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Hydraulic and Ecological Requirements for the Design of Stilling Basins at Flood Retention Basins with Ecological Passage

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Abstract: *River continuity is a main objective of the EU Water Framework Directive (WFD). Therefore, flood retention basins (FRB) located in the main channel have to include a full ecological passage in the dam structure. Animals of all species should be able to pass through at any time. Conventional hydraulically optimized constructions have to be adjusted to meet this requirement. During the last two decades the design of the outlet structure and the configuration of the pass channel were the focus of research in Germany to form an ecological culvert at FRB. The separation of the ecological culvert and the bottom outlet enlarges the necessary building area and the massive construction in an earth fill dam. A combined culvert effectuates that ecological requirements have to be applied to the stilling basin as well. The depression shaped stilling basin (DSSB) with its continuous river bed slope raises the expectation to meet these requirements. However, a lack of knowledge in design standards of DSSB leads to uncertainty in the planning and approval process. The aim of the research is to advance the design standards of DSSB by taking both hydraulic and ecological requirements into account. In a first step, decisive parameters are identified. Their value ranges are specified based on a literature search. The combination of parameters and the resulting dependencies are currently analysed at the Institute of Hydraulic Engineering and Technical Hydromechanics (IWD in Dresden). This paper presents the approach of analysing the conflicting influences of low water and flood water discharge on the length of the DSSB.*

Keywords: *Ecological Culvert, river continuity, depression shaped stilling basin, flood retention basin.*

1. Motivation

The first motivation for dam design and construction was based on the demand of drinking water supply. Generally, dams are multifunctional facilities used to provide process water, increase downstream water depth for navigability, produce energy and control floods. Therefore, all dams feature a permanent reservoir. As a result, the character of the watercourse is changed decisively. In the 1950s, the first dams in Germany were constructed exclusively for flood control; the first German FRB. Over a period of about twenty years an intensive construction activity in the field of FRB followed. Most of the FRB were constructed including a partial but permanently filled reservoir. The use of the newly created still water bodies as nearby recreation area became very important. Typical early construction designs during this period used the drop inlet spillway for flood discharge control. In the 1980s, the awareness for ecological requirements started to rise in the field of hydraulic engineering. This process is depicted in the development of the DWA/DVWK (German Association for Water, Wastewater and Waste) set of rules as follows:

In DVWK-M 202/1983 ecological aspects can be found as small paragraphs of other chapters. The advantage of basins with a permanent partial filling was pointed out regarding recreation and experiencing values such as landscape integration and balanced landscape scenery.

DVWK-M 202/1991 was the first set of rules to include a chapter on ecological aspects. Dry (green) basins are mentioned which are supposed to conserve the character of the watercourse in principle. The filling of the basins is limited to flood water periods. The dam construction itself was considered as a barrier interrupting the migration corridor for non-volant species.

DVWK-M 4/1993 summarized the state of knowledge concerning the impact of the operation of FRB on habitat, flora, and fauna communities based on a literature search. This research was meant to form the basis for operating rules for FRB, which consider requirements from water management and ecology with the final goal of environmentally friendly facilities. One important result of the report is the lack of published research concerning the fish migration through technical outlet structures. The outlet structures were assumed to have a barrier effect as pipe culverts were the typical construction type due to their simple design and construction. The smooth unstructured flumes cause high flow velocities. In the opinion of the authors of the report, the river continuity through FRB cannot be reached by changing operating rules but by modifying the constructions.

The 1996 published DVWK-M 1/1996 reacted to uncertainties that evolved from the practice of the Environmental Impact Assessment Directive. The report presented a list of impacts evolving from a multitude of hydraulic structures. To mitigate the environmental impact of FRB, outlet structures without top cover or at least equipped with light shafts are recommended. Furthermore, rapid bed slope changes with their respective changes in the flow should be avoided. To prevent high flow velocities and to enable physical habitat conditions for macrozoobenthos, a river bed should be configured with substratum in composition and shape of the river. During the last two decades the recommendations were upgraded, cf. LfU (1998), LUBW (2006) and BWR 24005 (2006). The research in this field was accelerated by the objectives of the WFD.

