Assessment of the Hydrological Characteristics of Shiroro Dam, Nigeria

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Abstract

Flooding in recent times has been linked to various hydrological characteristics that are associated with dams and their surrounding features, some of which are outflow, inflow, rainfall, temperature, and water elevation, among others. Although its causes have been traced to both natural and human-induced factors, it is also important to investigate the various hydrological characteristics of dams to understand and manage flooding. The relationship between these features has a great effect on the amount of outflow, which in turn relates to the flooding of communities downstream. This study seeks to assess and analyse the impact of inflow, rainfall, temperature, and water level on the outflow of water from the dam. This impact was evaluated using statistical techniques such as time series, correlation, and regression analysis. The result shows that outflow in dams has a positive correlation of 0.280738, 0.873933, 0.148858, and 0.55576 with rainfall, inflow, temperature, and water elevation, respectively. Water inflow and elevation thus have a greater influence on water outflow; R2 values show that inflow can predict 76.4% of the volume of outflow while temperature has the lowest value of 0.22%. More study of the factors that influence inflows has been recommended, as has the forecast of future outflows and output.

Keywords: Shiroro Dam, hydrological parameters, seasonality, trend, regression, and forecasting

1 Introduction

Flooding has been one of the major disasters ravaging lives and properties in recent years. It has been linked to various factors such as climate, man-induced disasters, and other factors. Features along the river course or floodplain are the major victims of the flood disaster (Gangrade *et al.,* 2019). Bilewu (2017) stated that there will be an increase in the frequency and intensity of flood events along this course in the coming years. The frequency of which was observed in the recent flooding events in Nigeria that drew international attention. It is therefore important to investigate the causes, effects, and management of flooding.

Hydrologically related infrastructure has also been one of the major sources of flooding. One of these infrastructures is the dam, which is the artificial catchment of water that is either for irrigation, fishing, water supply, or hydroelectric power supply purposes (Adie *et al.,* 2012). The dam as an infrastructure has served its purpose over the years but has also been one of the major sources of flood-related disasters.

One of the usual practises in flood management is outflow activities; the dam is often opened through the spillway to reduce the volume of water downstream. Several factors have influenced the volume of outflow, varying from temperature, inflow, and water elevation to other factors (Sivongacy *et al.,* 2017). Heavy rain, coupled with the rapidly increasing need for housing, frail implementation of building regulations, poor drainage systems, and choked waterways, cause rainwater to be diverted through populated areas, where it devastates communities. It is also common that, to forestall dam collapse at peaks of rainfall, authorities in Nigeria and in neighbouring countries like Cameroon open the spillways of the dam and release vast amounts of water into communities on the dams' floodplains. The human and material costs of such releases of water by the dam authorities and the resultant inundation of the dam's floodplain are enormous, but they are often either not reported at all or underreported (Olukanmi and Salmai, *et al.,* 2012).

On the other hand, in Nigeria alone, it is estimated that approximately 12% of the land area is within the 100-year floodplain (Sharma, 2017). The percentage of urban and rural areas within the floodplain is much higher (about 20%). The total property value within the floodplain already exceeds hundreds of millions of Naira and is growing at a rate of about 5% per annum. Flood disasters have increased tremendously everywhere in Nigeria in recent times, resulting in the loss of lives and properties, rendering thousands homeless, and disrupting economic activities.

Thus, the ability to simulate the propagation of flood waves is of crucial importance for the planning and operational management of river floods. Hydrodynamic and hydrologic numerical models provide such capabilities and represent conventional approaches to river flood modelling. Hence, without flood control and adequate drainage structures, the extent of destruction and damage would increase at an even faster pace. There were over 200 floods affecting over 180 million people, 8,000 deaths, and over £40 billion in damages in 2007 (Pitt, 2007).

Historically, many towns have been built on floodplains, and this is for a number of reasons, which include: access to fresh water; the fertility of floodplain land for farming; cheap transportation via rivers and railroads, which often followed rivers; the ease of development of flat land; and these towns are highly susceptible to flooding (Orukpe and Mohammed, 2015). However, the risk is greater for those living on the floodplain of the country's major rivers and its many dams, which are used for hydropower generation, irrigation, and fish farming. Many of the dams are poorly designed and maintained and are located close to towns and villages. During the rainy season, they can burst their banks, releasing deluges of water into neighbouring communities. It is also common that, to forestall dam collapse at peaks of rainfall, dam authorities in Nigeria, like those at Shiroro dam in Niger State and Oyan dam in Ogun State, open the spillways of the dam and release vast amounts of water into communities on the dams' floodplains, sometimes some kilometres away from the water's release point. It causes severe flooding, affecting farmlands, human life, and property settling on the river bank.

