters of the Keret River

| Parameter, unit of measurement | Value   |
|-------------------------------|---------|
| River length, km              | 100,1   |
| River fall, m                 | 90,6    |
| Catchment area, km²           | 3393    |
| Lake surface to drainage area, % | 17,5   |
| Relative fall, m/km           | 0,91    |
| Average flow module, l/s/km²  | 8,5     |
| Water discharge at the mouth, m³/s | 28,83  |

The fish fauna of the Keret River consists of 16 fish and fish-like species most of which inhabit the
main river channel and the tributaries (Table 2). European flounder occurs only in the lowermost near-
tributary stretch of the river. Acclimatized pink salmon comes for spawning mainly in odd years but
may be completely absent in even years.
Table 2. The fish fauna of the Keret River

| Family                  | Name                                      |
|-------------------------|-------------------------------------------|
| Salmonidae              | Atlantic salmon – *Salmo salar*           |
|                         | Trout – *Salmo trutta*                    |
|                         | Pink salmon – *Oncorhynchus gorbuscha*    |
| Coregonidae             | Whitefish – *Coregonus lavaretus*         |
| Thymallidae             | Grayling – *Thymallus thymallus*          |
| Percidae                | Perch – *Perca fluviatilis*               |
|                         | Ruff – *Gymnocephalus cernuus*            |
| Esocidae                | Pike – *Esox lucius*                      |
| Lotidae                 | Burbot – *Lota lota*                      |
| Cyprinidae              | Roach – *Rutilus rutilus*                 |
|                         | Dace – *Leuciscus leuciscus*              |
|                         | Minnow – *Phoxinus phoxinus*              |
| Cottidae                | Sculpin – *Gottus koshewnikowi*           |
| Pleuronectidae          | European flounder – *Platichthys flesus*  |
| Gasterosteidae          | Nine-spined stickleback – *Pungitius pungitius* |
| Petromyzontidae         | Pacific lamprey – *Lethenteron japonicum* |

Vyg hatchery is a part of the Karelian Branch of the federal budgetary institution – The Main Basin Directorate for Fisheries and Conservation of Aquatic Biological Resources (Glavrybvod FGBU). It is located in Sosnovets Town, Belomorsk District, Republic of Karelia, about 250 m from the Vyg River. It began operating in 1956. Every year it releases about 150 000 two-year-old salmon individuals into rivers.

The study of juvenile salmon on SFGGs were carried out using a pack type of electrical catching device during a low water level period in September at the light time of the day. Each water area was fished off at least three times at 10-minute intervals. The abundance of juvenile salmon inhabiting the fished-off stretch of the river was estimated by the removal method [7] using an applied computer program.

To estimate the intensity and extensity of infestation by the monogeny of *G. salaris*, the skin cover and fins of juvenile salmon were examined with a MBS-9 binocular microscope.

The mortality of juveniles caused by *Gyradactylus salaris* was quantitatively estimated using an imitational mathematical model [8]. Its structure imitates the life cycle of each generation from an egg to the return of adult fish for spawning. The death rate coefficients during a fingerling’s fluvial and marine life periods were estimated by long-term monitoring.

Laser studies on the effect of electromagnetic radiation on fertilized salmon eggs began at the end of 2019 in the incubation section of Vyg hatchery. Laser is a source of light, which is used to obtain coherent electromagnetic radiation in a short-wave, especially infrared and visible light regions. Unlike the radiation of usual light sources, laser radiation displays high spectral energy density, monochromatism, high temporal and spatial coherence, highly stable laser radiation intensity in a stationary regime and can generate very short light impulses. The parameters of the helium-neon laser used in our work are shown in Table 3.

Atlantic salmon eggs from the Keret River were placed for incubation into reference and experimental ponds in October 2019 at a water temperature of 5–7ºC. The water temperature was 0.6–0.4ºC in the winter period (November – December) and – 2ºC in spring (April) and the oxygen saturation of water was 80-90%. During the incubation period the eggs were periodically placed into curable baths for prophylaxis. A single hatching of salmon larvae was observed on 6 May, 2020 and active hatching on 12 May. The larvae were maintained since 18 May. On 22 May, they were first fed, and in June they were fed endogenously. In June-July, the larvae were placed in tonic salt baths with running water.
Our studies were carried out using the 2008-2019 data obtained by the Karelian Branch of Glavrybvod FGBU on Atlantic salmon producers from the counting fence area and on the amounts of hatchery-reared juvenile Atlantic salmon released into the Keret River in 2008-2019.