Best performance regarding the passage through a FRB can be observed at a culvert structure as an open ecological channel, Figure 1. This construction leads the river through the dam using wing walls and providing a large structural clearance. In the middle of the corridor, a flood retaining wall is installed which features at minimum two outlets. One outlet is located in the main channel (outlet 1 Figure 1b) and the second at the embankment (outlet 2 Figure 1b). During low water periods the outlets are permanently opened to ensure the ecological passage for aquatic, amphibian and terrestrial wildlife. During flood periods the outlets close in a controlled way to regulate the outflow of the basin. Ideally, gates due to their small construction thickness regulate the outlets. It is possible to integrate the spillway as well in the flood retaining wall, for example in form of a weir crest overfall.

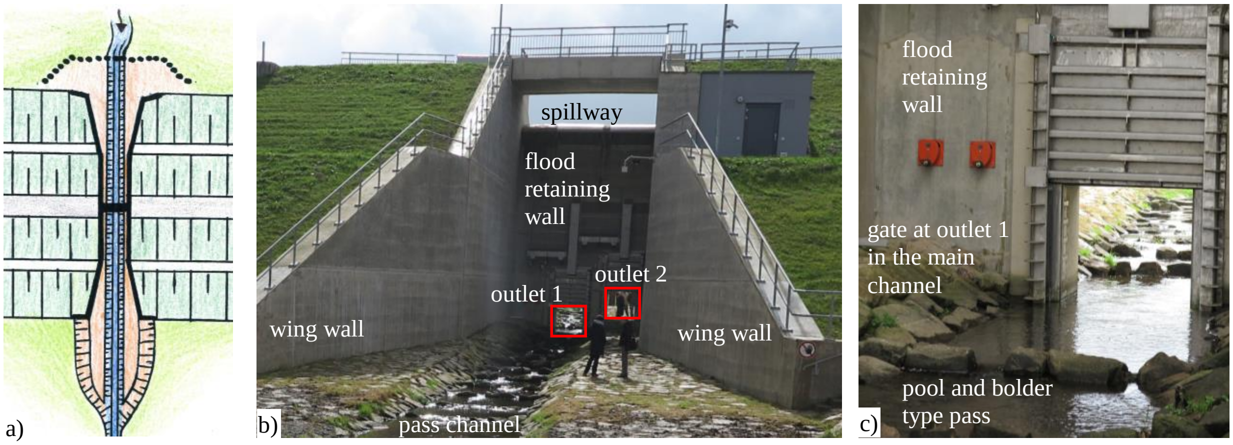


Figure 1. The open ecological channel at the FRB Neuwürschnitz, Saxony: a) top view sketch of the dam with open ecological channel; b) front view from downstream side into the ecological channel; c) detail bottom outlet with pass channel.

Downstream of the outlets, the energy dissipation system has to be provided. Especially high storage heights result in high flow velocities which have to be reduced within this structure. Conventional stilling basins are deepened and rectangular. They usually have, especially at a scheduled high load, a massive end sill. The sill represents an obstacle for benthic organisms. Therefore, it contradicts the objective of river continuity. Furthermore, the absences of a continuous riparian strip and a low water channel, as well as a corresponding substrate design, have a negative impact on the migration corridor. One solution is the separation of bottom outlet and ecological culvert, Figure 2.

Figure 2. Separation of the ecological culvert and the operation outlet: a) FRB Niederpöbel, Saxony (recently under construction); b) FRB Rennersdorf, Saxony (construction period 2006-2010).

However, an increased space requirement is demanded and the massive structures within the dam are enlarged. The total cost increases and particularly hinders the landscape aesthetics. It would, therefore, be optimal to combine the bottom outlet and ecological culvert. This extends the requirements resulting from the claim of river continuity to the area of the energy dissipation system. Thus, a structural adjustment is required in this area. To avoid the end sill, there is the possibility to use a kind of stilling recess. The so called depression shaped stilling basin (DSSB) is considered in this paper.

2. State of Knowledge Cconcerning Design Rules of DSSB

A DSSB has a rounded shape in plan form as well as in longitudinal section, Figure 3. Therefore, it is also described as ’spoon shaped’.

Figure 3. FRB Neuwürschnitz, Saxony: a) dam downstream side with ecological culvert, pass channel and DSSB; b) DSSB and ecological culvert; c) DSSB physical model test.