According to the National Emergency Management Agency (2018), in 2017, floods affected 250,000 people in the eastern and central regions; in 2016, 92,000 people were displaced and 38 died; in 2015, more than 100,000 people were displaced, with 53 deaths; and in 2012, devastating flooding forced two million Nigerians from their homes and 363 died. If the extent and potential levels of damage are known, perhaps a strategy that reduces losses and suffering downstream could be adopted. Thus, if the impact of flooding is to be reduced in the future due to its significant impact downstream, it is important to evaluate the potential of dam flooding. This will assist in analysing downstream human safety, especially where no dam flooding or prolonged flooding histories are documented (Song *et al.,* 2012). It therefore becomes necessary to effectively estimate and forecast flooding so as to prevent its ill-effects.

The hydrological implications of future climate change will likely require important changes to present-day water management policies (Sovacool and Bulan, 2012), with alteration of dam operations featuring prominently (Tang *et al.,* 2018). However, while much work has been documented on the potential impacts of climate change on operations at individual reservoir facilities (Vassoney *et al.,* 2012) or even in the context of tributary basins (Zeng, 2017), the impact of an entire population of reservoirs at a regional scale (i.e., across the entire regional network of rivers) has yet to be established.

The magnitude of the 2010, 2012, 2015, 2018, and 2019 floods caused by the opening of Shiroro dam spillways by the dam authority, the extent of damages, and the fact that absolute safety against flooding cannot be guaranteed make it imperative to carry out an in-depth study of the affected reaches of the Shiroro dam floodplain.

Since frequent release of the dam reservoir due to excessive rainfall is an identified cause of flooding within floodplains, this study presents an analysis of various hydrological characteristics (rainfall, temperature, inflow, and water elevation) of the Shiroro dam and its environs with a view to understanding its hydrological dynamics and correlating the same with past flood events within the study area. The outcome of this study will serve as a viable tool for determining hydrological considerations.

2 The Study Area

The Shiroro hydropower plant is located approximately southwest of the Kaduna River and was commissioned in 1990 with a capacity of 600 MW. It is located 550.325 m downstream of the confluence of the Kaduna River with its tributaries. The dam is geographically located between longitude 6º 20'00"E and 6º 50'00"E and latitude 9º 50'00"N and 10º 10'00"N. The dam is of rock type and stands 115 m above the original riverbed elevation across Shiroro Gorge for a crest length of 700 m. Shiroro hydropower plant has a surface area of about 320 km^2, a maximum length of 32 m, and a total storage capacity of 7 billion m^3 (Suleiman and Ifabiyi, 2015).

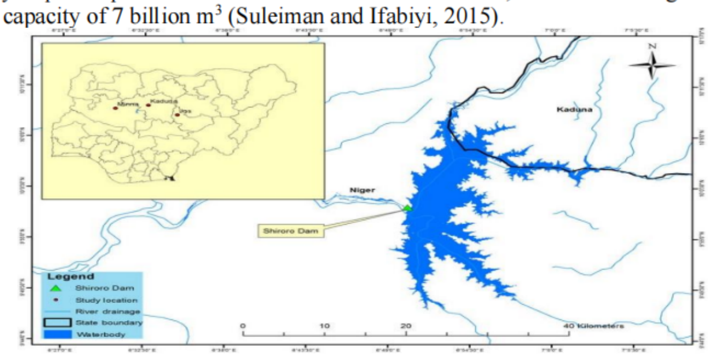

Figure 1: The study area Map

3 Materials and methods

This study adopted the quantitative research design and relied mostly on secondary data sourced from the dam authority.

Data on the hydrological characteristics of the dam were acquired over a period of 20 years at 5-year intervals, i.e., 2001, 2005, 2010, 2015, and 2020. The summary of the data used for the study is given in Table 1.

