Applying an eco-hydraulic model for European grayling (*Thymallus thymallus*) in the Aare River

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Abstract

This study aims to apply an eco-hydraulic model system for European grayling (*Thymallus thymallus*) in the Aare River and to confirm its predictive performance by comparing the calculated results with the surveyed data for fish habitat and fish population. In this paper, four habitat options were applied for the habitat quality simulation. The modified logistic population model and matrix population were used to predict the fish number. The results suggested that the simulated habitat quality depends on choosing suitable habitat combinations. The simulated fish number using the logistic population model for all these 4 options provided a good agreement with the surveyed data conducted by EAWAG (Swiss Federal Institute for Environmental Science and Technology). The matrix population simulation results also showed reasonable agreement with the surveyed data. These results demonstrated the applicability of the developed model system for European grayling habitat and fish population status in the study domain.

Keywords: Eco-hydraulic model, habitat and population model, Aare River, European grayling (*Thymallus thymallus*)

1. Introduction

Physical habitat index is a primary factor influencing the structure and composition of stream aquatic communities (Lammert & Allan, 1999). Fish habitat and population management are often affected by environmental changes, discharge alteration and unsuitable river management. Comparing to other systems, freshwater systems are relatively vulnerable to habitat change which may result in shifts in aquatic communities and decrease of fish abundance (Snyder et al., 2005). At an international level, river and stream habitat as well as fish abundance management are one of the greatest challenges to the conservation of biodiversity and is increasingly being valued by researchers and river management (Fausch et al., 2002).

River and stream physical conditions such as flow velocity, river depth, substrate type and distribution combined altogether form unique habitats which are facilitated the growth and survival of fish species and other aquatic communities (Yi Y et al. 2010). Many river ecologists and eco-hydraulic researchers believed that physical habitat features are the key determining factors of river aquatic community potential (Mouton et al. 2007). Besides, in order to represent the time series fish abundance fluctuation, fish population models need to be applied. Therefore, it is meaningful for the development of an eco-hydraulic model system to establish and analyze fish species habitat quality and fish population development.

Habitat suitability index (HSI) model is an eco-friendly way to simulate and predict river ecosystem evolution of target fish species. Habitat model is a very useful and important tool for developing information of fish suitability in stream systems which could help river managers to make intelligent management decision (Tomsic et al., 2007). The first habitat model was developed in the 1970s with the purpose of determining habitats in an ecosystem that was best suited for a particular species life stage (Lamouroux & Souchon, 2002). Habitat model is also a powerful tool to suggest conservation strategies for both native fish species and non-native species (Knapp, 2005, 2007). Beside habitat model, population model is used for determining species abundance and diversity (Bartholow, 1996). The population model had a wide range of applications and has been recommended as an effective tool in predicting and protecting both native and non-native fish population (Harvey et al., 2009). Recent developments in habitat and population models had proved that eco hydraulic models could combine river physical variables (i.e., velocity, water depth and substrate) inherent in the model system.

In this paper, based on the concept of habitat and population model, a model system has been proposed to examine the effects of flow discharge alteration on fish habitat, population number. The model system contains 4 models, namely hydrodynamics model, sediment transport model, habitat model and population model. The Aare River and European grayling (*Thymallus thymallus*) were selected as the target study site and target fish species. The European grayling is the typical species in the Aare River and very sensitive to any physical environmental changes. The aim of this study is to develop a habitat and population model for this target fish species and use the model system to predict quantitatively the habitat and population status change in a stretch of the Aare River.