The counter slope and the constriction at the end of the DSSB form the water cushion where the energy is dissipated. A hydraulic jump occurs in the DSSB. The hydraulic mode of operation corresponds in the broadest sense to those of a spatial stilling basin. Instead of a horizontal apron with end sill, a depression is formed in the longitudinal section. The plan form deviates from the rectangular shape and is rounded. For spatial stilling basins design rules exist. Special types of stilling basins are introduced in literature as follows:

In contrast to the similarly rounded types of energy dissipators (cf. USBR (1987): solid or slotted type bucket, plunge basin energy dissipator), the main jet in a DSSB emerges into the basin close to and parallel to the river bed. Peterka, J. (1984) provides design data for stilling basins with sloping aprons. Naudascher, E. (1992) includes design rules for stilling basins with counter slope and dentated end sill. Csallners’s investigations upon the river weir in Höchstädt/Danube carried out in 1968 are presented in Hack, H.-P. (2009). Among other aspects, the possibility of a trough shape in longitudinal section in contrast to the horizontal apron was investigated. Design rules resulted from these studies and found that the construction causes a particularly efficient energy conversion at relatively deep but small length of the basin. Furthermore, these structures have a high safety against downstream movements of the hydraulic jump. However, the investigations were not carried out with spatial hydraulic jumps.

The design of DSSB with its complex, spatial currents is not yet standardized. Therefore, their application yields uncertainties for planners. The previous studies on the development of the trough-shaped special form of stilling basins are purely based on an optimization of the requirements of hydraulic efficiency and cost-effectiveness by adapting the shape of the basin to the shape of the hydraulic jump in order to optimize the space requirement.

In response to the extreme floods in Saxony in August 2002, flood management concepts had to be revised. The State Reservoir Administration of Saxony commissioned a feasibility study to identify reasonable locations for flood retention basins. After a multi-leveled process, 74 locations were considered in the flood management concepts, cf. Müller (2010). As a part of the implementation of the concepts, a separate concept for FRB construction was installed, which provides the construction of 30 and the planning of 10 basins until 2020. The realization of the concept is behind schedule. An explanation can be found in the long approval process of FRB in Germany. The high necessity of standardized constructions becomes apparent.

3. Investigations

The investigation currently carried out at the Institute of Hydraulic Engineering and Hydromechanics (IWD) in Dresden focuses on DSSB at FRB with ecological passage. The objective is to create design rules that take into account hydraulic and ecological requirements. In a first step, the decisive ecological parameters are identified. Limiting values are designated as a result of a literature search. In a second step, these parameters are combined and subjected to sensitivity analyses. Finally, the resulting dependencies are converted into design rules. The following chapter introduces the approach to analyse the length of a DSSB concerning the conflicting influences of low water and flood water discharges.

3.1. Construction Parts of DSSB and Their Hydraulic and Ecological Requirements

A DSSB at a FRB with ecological passage must be split into two areas which have to fulfill different ecological requirements.

The main channel is the migration corridor for aquatic species. Caused by the counter slope, a small, but permanently stored water volume is formed within the main channel (Figure 4 highlighted in blue color). According to the requirements of the aquatic fauna and the character of the watercourse, respectively, a continuous leading current has to be maintained. The siltation of the river bed must be avoided. Thus, the flow velocity pattern in the DSSB resulting from low water discharge is analysed. Thermal barriers have to be avoided. To prevent unacceptable warming of the DSSB, the water renewal (ratio of inflow to stored volume) is under investigation.

Parameters which influence the flow pattern and the warming in the DSSB are length, width, length-width-ratio and river bed slopes.

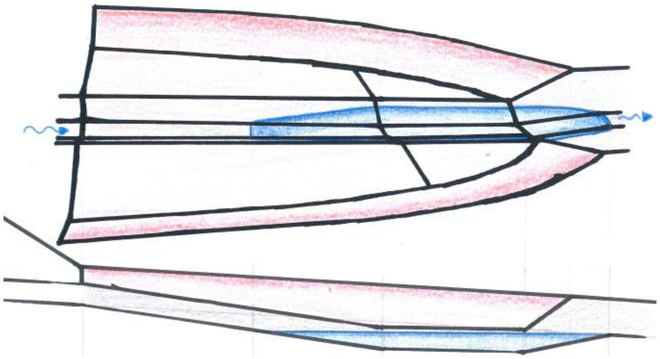


Figure 4. Schematic sketch of a DSSB: spatial perspective and longitudinal section in the main channel.