Table 1: Data used for the study

S/N	Data	Method of observation/collection	Duration
1	Rainfall	Automatic rain gauge	2001-2020
2	Inflow	Computed from record	2001-2020
3	Reservoir Elevation	Gauge from the dam	2001-2020
4	Temperature	Reading thermometer	2001-2020
5	Water outflow	Computed from record	2001-2020

Source: Shiroro dam authority, 2020

The average monthly value of the five-epoch data on each of the five hydrological parameters was generated.

The analysis helps establish a mathematical and statistical relationship between the independent hydrological variables (rainfall, temperature, water elevation, and inflow) and the dependent variable (outflow). Correlation analysis was carried out to investigate whether there is a positive or negative relationship between the dependent and independent variables.

3.1 Forecasted outflow data

There are several time series processes for analyzing and forecasting seasonal data, they are white noise, Auto Regressive Model, and Moving Average Model among others (Ivanosvski *et al.*, 2018). The Auto-Regressive Model is the one in which Y_t mathematically depend on its past value $Y_{t-1}, Y_{t-2}, Y_{t-3}$ and it is mathematically represented as,

$$Y_t = f\{ Y_{t-1}, Y_{t-2}, Y_{t-3}, \dots \epsilon_t \} \quad (1)$$

While the Auto Regressive Model for a dependent model, say p past values is given as,

$$Y_t = \beta_0 + \beta_1 Y_{t-1} + \beta_2 Y_{t-2} + \beta_3 Y_{t-3} + \dots + \beta_3 \quad Y_{t-p} + \epsilon_t \quad (2)$$

The moving average model when Y_t mathematically depend on random error is mathematically represented as,

$$Y_t = f\{ \epsilon_t, \epsilon_{t-1}, \epsilon_{t-2}, \epsilon_{t-3}, \dots \epsilon_{t-n} \} \quad (3)$$

While the moving average model for a dependent model, say q past values is given as,

$$Y_t = \beta_0 + \epsilon_t + \phi \ \epsilon_{t-1} + \phi \ \epsilon_{t-2} + \phi \ \epsilon_{t-3}, \dots + + \phi_q \ \epsilon_{t-n}$$

where Y_t represent the dependent variable (Outflow), $\in_t$ represent the seasonality index for each season, ϕ_q represents the past data and values for the independent variables, in this case is the Inflow data.
The Standard Centered Moving Approach (Standard CMA) was adopted in the list of seasonal index forecasting approaches because the analysis of residuals showed that the distribution could follow a linear regression approach. The Standard CMA was adopted because it is suitable for a linear distribution. Another approach to forecasting seasonality is the log-CMA approach, which is more suitable for non-linear variables.
Thus, the seasonalized index generated from this analysis was used to generate the forecasted outflow data for a duration of 5 years (2025, 2030, and 2035).
The regression analysis also helps measure how much of the dependent (outflow) is predicted by the independent variables. This information was then used to draw conclusions and make decisions about outflow and its relationship to flooding.

4 Results and Discussion

The results of the analysis include charts showing the average distribution of the hydrological characteristics over the years for a period of 20 years with 5-year intervals for data acquisition.

4.1 Time series analysis

The time-series description of the average rainfall is shown in Figure 2. Analysis of rainfall shows that the average dry season for the region is between November and March, except for an exceptional case in March 2015, where there was over 50 mm of rainfall.

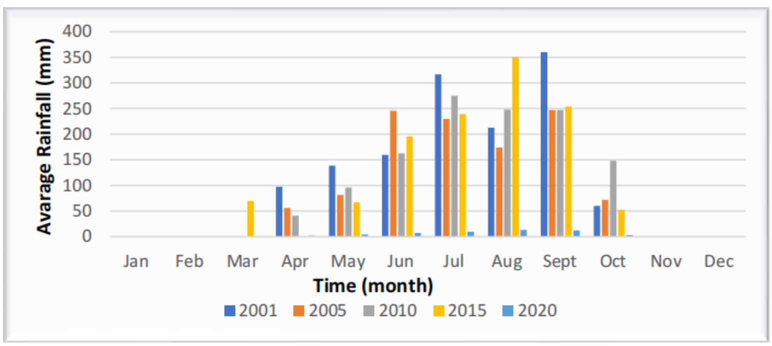

Figure 2: Average rainfall between 2001 to 2020

The rainy season lasts, on average, from April to October. This may be an indication of the period when outflow is high. The maximum rainfall is about 360 mm around September 2001, and the least is 0 mm.