2. Study area and model scheme

The study domain was located where the flows out of Lake Thun, 30 km south of Bern. The river rises in the Aare Glacier of the Bernese Alps in Bern canton, below the Finsteraarhorn and west of the Grimsel Pass, in the south-central part of Switzerland (Mouton et al., 2007). The river reach is a 1.35 km branch which is located downstream of the Thuner See. The width of the river ranges from 70 to 200m with a 45 m width tributary branch in the downstream of the computation domain (Fig. 1). The average annual flow is 111 m^3/s with maximum and minimum discharges of 570 and 23 m^3/s respectively (Fig. 2). In the computation domain, 50 cross-sections were defined and water depth was measured along each cross-section at an almost equal distance of about 1 m. The water depth was also measured and the substrates composition was assessed by underwater photography as well as visual assessment (Mouton et al., 2008). The river bed mixed with sand-sized substratum, gravel and organic clay. Gravel and cobble were deposited extensively on the river bank.

The Aare River provides living habitat for the European grayling. The spawning European grayling were visually identified, localized and counted by GPS data. Based on the survey, the European grayling had strong preferences for their local habitat in Aare River. The physical parameters suitable for spawning European grayling are in a narrow range. The small changes in the environment caused by the regulation of river flow or water level may disturb the spawning behavior of grayling and may cause a decrease in population number and even extinction (Gönczi, 1989). The spawning European grayling preferred velocity between 0.25 and 0.65 m/s. The spawning European grayling is a typical species preferred in shallow water and the most suitable depth for spawning European grayling is ranged from 0.25 to 1.8m. For the substrates preferences, spawning European grayling preferred bottom substrate was composed of 10–40 percent gravel (2.83-45.3mm), 50–60 percent cobbles (90-128mm), 10–30 percent boulders (128-256 mm) and mixed with a few bigger stones (EAWAG, 2002).

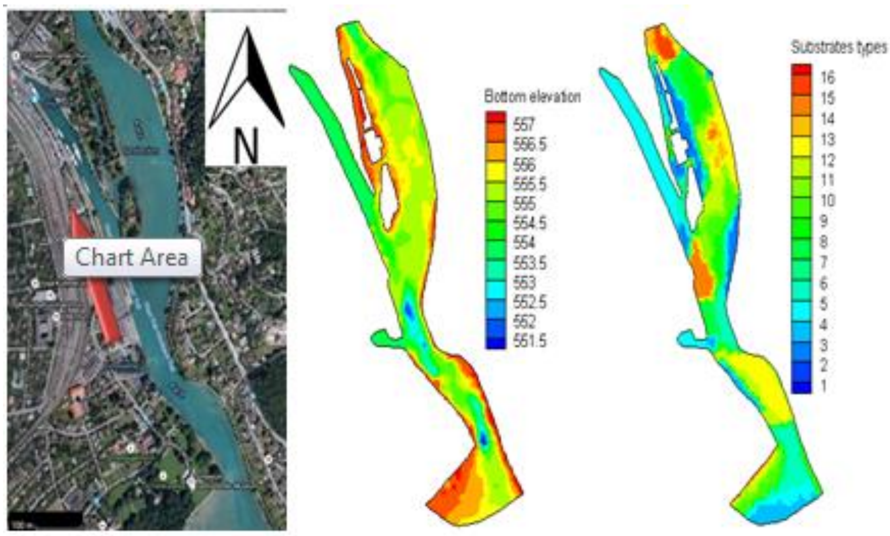

Fig. 1 Computation domain geometry and the substrates types based on the observations conducted by EAWAG (2002).

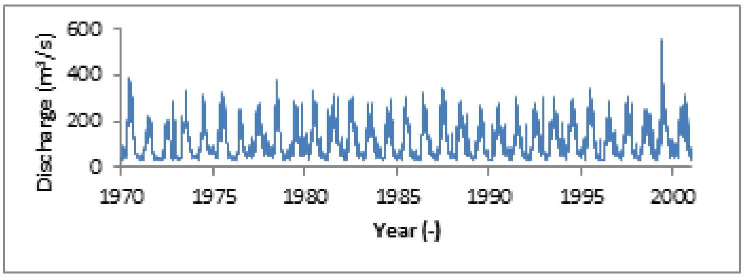

Fig. 2 Aare River flow discharge from 1970 to 2000.

