E3S Web of Conferences **346**, 01026 (2022) https://doi.org/10.1051/e3sconf/202234601026
Sharing Water: Multi-Purpose of Reservoirs and Innovations

Long-term modelling of the Arkun multipurpose reservoir

Modélisation à long terme du réservoir polyvalent d'Arkun

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Abstract. The Arkun hydropower and dam project is located on the Coruh River in the North-west of Turkey. The project was completed in 2014. The reservoir is mainly used for energy generation. For this purpose, a main powerhouse with 225 MW and an environmental powerhouse with 12 MW were constructed. Additionally, the reservoir and operation scheme shall contribute to mitigate floods. A minimum ecological flow is mandatory in the Coruh River between the river section reaching from the eco powerhouse which is located downstream of the CFSGD dam and the main powerhouse which is connected to the reservoir via a 14 km headrace tunnel. During the feasibility stage the hydropower projects in Turkey frequently applied simplified methods for the estimation of the energy generation potential. This approach led to an overestimation of the energy general in many cases. Therefore, a reservoir operation model was created which considered monthly runoff data from 1963 to 2005. This model considered the operation of the two powerhouses, evaporation, potential irrigation uses, and spilling. In order to provide a reliable annual generation prognosis, the future development status was considered by the adaptation of the run-off time series. The results of this modelling confirm both the estimated power production during feasibility stage and the actual power production during the operation period.

Résumé. Le projet hydroélectrique et de barrage d'Arkun, achevés en 2014, sont situés le long de la rivière Coruh dans le nord-ouest de la Turquie. Puisque le réservoir est principalement utilisé pour la production d'énergie, une centrale électrique principale de 225 MW et une centrale environnementale de 12 MW ont été construites. En outre, le réservoir et le programme d'exploitation devront contribuer à atténuer les inondations. Un débit écologique minimal entre la centrale écologique située en aval du

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barrage CFSGD et la centrale électrique principale est obligatoire pour alimenter la rivière Coruh. Le barrage CFSGD et la centrale électrique principale sont reliées au réservoir par un tunnel d'amont de 14 km. Au cours de l'avant-projet de faisabilité, le projet hydroélectrique en Turquie a fréquemment appliqué une méthode simplifiée pour l'estimation du potentiel de production d'énergie. Cette approche a conduit à une surestimation de l'énergie générale dans de nombreux cas. Par conséquent, un modèle d'exploitation des réservoirs a été créé, qui considérait les données mensuelles des écoulements de 1963 à 2005. Ce modèle considérait le fonctionnement des deux centrales électriques, l'évaporation, les utilisations potentielles de l'irrigation et les déversements. Afin de fournir un pronostic de génération annuel fiable, le développement futur a été pris en compte par l'adaptation.

1 Introduction

Hydropower has a long tradition in Turkey and is a strong energy resource in Turkey. The technical feasible hydropower potential is 220 10^3 GWh/a [7,8]. A detailed overview of hydropower in Turkey is given in Haselsteiner (2014) [6].

Referring to the year 2000 10,538 MW installed capacity was provided by hydropower in Turkey. Almost 40 % of the overall installed capacity resulted from hydropower at that time.

This represented 30 % of the whole energy production of 36.7 103 GWh/a. Within five years of the privatisation of the energy market installed capacity increased by 23 % to 12,941 MW and the power generation reached 42 103 GWh/a. This represented an increase of 13 % [5].

2 The Project

2.1 Location

The Arkun Dam and HEPP Project is located on the Çoruh River North-east of Turkey. Arkun is one of several hydro projects which belong to the Çoruh master plan. Most of them are completed and in operation, some are under construction, e. g., Yusufeli Dam which will be one of the largest double curvature arch dams in the world (Fig. 1).