Figure 3 depicts a time series analysis of the inflow, which shows that the inflow is generally low between November and April each year, with the average highest inflow occurring in September over the years. The inflow visually correlates with the rainfall chart; the maximum inflow is approximately 2,366 mm around September 2020, and the least is approximately 9.20 mm in April 2015. Between May and September, the inflow pattern gradually increases, peaking at that time before declining.

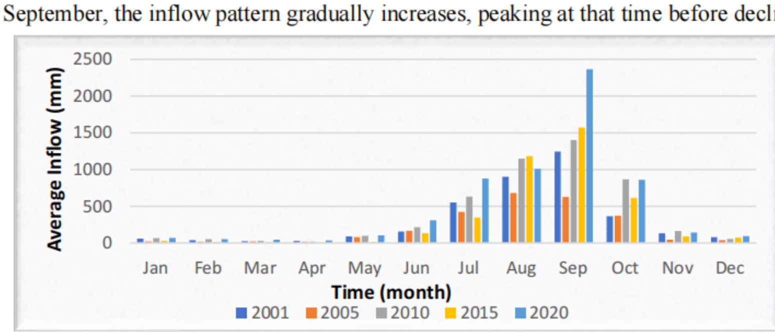

Figure 3: Average inflow between 2001 to 2020

The time series analysis of temperature in the study area reveals a temperature range of 20ºC to 35ºC between January and July of the year and an average range of 25ºC to 30ºC. The temperature seems to increase on average over the years, as observed in 2020 in Figure 4. The maximum temperature across the year is 39.45ºC in October 2020, and the minimum is 21.52ºC in January 2015.

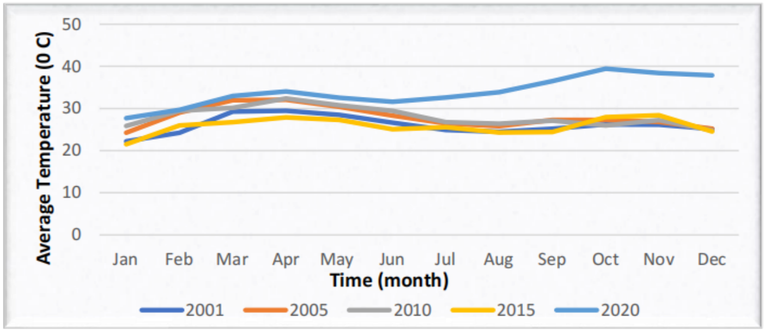

Figure 4: Average temperature between 2001 to 2020

The time series analysis of water elevation, as shown in figure 5, shows that the minimum water elevation in the study area is experienced around May to July and the highest range of water elevation is around September, October, November, and December, respectively. The highest water elevation observed over the years is 382.51 m in October 2020, and the least is 353.19 m in August 2005. The elevation of water also has a significant relationship with the outflow of water, as seen on the chart.

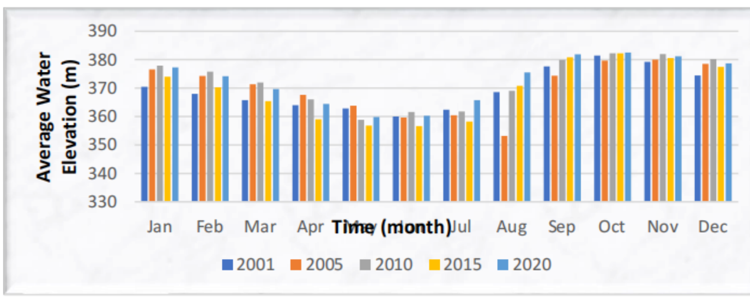

Figure 5: Average water elevation between 2001 and 2020

The time series analysis of the outflow of water, as seen in figure 6, showed the distribution of outflow across the years. It was discovered that the outflow increases from July to September and then gradually decreases until December of each year. The highest volume of outflow is 2214.95 mm in September 2020, and the least is experienced in May 2015 (-26.69 mm). The months with the highest range of outflows are periods where flooding incidents are mostly recorded in the settlement downstream.