The Aare River eco-hydraulic model system was developed by integrating a hydrodynamic model, hydro-morphology model, habitat model, logistic population model and a matrix population model. In the hydrodynamic model the velocity field and water depth were calculated from the two-dimensional shallow water equations including the effects of bed friction and turbulence. The bed shear stresses were determined by the quadratic friction law. The hydro-morphology model was calculated based on semi-empirical concepts, which included bed-load computation, bed evolution and sand grading effects. The hydro-morphology model was coupled with the hydrodynamic model.

The habitat model was used to calculate habitat suitability index (HSI), weighted usable area (WUA) and the overall habitat suitability index (OSI). For HSI calculation, the following 4 different options with the preference curves showed in Fig. 3 have been applied.

Option 1 $$HSI = (SI_v \times SI_d \times SI_s)^{1/3} \quad [1]$$

Option 2 $$HSI = (SI_v + SI_d + SI_s)/3 \quad [2]$$

Option 3 $$HSI = SI_v \times SI_d \times SI_s \quad [3]$$

Option 4 $$HSI = Min(SI_v, SI_d, SI_s) \quad [4]$$

Where SI_v, Si_d and SI_s are the suitability index for velocity, water depth and substrates types respectively.

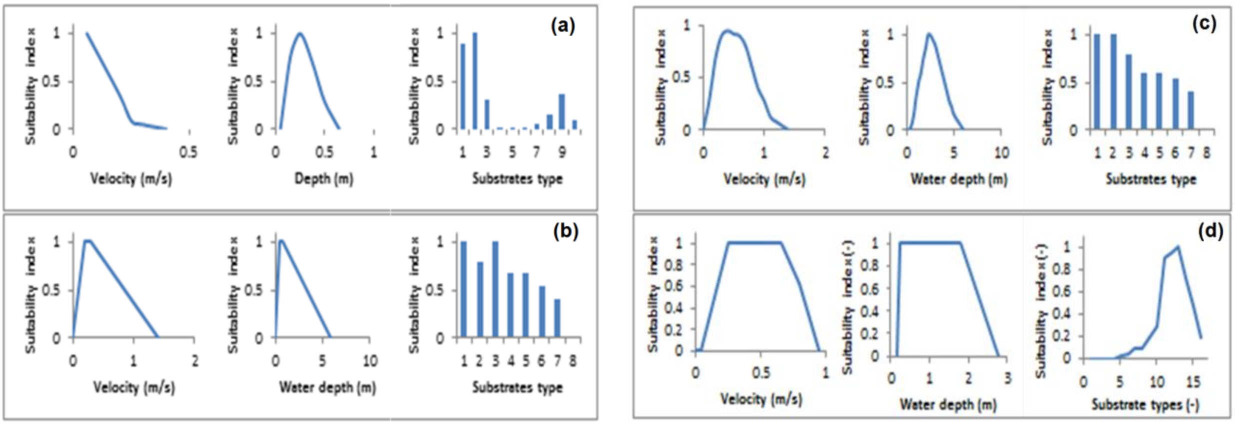

Fig. 3 Fry (a), juvenile (b), adult (c), and spawning (d) European graying suitability index for velocity, water depth and riverbed substrate.

The WUA and OSI indexes were defined as follows:

$$WUA_t = \sum_{i=1}^{M} A_i HSI_{i,t} \qquad [5]$$

$$OSI = \frac{\sum_{i=1}^{M} A_i HSI_i}{\sum_{i=1}^{M} A_i} \times 100\% \qquad [6]$$

Where A_i is the mesh area for the mesh i.

In the population model, the population dynamics can be calculated based on the results of habitat model using the following logistic equations:

$$P^F_{t+\Delta t} = \frac{\beta \times WUA^F_{t+\Delta t} \times P^F_t \times e^{\alpha \times \left(OSI^F_{t+\Delta t} - OSI^F_t\right)}}{\beta \times WUA^F_{t+\Delta t} + P^F_t \times \left(e^{\alpha \times \left(OSI^F_{t+\Delta t} - OSI^F_t\right)} - 1\right)} \qquad [7]$$

Where P^F_t and $P^F_{t+\Delta t}$ are population numbers in the time steps t and $t+\Delta t$; α and β are model parameters related to the study domain and fish species.

