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Evaluation of the Reliability, Resilience and Vulnerability of Jebba Hydropower Reservoir Operation, Nigeria

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Abstract: The operational status of a hydropower dam is described as either satisfactory or unsatisfactory. The ability of existing and proposed hydropower dams to operate satisfactorily under wide range of possible future demands and hydrologic conditions is an important system characteristic that can be assessed by estimating the reliability (the probability that a system will remain in a non-failure state), resilience (the ability of a system to return to non-failure state after a failure has occurred) and vulnerability (the likely damage of a failure event) of the system. The main sources of the data and other useful information for this research were previous research works, government documents, bulletins and gazettes from hydropower related ministries, agencies and organizations. Desktop analysis was carried out to estimate the water requirement to generate power by various combinations of units at the Jebba hydroelectric dam. Linear programming was used to obtain the monthly reservoir releases that maximized annual total energy generation. Both monthly and annual simulations were carried out using the operation policies from the LP optimization algorithm and the generated inflow series. Duration of the failure event (d(j)), the total number of failure events (M) and the deficit volume of the failure event (v(j)) were obtained from the simulation processes and used to evaluate the reliability, resilience and vulnerability of the Jebba dam. The results obtained showed that the performance of Jebba hydropower dam when three or more units are in use is generally poor. The reliability obtained over the period of historical record varied from 0.024 for six units to 0.994 for one unit in use. Reliability based on the optimized operation policy was not less than 60% and was as high as77%. The resilience was 0.292 and vulnerability was 3298.19 Mm3 at 60% reliability. These results confirm that the operational status of the dam can be improved by adopting real time reservoir release policies obtained by optimization of the reservoir operation.

Keywords: Reliability; Resilience; Vulnerability; Simulation, Releases

INTRODUCTION

Nigeria is well endowed with abundant water resources. The country is well drained with a reasonably close and dense network of rivers and stream. Some of these rivers, particularly the smaller ones, are, however seasonal, especially in the northern parts of the country where the rainy season is only three or four months in duration. In addition, there are natural water bodies like lakes, ponds as well as lagoons, particularly in the coastal area [1]. Nigeria's surface water resources potential is estimated to be some 267.3 billion cubic meters per annum [2]. The country has developed many single and multiple purpose dams to utilize the available water resources. Major hydropower dams in the country include Kainji, Jebba and Shiroro. The Zungeru hydropower dam is under construction while there are numerous small scale hydro schemes in several regions of the country

Hydropower currently accounts for about 32% of the total installed commercial electric power capacity in Nigeria. The electricity demand of Nigerians has never been met. The situation is compounded by the failure of the existing power stations to operate at full capacities [3]. In order to assess various aspects of performance of a water resource system it is often necessary to use multiple performance criteria to characterize system alternatives, demand scenarios and operation policies. Hashimoto *et al*. [4] have discussed the three criteria of reliability, resilience and vulnerability for evaluating the performance of water resources system. These measurements describe how likely a system is to fail (reliability), how quick it recovers (resiliency) and how severe the consequences of the failure may be (vulnerability). These criteria can be used to assist in the evaluation and selection of effective design and operating policies for a wide variety of water resources project [5]. The objective of this study is therefore to evaluate the reliability, resilience and vulnerability of water use to generate power at the Jebba dam, north central Nigeria.

The Jebba hydropower plant with a total installed capacity of 560 MW was officially commissioned on April 13, 1985. A total of six (6) turbines, each with a capacity of 93.3 MW were installed. The turbines are fixed blade propeller type with rated operating head of 27.6 metres and maximum flow per unit of 380 m^3/sec. Each turbine is coupled to a generator of 119 MVA maximum continuous rating but 103.50 MVA base load rating [6]. Each generator is connected to a step up transformer of 119 MVA rating. All the six units are connected in the switchyard through 330KV switchgears into two 330 KV bus-bars with two outgoing lines to Jebba transmission switchyard. Jebba reservoir depends solely on discharges from the Kainji Hydropower dam which local about 100 km upstream during the black flood (December to March). During the white flood (Rainy season) some rivers downstream of Kainji discharge into Jebba Reservoir in addition to the Kainji discharge. This and effective water management by the station allow the operation of Jebba units all the year round [6].