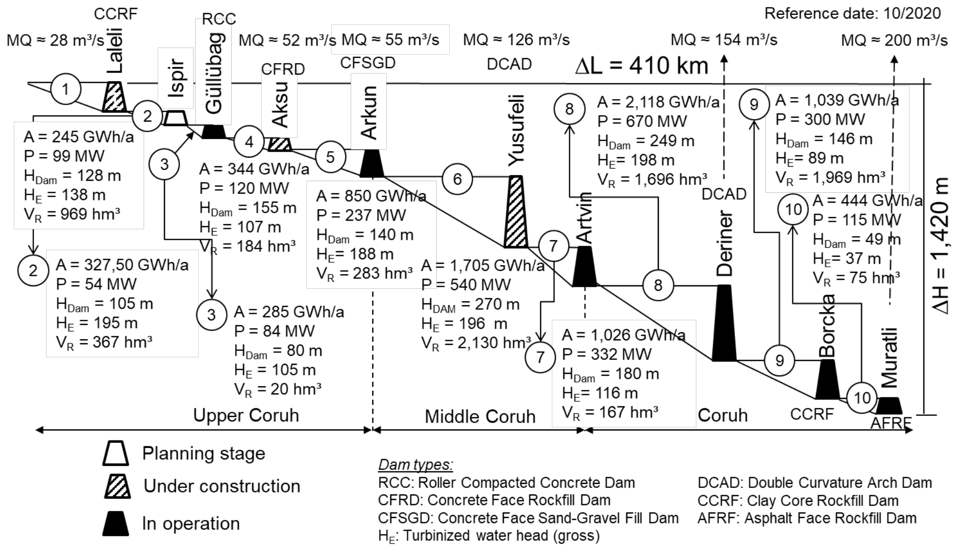

Fig. 1. Development of hydro on the Çoruh river (adapted from [4]; after [9]; and after [10]).

2.2 Arkun dam and HEPP scheme

The Arkun hydroelectric project hosts a main dam of CFSGD (concrete face sand-gravel fill dam) type with a height of 140 m and a gated spillway for a design flood of $Q_{PMF} = 4{,}701$ m³/s which results in a spillway capacity of $Q_{D,Sp} = 4{,}570$ m³/s. The spillway hosts three radial gates. The chute of the spillway ends up in a flip bucket which diverts the flood discharge in the old river bed of the Çoruh. The crest elevation of the main dam is at 940 m asl.

The CFSGD is fit with a special sealing consisting of concrete slaps on the upstream slope and a 70 m deep cut-off wall which is connected via an articulated plinth to the concrete face. At the crest a parapet wall was placed in order to reduce the amount of fill materials. The dam body is zoned corresponding to modern design criteria [2] using sand-gravel fill in the shoulder and coarse rockfill downstream for seepage control and drainage. A L-shaped drain/filter is placed in the centre of the dam body for drainage reasons. The L-shaped drain/filter is protected by an upstream suffusion filter since the sand-gravel is susceptible to suffusion. The upstream and downstream slopes show inclination of approx. V:H = 1:1.6 [4].

A service tunnel was connecting the downstream to the upstream area during the construction period on the left abutment of the main dam. The diversion tunnel with a diameter of 6.4 m and a length of 640 m was later fitted with the penstock for the environmental powerhouse and the corresponding inlet structure.

The main powerhouse is located several kilometres downstream, the environmental powerhouse was placed close to the main dam (see Fig. 2) utilizing the ecological flow for energy production. The ecological flow is defined in consideration of the mean flow and ranges from 5.3 to 10.0 m³/s which amounts to 10 to 20 % of the average flow which is approx. MQ ≈ 55 m³/s.

Fig. 2. Downstream view of the main dam with environmental powerhouse on the right side of the picture (Source: EnerjiSA).

2.3 Installed hydroelectric works and structures

Two powerhouses were constructed, the main powerhouse (MPH) and the environmental powerhouse. Latter one is also called Eco-Powerhouse (EPH) since it serves ecological purposes and utilizes the residual flows. The main powerhouse is connected via an approx. 14 km long headrace tunnel to the reservoir. The headrace tunnel shows a diameter of 6.4 m. The MPH is fitted with an machinery providing an installed power of P_{MPH} = 225 MW hosting three vertical Francis turbines with an installed power of 75 MW each. The intake is located upstream of the spillway on the right abutment of the reservoir. The small environmental powerhouse shows an capacity of P_{EPH} = 12 MW and is located close to the main dam at the downstream left bank (see Fig. 2). Two horizontal Francis turbines were installed. The penstock for the environmental powerhouse is placed in the former diversion tunnel which was plugged at the beginning of impoundment in the year 2013 (see also [4]). The annual energy generation was assumed to be approximately A = 830 to 850 GWh/a according to different authors including the generation of both powerhouses (see also Fig. 1).