In order to simulate each life stages fish species number and the matrix population model can also be applied:

$$\begin{bmatrix} N_{1,t+\Delta t} \\ N_{2,t+\Delta t} \\ ... \\ N_{i,t+\Delta t} \\ ... \\ N_{j,t+\Delta t} \\ ... \\ N_{n-1,t+\Delta t} \\ N_{n,t+\Delta t} \end{bmatrix} = \begin{bmatrix} F_{1,t} & F_{2,t} & ... & F_{i,t} & ... & F_{j,t} & ... & F_{n-1,t} & F_{n,t} \\ S_{1,t} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & S_{1,t} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & ... & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{i,t} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & ... & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{j,t} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & ... & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{n-1,t} & S_{n,t} \end{bmatrix} \times \begin{bmatrix} N_{1,t} \\ N_{2,t} \\ ... \\ N_{i,t} \\ ... \\ N_{j,t} \\ ... \\ N_{n-1,t} \\ N_{n,t} \end{bmatrix} \quad [8]$$

With

$$F_{i,t} = f_i \times \left(1 + \frac{e^{(OSI_{i,t}-a)} - e^{-(OSI_{i,t}-a)}}{e^{(OSI_{i,t}-a)} + e^{-(OSI_{i,t}-a)}}\right); \qquad S_{i,t} = s_i \times \left(1 + \frac{e^{(OSI_{i,t}-b)} - e^{-(OSI_{i,t}-b)}}{e^{(OSI_{i,t}-b)} + e^{-(OSI_{i,t}-b)}}\right) \quad [9]$$

Where $N_{i,t}$ and $N_{i,t+\Delta t}$ are fish numbers at time *t* for fish stage *I*; $S_{i,t}$ is the model survival rate at time *t*; $F_{i,t}$ is the birth rate for spawning fish at time *t*; $f_{i,t}$ is the basic birth rate at time t for the stage of *i;* $s_{i,t}$ is the basic survival rate at time *t* for the stage *i*; *a* and *b* are the basic overall suitability index for fish spawning and fish survival.

In the eco-hydraulic model system, the hydrodynamic model has been solved by the open source Telemac 2D and the sediment transport model has been solved by the open source Sisyphe with some subroutine modified by the authors. The habitat and population models have been developed by the authors. The detailed description of the boundary conditions can be found in Telemac user manual (Riadh et al., 2014; Tassi & Villaret 2014).

3. Result and discussion

Fig. 4 shows the calculated HSI distributions using the 4 combination options at the end of several years. It can be seen that for the year 1970, most of the unsuitable habitats were found in the branch of the Aare River and in the deep water regions of main river for option 1. Further, the HSI values for the rest of the areas were kept at the level of 0.5. Using option 2, the HSI quality was better than option 1, with HSI values ranging from 0.3 to 0.7 in the main river and the HSI value in branch was kept at the level of 0.1. The habitat quality for option 3 and option 4 were worse than for option 1 and option 2. At the end of 1980 and 1970, the HSI distribution trend for option 1 was almost similar, except for few high HSI values scattered along the river. These small regions with high HSI values also scattered along the river for the option 2, 3 and 4. It was also noticed that for all 4 options at the end of 1980, the main river had higher suitability than in 1970. The same HSI distribution trend was observed at the end of 1990 for all 4 options. The figure also indicated that option 2 provided better habitat quality than other options and the habitat quality based on option 3 and options 4 had the worst habitat qualities.