### Table 3. Physico-technical parameters of a helium-neon laser

| Parameter, unit of measurement | Value |
|-------------------------------|-------|
| Radiation wave length, µm    | 0.63  |
| Radiation power, mWt         | 46    |
| Readiness time, min          | 10    |
| Spectral composition of radiation | multi-mode |
| Radiation polarization       | non-polarized |
| Laser radiation beam diameter at γ=0.9, mm | 1.9 |
| Energy divergence of radiation at γ=0.9, mrad | 1.7 |
| Consumed power, Wt           | 60.0  |

### 3. Results

Atlantic salmon is a diadromous cold-water fast-growing species living in the northern Atlantic Ocean. In Russia, salmon occurs in the Baltic, Barents and White sea basins [2]. The eastern boundary of its distribution area is the Kara River. In large lakes salmon develops a special freshwater form.

The total population stock of Atlantic salmon reproducing in Russia’s rivers makes up a large portion of global salmon resources, ensuring catches in the territorial waters and general commercial fishing areas in the northern Atlantic Ocean [9]. In Russia, natural reproduction persists in about 450-480 rivers. About half of the total population stock is concentrated in the White Sea basin with 44% of salmon rivers and in the Barents Sea with 26% of salmon rivers.

There are three geographic regions in the White Sea basin inhabited by Atlantic salmon: the Kola Peninsula, Karelia and the Northern Region (Arkhangelsk Oblast) [9]. On the Karelian shore, the rivers flowing into the White Sea, like those on the Kola Peninsula, are montane to semi-montane. They have extensive rapids commonly occurring in their middle and lower stretches. The region has a high ratio of lake surface to drainage area. The coefficient of lake percentage of many rivers is over 12-15%. Some rivers are typical lake-river systems, in which rapid stretches of rivers alternate with long channel lakes.

In Karelia, Atlantic salmon occurs in 17 small rivers varying in length from 46 to 194 km. The Kem and the Vyg, where large-scale salmon fishery existed for many centuries, used to be the most productive rivers in the region. More recently, however, both rivers were regulated by hydropower plant dams, limiting natural salmon reproduction [2]. Nowadays, the Keret, where small-scale salmon fishery is maintained for fish management, is the most productive river on the Karelian shore of the White Sea.

Salmon’s life cycle is divided into two periods: fluvial and marine. Salmon feeds and grows in the sea and migrates upstream to the rivers flowing into the sea. In its natural habitat salmon is represented by two races – hiemal and vernal. Vernal Atlantic salmon matures at the age of 3–4 years and spawns in the same year when it migrates to rivers. A hiemal form matures 1 to 2 years later than a vernal form, migrates for spawning with underdeveloped sexual products and spawns next year. Atlantic salmon spawns in September-October in northern areas and in November-December in southern areas. Its fecundity varies from 10 to 22 thousand eggs. An incubation period lasts for an average of 180 days. Some of producers die after spawning, while survivors migrate downstream into the sea and come back for spawning next season or next year. Cases of recurrent spawning (up to five times) are known. Larvae are hatched in late April-early May. In a river, juveniles commonly live for 2–3 years, seldom up to 5 years. Atlantic salmon migrates downstream into the sea in spring, after ice drift. It comes back to rivers for spawning after 2–3-year summer feeding and growing in the sea. In the marine period of its life fish is salmon’s major food item; sexually mature individuals do not feed in rivers.
Nowadays, artificial reproduction is the most efficient way of restoring the abundance of Karelian salmon populations. Two-year-old juveniles, weighing at least 19 g, were released into the Keret, Vyg, Suma and Kem rivers. The official data obtained by the Karelian Branch of Glavrybvod FGBU show that 95 to 22 thousand two-year-old Atlantic salmon were released into the Keret River in 2008-2019.

In spite of fairly intense artificial reproduction, the abundance of Keret River salmon remains extremely low: only a few hundred fish return for spawning every year. In 2008-2019, the abundance of «wild» Atlantic salmon of natural origin in the Keret River varied from 70 to 507 fish, averaging 251 fish. The bulk of spawning migrants in this period was formed by hatchery-reared fish that displayed an abundance of 43 to 223 individuals and an average of 105 fish (Figure 1).

The average density of juveniles aged 1+ and older throughout the study period was as low as 1.6 fish/100 m². A maximum density of 4.7 fish/100 m² was recorded in 2012 and a minimum density of 0 fish/100 m² in 2017. Other fish species dominated by sculpin (Cottus gobio L.) were also encountered in the typical biotopes of juvenile salmon.