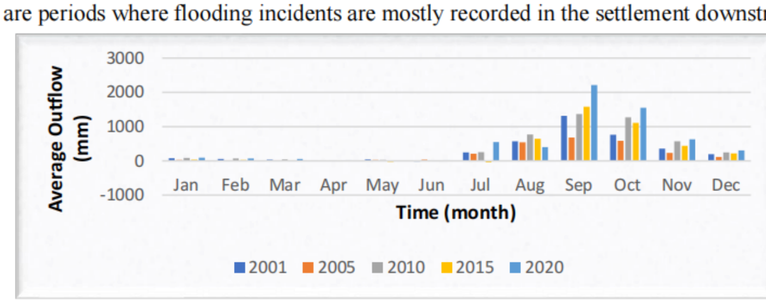

Figure 6: Average Outflow between 2001 and 2020

4.2 Correlation and regression analysis

The correlation and regression analyses are shown in Table 2. The correlation analysis between outflow and rainfall reveals a weak positive correlation of 0.280738, which is the second-lowest among other hydrological characteristics. The R-squared statistic shows that rainfall only predicts about 7.8% of the outflow incidents. The correlation analysis between inflow and outflow indicates a near-perfectly strong positive correlation of 0.873933, and the R squared values show that 76.4% of the outflow is predicted by the inflow. This is a strong statistical indication of the effect of inflow on outflow. The inflow also has the lowest standard deviation when compared to others. Similarly, a weak positive correlation of 0.148858 exists between temperature and outflow, indicating that, while temperature has a direct effect on outflow, it does not have a strong relationship in influencing the volume of outflow. This is supported by a very low R squared value of 0.0022159, which means temperature is only able to predict 0.22% of the volume of outflow. The correlation analysis shows a positive correlation of 0.55576 between the water elevation and the outflow of water, and the R square values show that the water elevation is able to predict about 30.89% of the volume of outflow in the dam. This shows that aside from inflow, water elevation is the next factor that influences the outflow of water in the study area. It also has the next-lowest standard deviation, as seen in Table 2.

Table 2: Correlation and regression analysis

Outflow (Y)	**Rainfall (X)**	**Temperature (X)**	**Inflow (X)**	**Water Elevation (X)**
Correlation	0.280738	0.148858	0.873933	0.55576
R Square	0.078814	0.0022159	0.763759	0.308887
Standard error	473.179	487.5128	238.4201	409.8513
Equation of line	Y= 1.262497*X +241.5391	Y= 18.77499*X - 186.464	Y= 0.869544*X + 48.66686	Y= 32.12798*X -11566

The forecasted volume outflow from 2025 to 2035 at 5-year intervals is shown in Table 3, while Fig 8 depicts the plot of the predicted and observed outflow.

Table 3: Forecasted Outflow data for 2025, 2030 and 2035

Forecasted/ Outflow	**2025**	**2030**	**2035**
Month	**m/s³**	**m/s³**	**m/s³**
Jan	84.03105	88.84043	93.64981
Feb	63.67316	67.3001	70.92703
Mar	45.33419	47.9043	50.47442
Apr	5.521139	5.832675	6.14421
May	12.59561	13.30301	14.0104
Jun	23.76461	25.09306	26.42151
Jul	275.0542	290.3585	305.6629
Aug	749.189	790.6823	832.1756
Sep	1642.93	1733.504	1824.079
Oct	1285.324	1355.859	1426.395
Nov	521.0542	549.5183	577.9824
Dec	259.1367	273.2287	287.3206

As seen in Figure 8, the model adopted approximately fits with the existing data for outflow and could thus be adopted to make a decision; this is also confirmed by the residual analysis, which is approximately distributed as zero.