The embankments are the migration corridors for amphibious and terrestrial species. This area should not be obstructed for species migrating parallel to the river. Thus, the embankment slopes are of interest. To support the orientation of the migrants, the planform layout and the bottom substrate design must be taken into account. The area within the DSSB shaped according to the named requirements is highlighted in red in Figure 4.

Both parts together must ensure the adequate energy conversion at the DSSB. All parameters named above influence the hydraulic effectiveness. As contradicting design scenarios, the low water discharge and the flood water discharge must be analysed. In addition, the presence of multiple outlets (in the main channel and on the embankment) make it possible to study advantages and disadvantages of asymmetric/symmetric loading.

With increasing height of the dam and flood water discharges, the hydraulic load on the DSSB rises. So, while the hydraulic requirements increase with the dam height, the ecological requirements remain uninfluenced by the latter parameter. The compatibility of both requirements is correspondingly more demanding, the higher the dam structure. The present investigations, therefore, focus on FRB with large storage heights (higher than 15 m).

The requirements related to the low water discharge depend on the FRB location. Near to the spring of a river, the catchment area and the low water discharges are small. The fish species in the upper regions of a river are used to relatively cold water and high flow velocities.

The locations of existing basins, basins currently under construction, and those designated in the flood management concepts in Saxony compared to the regions of predominant fish are shown in Table 1. The region that is particularly suitable for flood protection by FRB in Saxony is predominantly similar to the trout region. The transferability of this statement to other federal states within Germany and other countries is under review.

Table 1. Locations of FRB in Saxony referring to the regions of predominant fish.

	Trout region		Grayling region		Barbel region	
	Number	Proportion	Number	Proportion	Number	Proportion
Existing basins	18	82%	2	9%	2	9%
Basins under construction	7	88%	1	12%	0	0%
Locations designated in the flood management concepts	62	84%	6	8%	6	8%

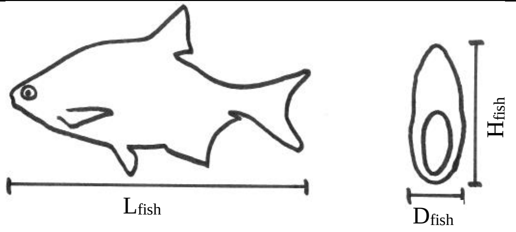
Independent of this review, however, trout can be identified as the most demanding fish species. Adults of most species need a leading current with a flow velocity of minimum 0.2 m/s according to Pavlov (1989). Salmonids show directed swimming behavior beginning at a flow velocity of 0.3 m/s, cf. Adam, B. and Lehmann, B. (2011). The water temperature of 18°C is the limit for preserving the character as distinct trout waters according to DVWK-M 4/1993. LfU (2005) indicates water temperatures > 25-30°C as lethal temperature for trout and > 32-33°C for grayling and barbe. Therefore, the investigations are limited to the trout region. This predefinition influences the limiting values of the parameters as well as further input variables as presented in the following chapter.

3.2. DSSB Length Dependencies on Low and Flood Water Discharge

For adequate energy conversion, a suitably sized water cushion in the DSSB and corresponding geometry is necessary. In the trout region, slopes $S > 0.006$ naturally exist. In order to shape the depression, the slope of the river bed must be increased in relation to the natural slope of the watercourse. The steeper the gradient in the passage, the smaller the water depth provided in the migration corridor. The minimum water depth is depending on the height of the design fish. With a specific design low water discharge available at the FRB location and the water depth required by the trout, a maximum slope of the pass channel is feasible.

By example, this dependency is presented by the following analytical calculations according to the approaches given in DWA-M 509 (2014). The migration corridor is formed as a pool- and boulder type pass with crossbars and vertical slots. Table 2 shows the used dimensions according to the predominant fish, brown trout, as a maximum flow velocity 2.1 m/s is defined according DWA-M 509 (2014).

Table 2. Selected geometries of predominant fish and fish pass according to DWA-M 509 (2014).