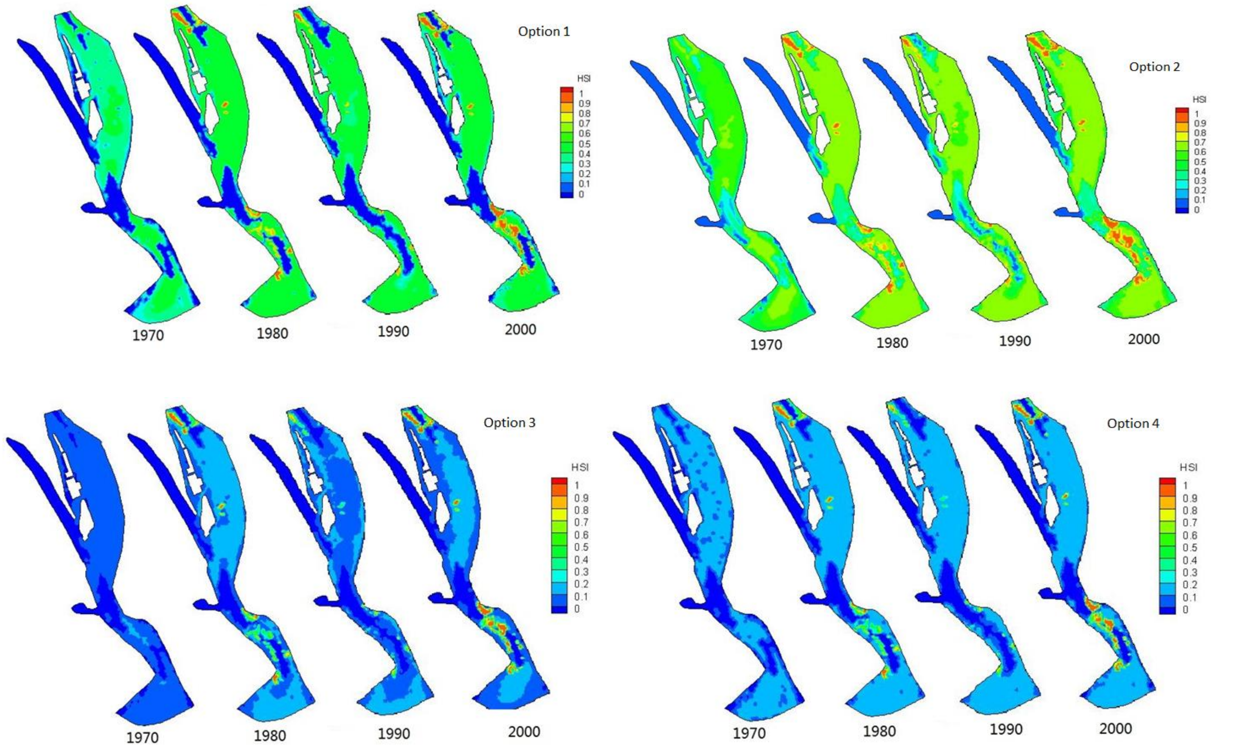

Fig. 4 Calculated HSI distributions during 1970, 1980, 1990 and 2000 using 4 different options.