3 Energy production modelling

3.1 Basics and model

A reservoir model was established applying following reservoir equation:

$$\frac{d}{dt}V_R(t) = Q_{IN}(t) - Q_{IRR}(t) - Q_{MPH}(t) - Q_{EPH}(t) - E(t) - Q_{SP}(t) \qquad (1)$$

with reservoir volume V_R (t) at the time t; Q_{IN} (t) inflow, Q_{IRR} (t) irrigation flow; Q_{MPH} (t) flow though the main powerhouse; Q_{EPH} (t) flow through the environmental powerhouse; E (t) evaporation losses; Q_{SP} (t) flow spilled via spillway.

A similar model was prepared for the Söylemez Dam and HEPP project located close to Erzurum on the Aras river in East Turkey. In that case study the model was used to optimize the design flow and capacity. Also, different development scenarios regarding future irrigation were considered similar to the Arkun project. The details are described in [3]. The model considered 516 months or 43 years of runoff data (Q_{IN}) which were processed for both the undeveloped and developed river status. The runoff records include the period between 1963 and 2005.

The model considered and/or integrated following aspects:

- Max. Operation elevation = 935.00 m asl (total reservoir capacity 283 hm^3).
- Operation elevation 1 = 871.50 m asl (active storage 49 hm^3; $H_{min,1}$).
- Operation elevation 2 = 900.00 m asl (active storage 126 hm^3; $H_{min,2}$).
- Weighted Operation elevation = 930.00 m asl (active storage 256 hm^3; $H_{min,3} = H_{ave}$).
- Design discharge Q_D = 135.00 m^3/s (3 units x 45.00 m^3/s) ($Q_{max} = Q_D$).
- Minimum Operation Discharge = 0.40 x Q_D (for one unit).
- Variable turbine efficiency represented by a representative efficiency curve (flow/design flow vs. degree of efficiency).
- The ecological residual flow is 20 % ($Q_{D,2}$ = 10.0 m^3/s) of the mean flow during wet months (March to June) and 10 % ($Q_{D,1}$ = 5.3 m^3/s) during the other months.
- The irrigation flow is (approx.) 2.7 % of the mean flow.
- Evaporation losses derived by the reservoir characteristic/surface were considered by a the given evaporation rates I [mm] per month with a maximum of 189 mm in August and a total amount of 678 mm per year.
- Flood and drought periods could be considered according to the considered inflow data.

The max. operation elevation (935.00 m asl) and the reservoir volume (283.24 hm^3) at this elevation have been considered as constant values, but for the minimum operation elevation three values have been applied $H_{min,1}$ = 871.50 masl, $H_{min,2}$ = 900.00 masl and $H_{min,3}$ = 930.00 masl (= H_{ave}). The operation water level H_{ave} is a weighted operation elevation which means most of days in a year water is taken from this elevation. Hmin,1 is also the target reservoir level during or before the flood period in spring time for providing retention volume for flood protection.

3.2 Considered schemes

Two operation schemes were considered. The present scheme (E) and the future scheme (F). The future scheme considers the status when all upstream dam projects from Laleli to Aksu are in operation (see also Fig. 1).

There are still dam projects which are under construction upstream of Arkun Dam. The existing status (E) at the time in 2011 when the model was prepared shows a mean annual flow of approx. V_M = 1,814 hm^3/year or MQ = 57.5 m^3/s. The annual irrigation uses shall reach a value of 49.5 hm^3/a which is only 2.7 % of the mean annual inflow. For the future scheme a mean annual runoff volume of V_M = 1,728 hm^3/year or MQ = 54.8 m^3/s is considered.

It has to be mentioned that the responsible authority is entitled to change these water uses without any possibility to claim by the Owner. According to the valid license it is not expected that the irrigation uses will be changed within the next 20 years or earlier. For both schemes the inflow data were processed for a period of modelled 516 months (see Fig. 3). The developed stage is characterized by smaller peak flows but also an increase of the flows during the dry months. Both effects are a result of the operation of reservoirs upstream.

Particular aspects of climate change effects were not considered at that time. Updated scientific studies predict an increase of the surface runoff in the Çoruh river catchment which could have positive effects on the energy generation [1].