Decisive dimensions of brown trout		Selected dimensions of the fish pass	
	$H_{fish} = 0.1$ m		
	$L_{fish} = 0.5$ m	Pool length	$L_{pool} = 1.8$ m
	$D_{fish} = 0.05$m	Vertical slot width	$b_s = 0.2$ m

The smallest water depth, h_2, in a pool and bolder type pass occurs directly downstream of the vertical slot, cf. Figure 5. The required minimum water depth is, according to DWA-M 509 (2014), twice the design fish height. Furthermore, a safety coefficient for pool and bolder type passes 1/0.8 and enlarges this value to $h_2 = 0.25$ m. This value remains constant in all following calculations. Therefore, the flow cross-section at the slot is defined with the constant value $A = h_2 \cdot b_s = 0.25 \text{ m} \cdot 0.2 \text{ m} = 0.05\ m^2$. The water table within one pool is simply defined to be horizontal.

The step between water tables of two neighboring pools is performed within the slot. With the required minimum pool length for trout fish (cf. Table 2), the maximum water depth in the pool is calculated using Equation (1) (Figure 5).

$$h_1 = h_2 + S \cdot L_{pool} \tag{1}$$

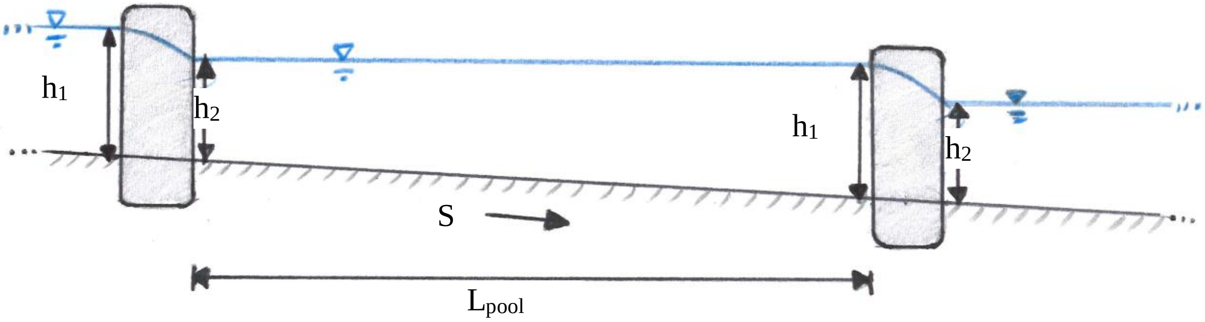


Figure 5. Schematic sketch of the fish pass.

The approach of DWA-M 509 (2014) is based on the simplified POLENI-formula Eq. (2). σ considers the backwater effect at the vertical slot and is calculated according to Equation (3) by Krüger, cf. DWA-M 509 (2014). In addition, the constant values are chosen as given in Table 3.

$$Q = \frac{2}{3} \cdot \mu \cdot \sigma \cdot f \cdot b_s \cdot \sqrt{2 \cdot g} \cdot h_1^{3/2} \tag{2}$$

$$\sigma = 1 - \left(\frac{h_2}{h_1}\right)^{11} \tag{3}$$

Table 3. Constant values used in Equation (2).

μ = 0.55	continuous river bottom without low water sill [-]
f = 1.1	considers small discharges between the stones of the crossbars [-]
g = 9.81	acceleration of gravity [m/s²]

Table 4 shows the necessary low water discharges, Q, at a planned location for a FRB according to Equation (2) to ensure the required water depth with increasing river bed slope S.

Table 4. Calculated discharges Q according to (1) and corresponding mean flow velocities.

S [%]	h_1 [m]	σ [-]	Q [m³/s]	v_m [m/s] = Q/A
1.5	0.277	0.676	0.035	0.70
3	0.304	0.883	0.053	1.06
4	0.322	0.938	0.061	1.22
5	0.340	0.966	0.068	1.36

The resulting mean flow velocities at the slot represent the inflow conditions into the DSSB (Table 4 last column). This current impulse decreases in the DSSB with increasing length. To meet the required minimum flow velocities in the leading current according to the swimming behavior of the trout the length of the DSSB has to be limited.

For adequate energy dissipation during flood periods, the DSSB must provide a length corresponding to the length of the hydraulic jump.