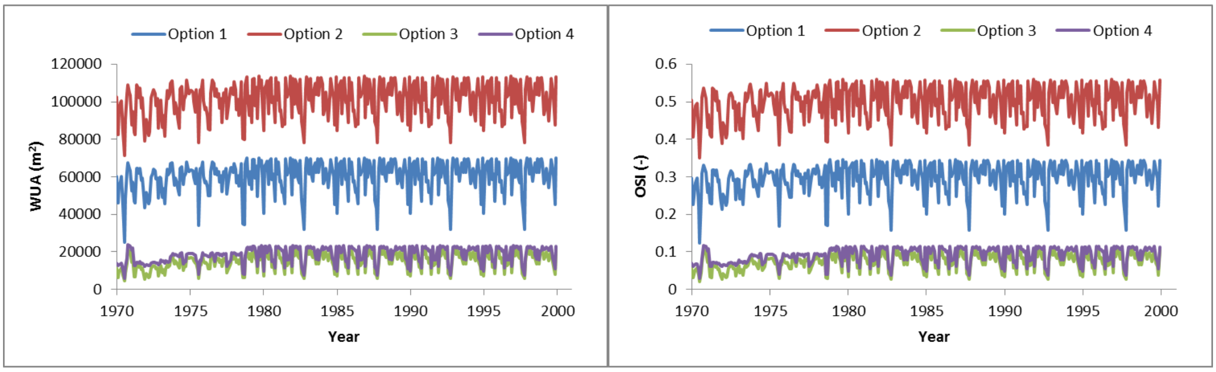

Fig. 5 calculated WUA and OSI distribution from 1970 to 2000 for 4 options.

The WUA and OSI distributions were showed in Fig. 5. It was noticed that the WUA for option 1 fluctuated between 4.7×10^4 m^2 and 7.0×10^4 m^2, while the corresponding OSI values were ranged from 0.23 to 0.34. In option 2, WUA values fluctuated between 1.1×10^5 m^2 and 8.0×10^4 m^2, while the corresponding OSI values were changed between 0.44 and 0.55. The WUA and OSI for option 3 and 4 had the same trend with WUA fluxed between 1.2×10^4 m^2 and 2.3×10^4 m^2 while OSI fluxed between 0.047 and 0.1.

Applying the logistic population model, the simulated European grayling fish number fluctuation was shown in Fig. 6. It was recognized that the simulated European grayling fish number was in reasonable agreement with the surveyed fish number in all 4 options. The numerical results also indicated that there were relative large fluctuations for fish numbers from 1970 to 2000 using option 1 and option 2. The simulated fish number fluctuation using option 3 and option 4 were insignificant compared to other options. For all 4 options, the simulated fish number decreased from 1.4×10^5 in 1970 to the level of 2.5×10^4 in 2000.