BASIC CONCEPTS

Available power

Hydropower is a renewable energy source where power is derived from energy of moving water from higher to lower elevations. It has been proved to be a predictable and price competitive technology. It also has the highest energy payback ratio. Though, it requires a relatively high initial investment but has the advantage of very low operation costs and a long lifespan compared to others [7]. The potential annual power generation of a hydropower project is proportional to the head and flow of water.

The power, P from water falling through a height h and at a flow rate Q, through a turbine is given as

$$P = \eta\rho ghQ \qquad (1)$$

Where ρ is the density of the water (10^3 Kg/m^3), h is the head of water (m) and g is the gravitational constant (9.81 m/s^2), Q is the volume of water flowing per second (the flow rate in m^3/sec) and η is the efficiency of the turbine.

Measures of System Performance

The likely performance of water resource systems is often described by the mean and variance of benefit, pollutant concentrations or some operating variable [4]. Additional performance criteria that capture particular aspect of possible system performance which are especially important during periods of drought, peak demands or extreme weather have been developed. These criteria are called reliability, resilience and vulnerability. These performance measures should be useful in the selection of water resource system capacities, configurations, operating policies and targets.

Failure

The operational status of a water resource system can be described as either satisfactory or unsatisfactory. Failure is defined as the inability of the system to deliver the desired yield or demand. The system under consideration at a given time *t* can be in either a satisfactory (i.e. non-failure) state *NF* or an unsatisfactory (i.e. failure) state *F*. The *NF* state occurs when water supply is able to meet water demand and, hence, the *F* state is when supply cannot meet demand.

Reliability of Water Resources System

Reliability is the probability of a device or system performing its intended function adequately for the period of time intended, under the operating conditions required. This measurement describes how likely a system is to fail [8]. The basic notions of the mathematical theory of reliability are the reliability function and the availability function. The reliability function defines the probability that the system has not entered state NS (Non-Satisfactory) until a given time, while the availability function defines the probability that the system is in state S (Satisfactory) at a given time [9].

The most widely accepted and applied definition is occurrence reliability, which can be estimated as:

$$\text{Re}\, l = 1 - \frac{\sum_{j=1}^{M} d(j)}{T} \qquad (2)$$

Where $d(j)$ is the duration of the *j*th failure event, *M* is the number of failure events, and *T* is the total number of time intervals.

Resilience of Water Resources System

Resilience is the ability of the system to return to non-failure state after a failure has occurred. Although it is not economical to design fail-safe systems, it is desirable that an acceptable level of functionality is recovered quickly after failure [10]. Different definitions have been suggested for resilience by researchers. However, all the suggested definitions in water resources field can be categorised under three main concepts: 1) Resilience is the amount of disturbance or pressure a system can absorb and still maintain its functions; 2) Resilience is the required time to return to equilibrium after a perturbation or failure and 3) Resilience is adaptive capacity of the system.

By this definition, the higher the probability of recovery, the higher the resilience; therefore, in essence it represents the rapidity of the system returning to a satisfactory state after an occurrence of failure [11]. Hashimoto et al. [4] proposed one of the earliest mathematical approaches to assess resilience of water resource systems. They suggested that resilience is a function of the average number of time steps for a system remaining in an unsatisfactory state after a failure event

$$\mathrm{Re}s = \{E[T_f]\}^{-1} \qquad (3)$$

Where $E[T_f]$ is the average length of failure events. Hashimoto et al. [4] showed that (3) is equivalent to the probability that the system will recover from failure after a single time step. Hence resilience is the average probability of recovery at time step (t+1) from a failure state at time t. Equation (3) has been the basis of most of later studies on resilience of water supply systems. According to Kjeldsen and Rosbjerg [12] this definition of resilience is equal to the inverse of the mean value of the time the system spends in an unsatisfactory state. This is given as

$$\mathrm{Re}s_1 = \left(\frac{1}{M}\sum_{j=1}^{M} d(j)\right)^{-1} \qquad (4)$$

Where $d(j)$is the duration of the j^{th} failure event and M is the total number of failure events.