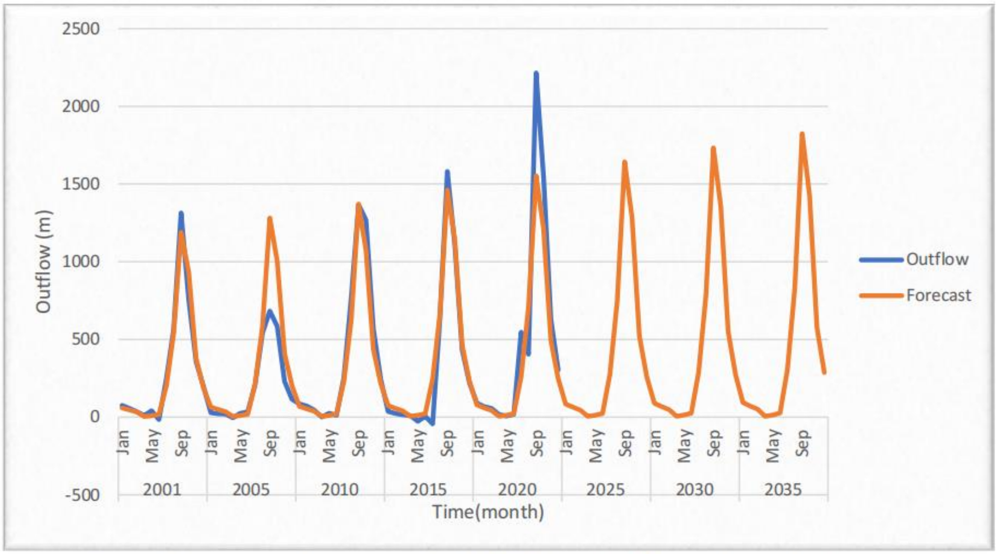

Figure 8: Previous and Forecasted (for 2025, 2030, and 2035) Outflow at the dam

The residuals plot for the forecasted and actual outflow values shows a reasonable spread around zero, which justifies the use of the model adopted in the study, as seen in Figure 9.

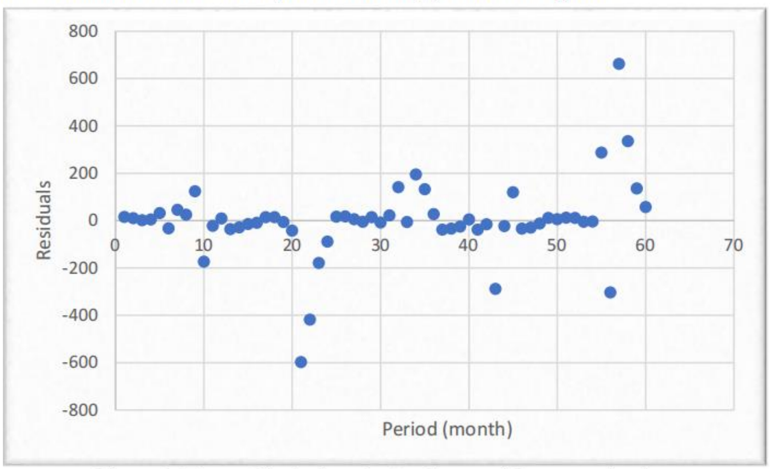

Figure 9: The residual plots for Outflow and Forecasted value

The time series and correlation analysis for rainfall show that rainfall does not really have the greatest impact on the outflow of water at the dam; the statistical analysis reveals a weak contribution to the overall flooding in the area. If the outflow is well predicted by the inflow, then it is important to investigate what the possible factors are that cause the inflow to rise. According to the analysis, temperature has the least impact on outflow; thus, inflow does not appear to have a large influence on the volume of outflow. The elevation of the water is the next factor after the inflow that has a greater influence on the volume of outflow, as seen in the analysis. The months with the highest volume of outflow also coincide with reported flooding incidents in the study area. This is proof that outflow has a greater influence on the flooding incidents experienced in the region.

5 Conclusion

Time series modelling and forecasting have fundamental importance for various practical domains, having in mind that time series forecasting enables predicting the future by understanding the past. Several factors may lead to flooding in relation to a dam and its features; the outflow from a dam, whether through release from a spillway or accidents relating to dam failure, has a greater effect on the settlements that are located downstream. The records of flooding incidents have increased over the years, and a proper study must be carried out to investigate the cause and a possible management approach. Four different factors were assessed in this study: rainfall, temperature, inflow, and water elevation, and the obtained result showed that inflow is the factor with the greatest influence on the volume of outflow, while other factors in decreasing order of their influence are water elevation, rainfall, and temperature, respectively. Since inflow is a major factor that influences outflow, the study thus recommends further study of inflow and the factors that influence its increase. Accuracy checks can also be carried out on the forecasted data to check the accuracy of this analysis and its recommendation.

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