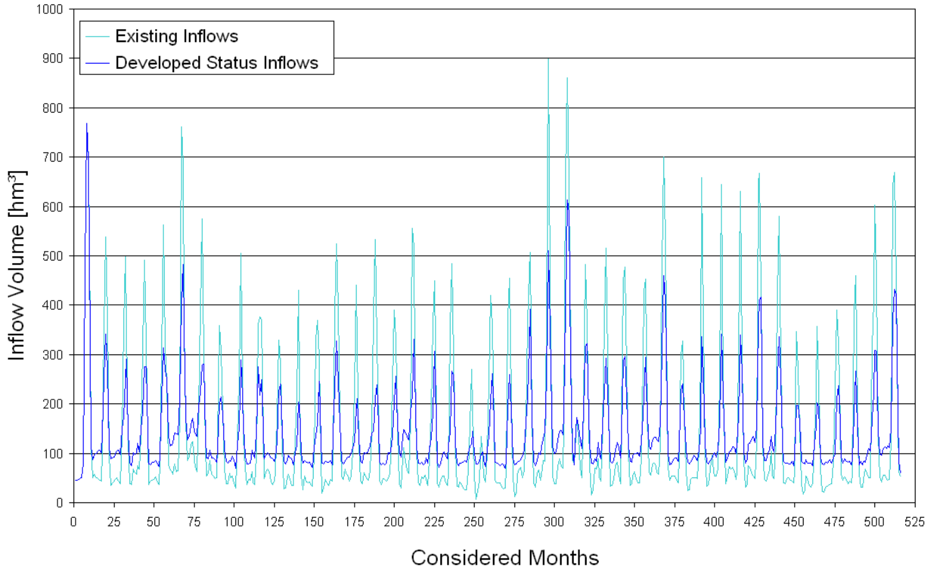

Fig. 3. Inflow values for existing (E) and for future scheme (F) for the Arkun reservoir (516 months).

The model should also help to clarify some questions regarding the operation strategy with the aim of the optimum use of the available, predicted water resources in order to gain utmost energy generation. Hence, three different minimum water tables were investigated keeping the maximum water level constant at 935.00 m asl. Low operation reservoir levels provide a better flood protection, high operation reservoir levels result in higher spilling discharges during floods. Due to the multiple reservoir purpose (energy generation, irrigation, flood protection) the actual operation scheme has to consider all purposes and does not only aim for the optimization of the energy generation.

The effect of keeping a high head against using maximum flow volume was investigated in detail. Within the considered schemes also different average daily operation periods, 12 or 24 h, were investigated. The presented results show only the permanent 24 h operation scheme.

Later during the operation the energy spot market could show an critical effect on the operation strategy. And the energy market is subject to the global economy. Thus, Arkun is considered only to be one of many energy producing units of EnerjiSA which are operated to gain the highest profit on the energy sales market in accordance to the contractual restriction with the buyer of consumer.

The optimization of the utilization of the water resources of a single hydropower plant is subject to the up-to-date electricity retail aims on a daily spot market which affects the complete portfolio and energy production of an owner. Hence, not the accumulated energy production of a single hydropower plant is crucial but the sales price and time as well as the contribution and interaction of the all other factors such as flood protection, irrigation, the global oil and energy prize which is affecting the complete portfolio of energy suppliers including hydro, wind, thermal, and solar energy sources. Concluding, the actual operation of Arkun may differ significantly from the modelled scenarios which are mainly aiming on the maximisation of the energy production in respect to competing aims of water resources management such as flood protection and irrigation.

3.3 Results

In consideration of the aforementioned aspects and constraints the model was prepared providing output diagrams as shown in Fig. 4 including monthly values for flows and energy production. As soon as the reservoir capacity due to floods is exceeded spilling takes place. The presented diagram shows the scheme for a high minimum operation water table at 930.00 m asl so that only the lamella between 930.00 m asl and 935.00 m asl is operated which shows a flexible reservoir volume of only 27 hm³.

The graph illustrates also the (theoretical) continuous operation of the environmental powerhouse which is utilizing the required minimum environmental flow between the main dam and the main powerhouse which is released at the environmental powerhouse. The energy generation of the EPH follows strictly the environmental flow whereas the generation of the MPH shows considerable fluctuations resulting from the varying inflow values and reservoir levels.