Another mathematical measure of resilience was suggested by Moy et al. [19] as the maximum consecutive duration the system spends in unsatisfactory state. This is stated as

$$\mathrm{Re}s_2 = \{\max[\ d(j)]\}^{-1} \qquad (5)$$

Where $d(j)$ is the duration of jth failure event. The definitions of resilience in (4) and (5) are used to assess the operational status of Jebba dam in this work.

Vulnerability of Water Resources System

Vulnerability is a measure of the likely damage in a failure event, if one occurs. Sometimes the consequences of the failure of a low probability event may be of large magnitude; hence prior strategies should be adopted to deal with the possible consequences of failures due to such events [13]. Hashimoto et al. [4] defined vulnerability as:

$$Vul = \sum_{j\in F} s(j)e(j) \qquad (6)$$

Where $s(j)$ is the most severe outcome of the jth sojourn in unsatisfactory state and $e(j)$ is the probability of $s(j)$ being the most severe outcome of a sojourn into the unsatisfactory state. When the probability of each event is taken to be equal, i.e. $e(1) = ... = e(M) = 1/M$, where M is the number of failure events, then vulnerability estimated as the mean value of the deficit events $v(j)$ is:

$$Vul_1 = \frac{1}{M}\sum_{j=1}^{M} v(j) \qquad (7)$$

Another definition based on the use of the maximum event as a better estimator than the event-based mean value is

$$Vul_2 = \max\{\ v(j)\}\ ;\text{over all j} \qquad (8)$$

Where v_j the deficit volume of the failure event is calculated as the cumulative difference between demand and availability as:

$$v_j = \sum_{t=1}^{d(j)} \left[D(t) - Y(t)\right] \qquad (9)$$

where $d(j)$ is the duration of the failure, $D(t)$ and $Y(t)$ are the water demand and the water actually supplied, respectively

METHODOLOGY

Data collection and analysis

The evaluation study involves data collection and analysis. The main source of the data and other useful information were previous works, government documents, bulletins and gazettes from hydropower related ministries, agencies and organizations.

There are two main categories of reliability evaluation techniques [14]:

1. Analytical: Analytical techniques represent the system by a mathematical model and evaluate reliability indices by mathematical solutions.
2. Simulation: Simulation on the other hand estimates the reliability indices by simulating the actual process and random behavior of the system.

Both techniques were adopted in this study to evaluate the reliability, resilience and vulnerability of the Jebba hydropower dam. The basic data on Jebba hydropower dam is given in the Table 1.

Table 1: Basic Data on the Jebba Hydropower Dam

Parameters	**Jebba Station**
First year of operation	1984
Installed capacity (MW)	560
Design power plant factor	0.70
Number of generators (Units)	6
Reservoir flood storage capacity (Mm^3)	4000
Reservoir Flood Level (m)	103.55
Maximum operating reservoir elevation (m.a.s.l)	103.00
Minimum operating reservoir elevation (m.a.s.l)	99.00
Maximum storage capacity (Mm^3)	3880
Minimum storage capacity (Mm^3)	2880
Rated operating head (m)	27.6

Source: Salami [16]

Reservoir Operation data at Jebba hydropower station from 1984 to 2011 was obtained from the previous work. The data contained the following on monthly basis:

1. Inflow into the reservoir
2. Elevation of reservoir
3. Tailrace elevation
4. Release to turbines
5. Storage volume of reservoir.