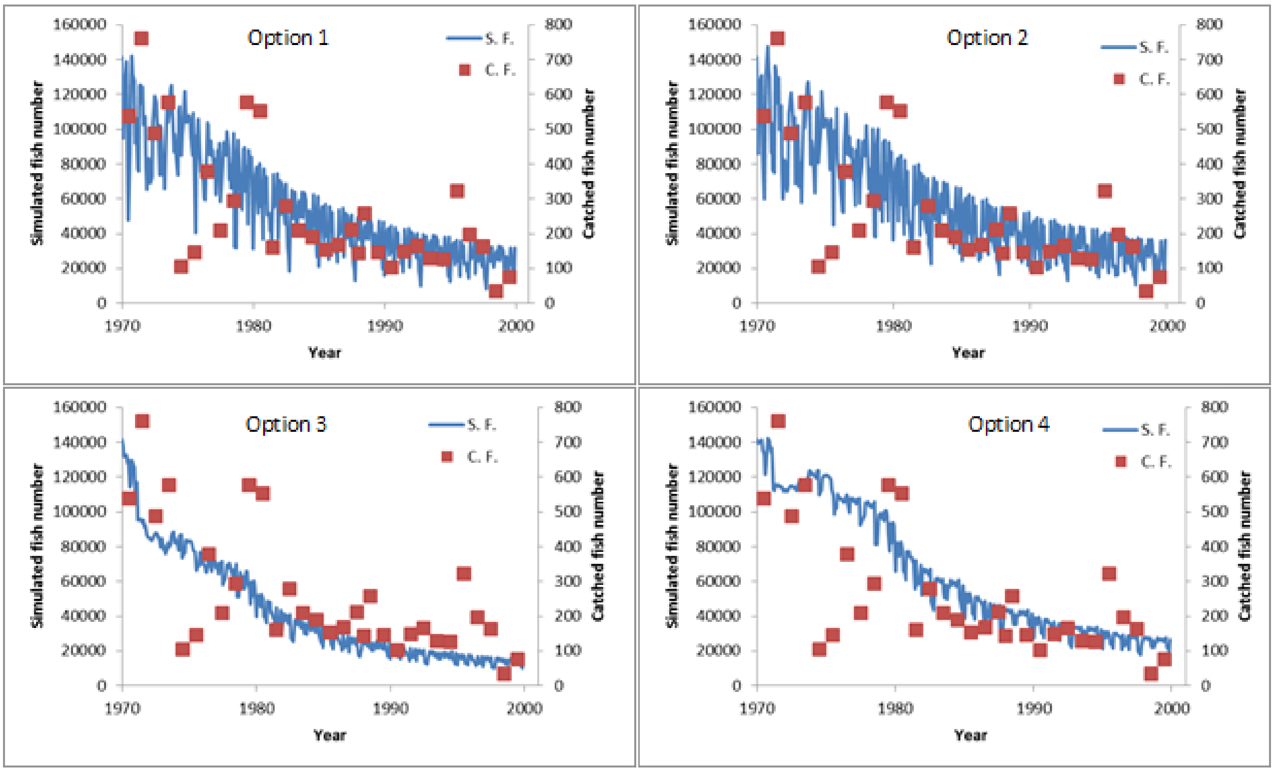

Fig. 6 European grayling number simulated by the logistic population model (Option 1: α=8, ß=7; Option 2: α=8, ß=3; Option 3: α=7, ß=15; Option 4: α=7, ß=15).

Tab. 1 The survival rate and birth rate of European graying for matrix population model.

Life stage		1	2	3	4	5	6	7	8	9
European	f_i	0	0	29	37	46	47	48	48	48
graying	s_i	0.127	0.146	0.171	0.206	0.259	0.35	0.537	0.838	0.0001

Applying the matrix population model, the European grayling numbers for all life stages were simulated. The initial fish survival rate, fertility rate and life stages distribution were modified based on the Robson & Chapman method (1961) and the parameters were shown in table 1. The calculated results of fish number and the life stage distribution were shown in Figs. 7 and 8. It was noticed that in all life stages and in all simulation times (1970 to 2000), the 1st life stage occupied a large proportion of the total fish population number. The simulated fish number declined from 141900 in 1970 to 16424 in 2000 for option 1, to 24805 in 2000 for option 2, to 24294 in 2000 for option 3, and to 21474 in 2000 for option 4. For all 9 life stages, it always showed a decreasing trend from year 1 to year 9. For all 4 options the life stage structure had almost the same trend.