In Table 1 the results of the energy generation modelling are shown for the MPH, EPH and for both in sum. The results indicate that it is better to keep a high reservoir level than to utilize a larger flow volume or reservoir volume for energy generation in terms for maximizing the energy production and providing less reservoir volume for flood protection purposes. This is valid for the existing and future conditions and especially for the MPH. The EPH is working on constant base flows so that future and existing conditions are differing only little.

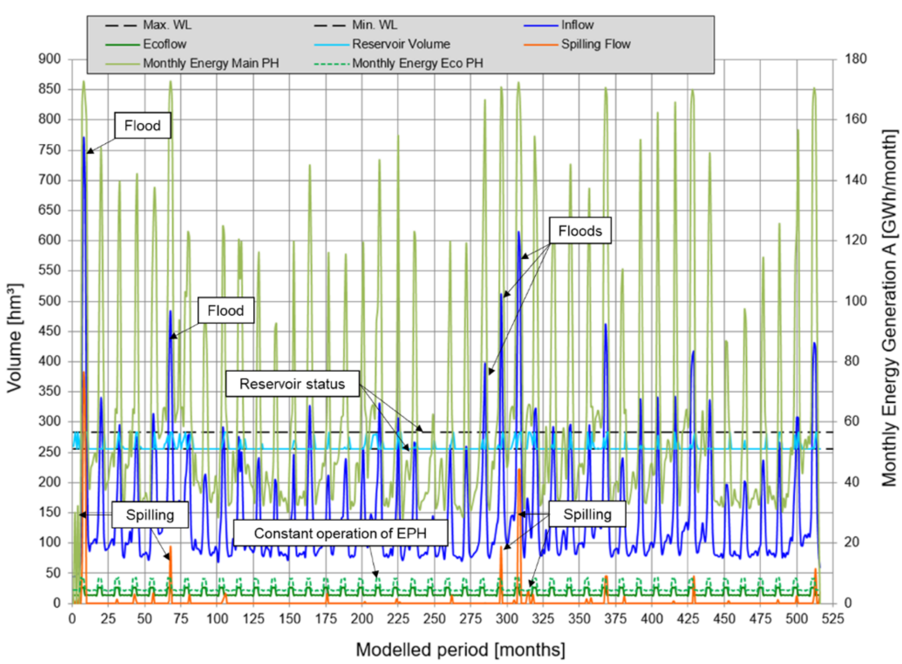

Fig. 4. Output diagram for the modelled period of 516 months showing monthly flows and production values (scheme 6, see Table 1).

For the operation of the MPH in the future the fixing of a high minimum water level, e. g., at 930.00 m asl results in 11 % more generation when the results of scheme No. 3 is compared to scheme No. 6. If flood protection purposes will prevail lower operation levels need to be kept, at least seasonally, so that lower production figures will be achieved. The current operating rules instruct that the reservoir is lowered to the minimum reservoir level Hmin,3 = 871.50 masl in April to May in order to cover the spring floods which are also affected by the annual snow melt. EnerjiSA (ESA) signed an agreement with the General Directorate of State Hydraulic Works (DSİ) so that the company is liable for any damage downstream.

Table 1. Results for energy production for MPH, EPH and total production including also losses by spilling and evaporation referring to flow volume.

	General					Main Power Plant				Environmental Power Plant					Total	Losses	
						Turbine		24 h		Turbine			24 h (+24 h Main)		24 h + 24 h		
No.	Status	$H_{max.}$	$V_{max.}$	$H_{min.}$		Type	Q_D	H_N	A_{Main}	Type	$Q_{D,1}$	$Q_{D,2}$	H_N	A_{Env}	A_{Total}	Spillway	E
		[m]	[hm³]	[m]			[m³/s]	[m]	[GWh/a]		[m³/s]		[m]	[GWh/a]	[GWh/a]	[%]	[%]
1	E Existing Status	935	283	$H_{min,1}$	871,50	3 x Francis	135,0	165,83	**600,82**	2 x Francis	5,3	10,0	74,97	**38,24**	**639,06**	4,8%	2,9%
2				$H_{min,2}$	900,00			190,02	**663,11**				98,88	**50,69**	**713,79**	6,4%	3,9%
3				$H_{min,3}$	930,00			216,14	**684,39**				124,20	**63,89**	**748,28**	12,2%	5,2%
4	F Future Developed Status			$H_{min,1}$	871,50			160,18	**577,71**				66,58	**34,21**	**611,92**	1,1%	2,0%
5				$H_{min,2}$	900,00			187,50	**671,21**				93,88	**48,29**	**719,50**	1,3%	3,2%
6				$H_{min,3}$	930,00			216,51	**760,46**				122,71	**63,19**	**823,64**	2,6%	4,6%