The above data was analyzed to determine the mean, median, standard deviation, coefficient of variation, skewness coefficient, maximum and minimum for the period of operation. The results were used in the generation of long term flow, system optimization and simulation

Analysis of Power Output

The power generation of a hydro scheme is given by the equation

$$P = \eta\rho\, ghQ \qquad (10)$$

Where ρ is the density of the water ($10^3 Kg/m^3$), h is the head of water and g is the gravitational constant ($9.81 m/s^2$), Q is the volume of water flowing per second (the flow rate in m^3/sec) and η is the efficiency of the turbine.

The total installed capacity at Jebba dam is 560MW, then each of six units is rated at 93.33MW. Assuming an operating head, of h = 27.6 m (Abbey and Ogaji, 2015) and efficiency, $\eta = 0.90$, [15], then the turbine discharge Q is obtained from equation (10) as

$$Q = \frac{93.33 \times 10^6 \ Watts}{1000 \ kg/m^3 \times 9.81 \ m/s^2 \times 0.90 \times 27.6 \ m} = 383 \ m^3/s$$

Therefore, the required turbine release on monthly basis for one turbine = 383 x 30 x 24 x 60 x60 = 992.74 x 10^6 m^3 = 992.74 Mm^3

This is the release assuming power generation is done 24 hours a day all year round. The reliability, resilience and vulnerability of the reservoir operation using historical stream flow data as input were calculated for different number of units in operation. This desktop analysis presumes that the units will operate at full capacity all year round.

Optimization of Reservoir Operation

Linear programming technique is one of the most widely used mathematical programming methods in water resources management due to its convenience, ease of understanding and availability of solution algorithm. In this study, the optimal monthly releases from the Jebba reservoir were determined subject to various limitations and constraints using LINGO 14.0 [17].

The objective function of this optimization process is the maximization of the total annual energy generation $E_{T,}$

$$E = \max \sum_{t=1}^{t=12} E_t \qquad (10)$$

Where E is total annual energy generation (MWH), E_t is monthly energy generation (MWH)

Energy E_t is calculated as [18]:

$$E_t = 2.73\, Q_t H_t \eta \qquad (11)$$

The product $Q_t H_t$ can be linearized as [18]:

$$Q_t H_t = Q_t^0 H_t + Q_t H_t^0 - Q_t^0 H_t^0$$

(12)

Where

Q_t^0 = the average monthly release at Jebba dam from the historical data, (Mm^3).

H_t^0 = the average monthly generating head at Jebba dam from the historical data, (m).
= (Average monthly elevation – Average monthly tailrace level) (m).
Q_t = Optimized turbine release at time t, month (Mm^3)

H_t = Generating head at time t, month (m)
η = efficiency of Jebba plant
Using (11) and (12) in (10) gives the objective function as

$$E = \max \sum_{t=1}^{t=12} 2.73 \left(\left(Q_t^0 H_t + Q_t H_t^0 + Q_t^0 H_t^0 \right) \eta \right) \quad (13)$$

The constraints are
1. The continuity or mass balance constraint
The mass balance between the inflows and the outflows is given as follows

$$S_{t+1} = S_t + I_t - Q_t - X_t \quad t = 1, 2. \ldots 12 \quad (14)$$

Where
S_{t+1} = Final reservoir storage at the end of the month (Mm^3)
S_t = Initial reservoir storage at the beginning of the month (Mm^3)
Q_t = Monthly release (Mm^3)
X_t = Monthly Excess flow, if any (Mm^3)
I_t = Monthly reservoir inflow (Mm^3)