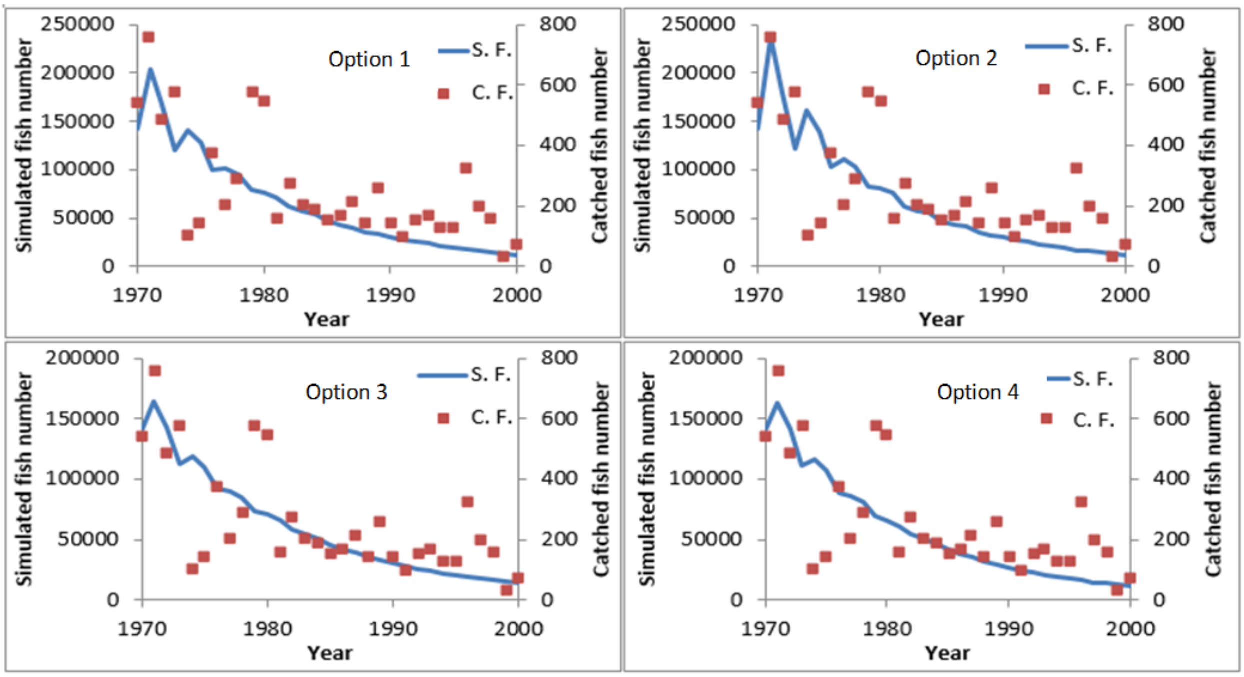

Fig. 7 Simulated European grayling number based on the matrix population model and 4 HSI options (S. F.: simulated fish number, C. F.: caught fish number) (option 1: a=0.41, b=0.41; option 2: a=0.60, b=0.61; option 3: a=0.25, b=0.25; option 4: a=0.27, b=0.27).

4. Conclusions

In this paper, the eco-hydraulic model system was applied in the Aare River and the impact of flow velocity, water depth and substrate on European grayling habitat and population number were studied. The eco-hydraulic model system was composed by hydrodynamic, hydromorphology, 4 different habitat options and 2 population models. The simulated results indicated that the eco-hydraulic model system can satisfactorily simulate the habitat population development of the European grayling (Thymallus thymallus) fish based on the natural flow as well as morphological pattern from 1970 to 2000 in the river reach.

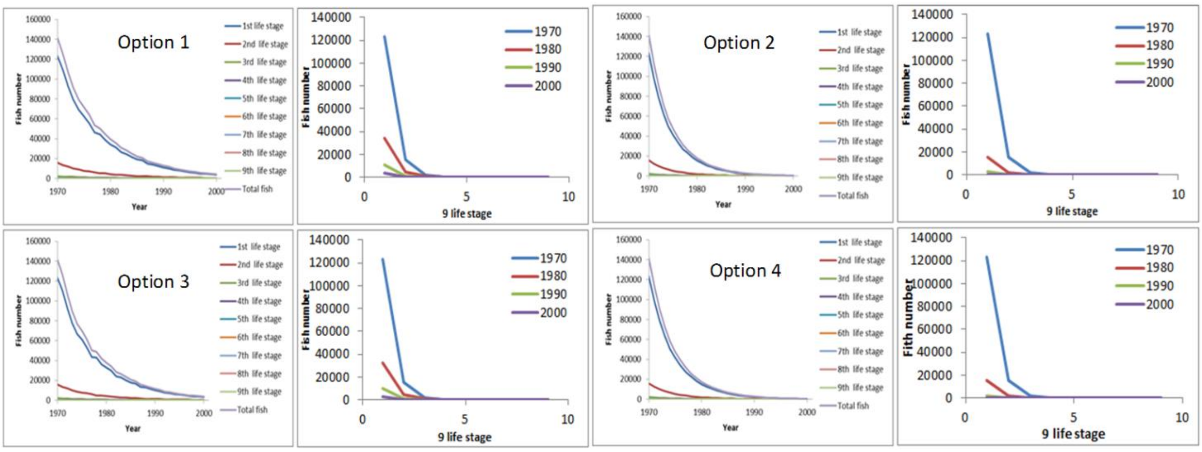

Fig. 8 European graying population number and life stage structure based on the matrix population model from 1970 to 2000 using 4 HSI options.

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