The model could confirm the data for the energy production presented in the feasibility study and the design phases showing only a difference of -1.0 % which is marginal in consideration of the uncertainties related to the inflow data and operation aspects especially in consideration of the future conditions.

For the future conditions also a decline of losses is observed which is depending on the uniformed inflows which are resulting from the operation of the upstream reservoirs. The future conditions promise a higher production whilst the mean inflow is less which is exactly a result of the more uniform inflow conditions. Especially, spillway losses are reduced by almost 10 % when again comparing scheme No. 3 to No. 6. Evaporation losses vary from 2.0 to 5.2 %. In this context the expected higher flows are mentioned which are predicted as an effect of the climate change [1]. The model did not consider any maintenance or rehabilitation periods or other energy production stops caused by malfunction, regional power breakdowns, etc. so that the values should be considered as upper borders.

4 Operation data and experience

After commission in 2014 both HEPPs started to produce hydroelectric energy. During the operation period of almost seven years the production reached a production value of 640 GWh/a in 2018. On average an annual generation of 630 GWh/a could be gained of which 580 GWh/a (92 %) were produced by the MPH and 50 GWh/a (8 %) by the EPH during the last three years.

The operation data confirm the results of the model. Since the Arkun reservoir is also utilized for flood retention in order to limit the downstream discharge to a maximum flood discharge of HQ = 350 m^3/s the operation water level is kept relatively low during flood season which also results in less energy production compared with the results of the operation strategies (scenarios 2, 3, 5, 6) of the model which were focussed on the optimization of the energy production.

From the start of the commercial operation in 2014 the operation scheme and strategy was continuously improved so that an increase of production compared to the first years of operation could be achieved. The production figures of both HEPPs stabilized during the last three years so that stable production conditions are expected also for the future in spite of all the unknowns resulting from climate change effects in the region. The effects of climate change could also result in higher production values if the increase of the surface flow will be utilized.

As aforementioned ESA is lowering the reservoir to $H_{min,3}$ in April/May in order to guarantee flood protection downstream. A flow of HQ = 350 m^3/s shall not be exceeded within the downstream area. Although no legal flood protection regulations exist in Turkey ESA plans for providing a flood protection level which is corresponding to 50-year flood discharge (HQ_{50}) in the future for residential and agricultural areas. The corresponding downstream flood area is limited downstream by the Yusufeli Dam which is currently under construction.

5 Conclusion and perspective

For the Arkun Dam and HEPP project the energy production was determined by preparing a reservoir model. The results of the model confirm the generation values provided in early project phases, whereas the early project phases tended always to provide data for an optimistic upper energy production potential.

The modelling also shows that the annual energy generation is reaching higher values when high reservoir levels are kept. Hence, the high hydraulic heads are more critical for the energy production than the utilized flows.

Due to the requirement to protect downstream areas against floods the operation water levels are kept intentionally low which results also in generation values less than the generation potential with high operation water levels as indicated in the model scenarios No. 3 and 6. Nevertheless, the operation data could confirm the predicted generation data from the model (scenarios 1, 2, 4, 5) whilst the high generation data from the feasibility study seem still too optimistic at the current stage of operation.

Thanks to the permanent improvement of the operation scheme higher generation figures could be gained and the production and operation could be stabilized during the last three years. Nevertheless, a superordinate integrated Çoruh model including meteorological and discharge data could benefit all owners and stakeholders simultaneously by optimizing energy production, flood protection, etc. for the scenario that all dam operators act jointly.

Climate change effects also predict an increase of the flows [1] of the Çoruh river which could be utilized for hydroelectric energy production as far as the volume of strong floods and long lasting droughts can be balanced by a coordinated operation of affected reservoirs.

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