Figure 6 recapitulates the dependencies that are currently being investigated at the IWD and should be included in design rules for DSSB located at FRB with ecological passage.

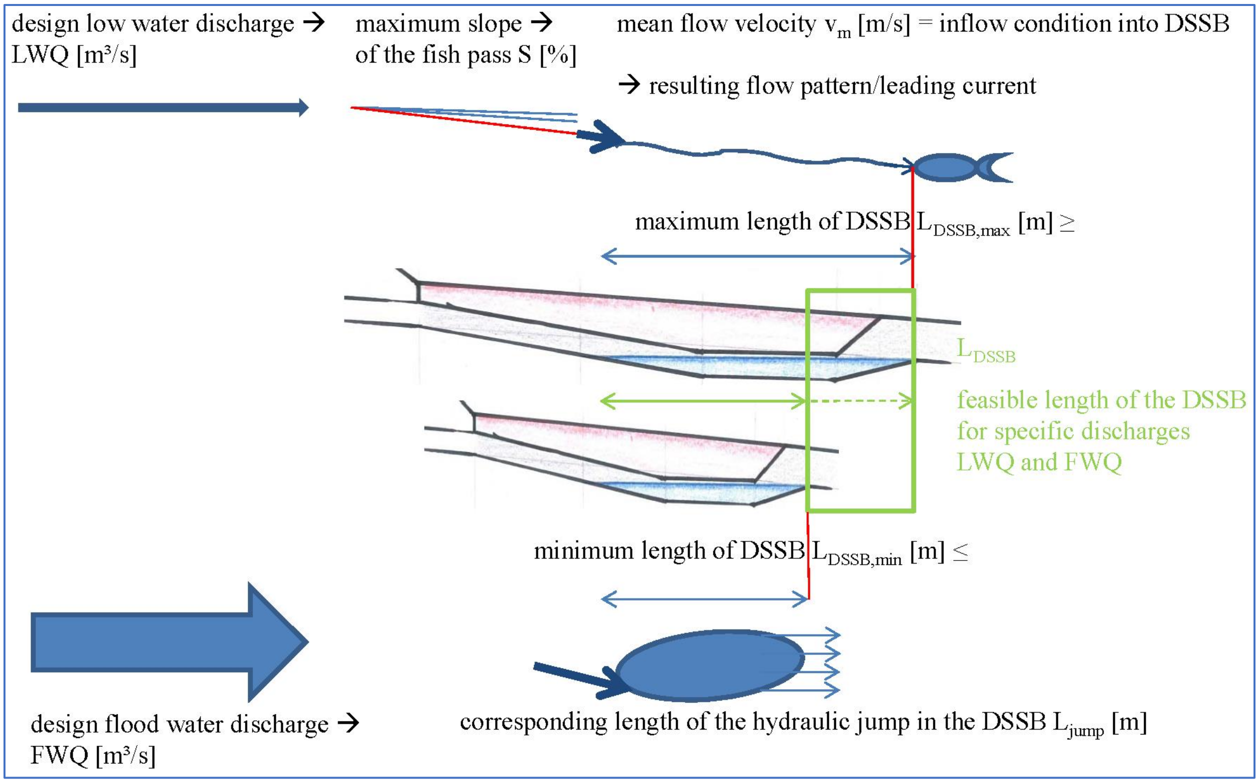


Figure 6. Feasible length of DSSB depending on LWQ and FWQ.

4. Conclusion

In order to include full ecological passage at FRB, the constructions needed to be adapted. A combined bottom outlet and ecological culvert requires an energy dissipating structure with ecological passage. The DSSB offers advantages concerning the river continuity. Therefore, it is recommendable at FRB with ecological passage. As the design of DSSB is not yet standardized, the application is afflicted with uncertainties. To finally develop design rules based on ecological and hydraulic requirements, investigations on DSSB are currently in progress at the IWD. This paper presents the approach of analysing length of DSSB and its dependencies of low and flood water discharges. Low water discharges and corresponding ecological requirements result in upper limits for the DSSB length. Flood water discharges and the corresponding hydraulic requirements define the minimum length of a DSSB. The final objective is to provide planners with upper and lower limits for DSSB length for given low and flood water discharges. In addition, for specific ratios of low and flood water discharges, the application of DSSB may not be feasible.

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