Parasitological analysis of juvenile salmon has shown that its infestation by the parasite Gyrodactylus salaris in the Keret River in some years was 100%. Long-term monitoring of the invasion of salmon by the parasite has shown not only a decline in fish infestation indices but also the absence of G. salaris in some years with high summer water temperatures [10].

Model experiments with a population of a corresponding structure were carried out to estimate the natural mortality coefficient in the river at which the spawning stock reaches the modern average level (in our case, 250 fish against 3000 fish prior to the beginning of epizooty. Losses are caused by natural mortality, which is higher than the preset value in the model. Modelling has shown that the annual mortality of juveniles in the river is no less than 70%.

While assessing the effect of electromagnetic radiation on fertilized salmon eggs using a laser, we monitored the condition, growth and development of the salmon eggs at blastula, eye pigmentation and larva hatching stages and those of fingerlings. Comparative analysis of the amount of eggs that have left the experimental and reference ponds has shown that this parameter in the experimental and reference ponds is slightly higher than the generally accepted norms (5-8%) for hatchery-reared Salmonidae. The mortality indices of the eggs exposed to laser radiation were twice as low as those in the reference pond. During the incubation period (November-April), 3.5% of the eggs left the experimental pond and 8.2% left the reference pond.
Analysis of the fish culture-biological characteristics of juvenile salmon in the first year of life has shown that larvae from the experimental pond bred from July to October displayed elevated weight growth indices and low mortality indices in comparison with those from the reference pool (Figure 2). For example, in July the average mass of a larva from eggs exposed to laser radiation was 2.6 g and the eggs that left the pond made up 0.07%, the corresponding values were 1.9 g and 0.15%; those in the experimental pond in August were 5.3 g and 0.3%, those in the reference pond were 4.3 g and 0.7%; those in the experimental pond in September were 8 g and 0.5%, those in the reference pond were 7.1 g and 1.1%; those in the experimental pond in October were 9.3 g and 1.2%, and those in the reference pond were 8.7 g and 1.5%, respectively. Thus, laser radiation contributed to the increase of growth rate and survival rate of the larvae in a salmon hatchery.

Figure 2. Growth data of the larvae in a salmon hatchery in 2020

A helium-neon laser emits radiation understood as a low-intensity factor, which enhances the compensatory adaptation of an organism highly sensitive to weak electromagnetic radiation. The physico-chemical basis of the high sensitivity of the organism to low-intensity factors, together with energy processes in a cell, is considered to be made up of resonance interaction effects [11].

The resonance effect of low-energy laser radiation on biological structures is based on photochemical and photobiological processes that change the ion permeability of cells and enhance RNA and DNA synthesis [12]. Owing to the resonance pattern of absorption, laser radiation invigorates regenerative and immune processes in the organism [13]. Upon photoresonance, the oscillation frequency of molecular bonds coincides with external light frequency, accelerating metabolic processes.

An important role in response to light excitation is played by membrane structures. A bio-stimulating effect is based on the structural-functional re-arrangements of membrane cell clusters and intracellular organelles [11]. This could be due to both resonance absorption by a specific acceptor in the corresponding region of the spectrum and the emergence of oscillation-excitation states, which results in changes in the peroxide oxidation level of lipids and the conformation of local membrane sites. This forms a physico-chemical basis for consecutive non-specific cell reactions, such as variations in the ion permeability and adenylate cyclase and ATPase system activity, resulting in the enhancement of bioenergetic and biosynthetic processes. All these variations at the cell level provoke reducing reactions in corresponding tissues and increase their functional potential and the resistance of the organism.

The response of a biological target to low-intensity laser radiation at cellular and tissue reaction levels, as well as adequate changes in the neurohumoral link of regulation is the final result of a photobiological process based on urgent adaptation mechanisms in the organism.

The use of small doses of monochromatic radiation from a helium-neon laser in fish culture is connected mainly with antioxidant prophylaxis and the need to enhance the adaptability of fish in
early ontogenesis. This is especially important in hatchery fish reproduction, because the embryonic and post-embryonic evolution of fish does not always take place under favourable conditions.

4. Conclusions
The studies conducted have shown that the salmon population in the Keret River is now in depressed condition. An important role in maintaining population abundance is played by hatchery salmon rearing (hatchery-reared fish makes up over 50% of the population), but its effectiveness is extremely low. One of the ways of increasing the quality of hatchery-reared products is to update salmon rearing technologies. The study of the effect of low-intensity laser radiation on Atlantic salmon in the early stages of ontogenesis has shown that red colour (wavelength is 633 nm) over a certain dose range enhances the adaptability of fish by decreasing mortality and accelerating growth processes, thus leading to a decline in the loss of hatchery-reared fish products.

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