2. Reservoir capacity constraint
The constraint for the reservoir capacity at any period t is given as

$$S_{\min} \leq S_t \leq S_{\max} \quad t = 1, 2, \ldots.12 \quad (15)$$

Where
S_{min} = Minimum capacity of the reservoir (Mm^3)
S_{max} = Maximum capacity of the reservoir (Mm^3)
S_t = Storage capacity of the reservoir at any period, t (Mm^3)
3. Non-negative constraint for the release

$$Q_t \geq 0 \quad t = 1, 2, \ldots.12 \quad (16)$$

Where Q_t = Monthly release (Mm^3)

4. Generating head constraint
The constraint for the reservoir generating head at any period t is given as

$$H_{\min} \leq H_t \leq H_{\max} \quad t = 1, 2, \ldots 12 \quad (17)$$

Where
H_{min} = Minimum generating head of the reservoir (m)
H_{max} = Maximum generating of the reservoir (m)
H_t = Generating head of the reservoir at any period, t (m)

5. Monthly energy generated equation
The equations for the energy generated monthly will be given as

$$E_t = 2.73 \eta \left(Q_t^0 H_t + Q_t H_t^0 - Q_t^0 H_t^0 \right) \quad t = 1, 2, \ldots 12 \quad (18)$$

Where E_t = Monthly energy generated (MWH)

Simulation of the System

Simulation of the Jebba reservoir operation was carried out using results of the optimization, the historical flow series and generated flow series at both monthly and yearly time scales. Each simulation started with the initial storage, (S_t) taken as the maximum storage capacity of the reservoir.

a) With an established or known inflow, (I_t) and turbine release or demand depending on the number of units in use, the final storage in period t is calculated as

$$S_{t+1} = S_t + I_t - D_t \quad (19)$$

Where
S_{t+1} = Final storage capacity at any given period, t (Mm^3)
S_t = Initial storage capacity at any given period, t (Mm^3)
I_t = Monthly inflow into the reservoir (Mm^3)
D_t = Monthly demand to generate power (Mm^3)

b) Final storage at the end of a period will be an initial storage for the next period but subject to the following conditions:

IF $S_{t+1} \leq S_{min}, S_t = S_{min}$ (20)
IF $S_{t+1} \geq S_{max}, S_t = S_{max}$ (21)
IF $S_{min} \leq S_t \leq S_{max}$, $S_t = S_{t+1}$ (22)

c) The actual release of the reservoir R_t will then be calculated as follows

$R_t = S_t + I_t - S_{min}$ IF $S_{t+1} < S_{min}$ (23)
Deficit Release = $R_t - D_t$ (-ve)
$R_t = S_t + I_t - S_{max}$ IF $S_{t+1} > S_{max}$ (24)
Excess Release = $R_t - D_t$ (+ve)
$R_t = D_t$ IF $S_{min} \leq S_t \leq S_{max}$ (25)

The reservoir will be in a non-satisfactory state (failure state) any time the actual release is less than demand. This is given as;
COUNTIF (deficit release,"<0") = Failure.

The simulation was done for different number of turbine units in use. The number of failures d(j) per failure event (j) were obtained. Other parameters were obtained such as v(j) the deficit volume of j[th] failure.

RESULTS

Solution to the Optimization Modeling

The summary of the results of the optimization modelling is shown in Table 2.

Table 2: Results obtained from the LP operation optimization algorithm

Month	Generating Head (m)	Reservoir Release (Mm^3)	Storage volume (Mm^3)	Energy generated (MWH)
January	29.24	1227.10	2880	81552.86
February	29.24	1981.37	3880	126834.10
March	29.24	2944.12	3880	185533.50
April	29.24	910.10	2880	60776.74
May	29.24	1829.51	3880	116208.30
June	29.24	2748.41	3880	174335.50
July	29.24	1675.10	2880	107012.20
August	29.24	2181.42	2880	139434.10
September	29.24	2329.16	2880	150189.70
October	29.24	3474.83	3880	219505.00
November	29.24	3114.21	3880	196124.40
December	29.24	2325.35	2880	148040.30

Performance of Jebba dam operation from the Desktop analysis

The failures observed from the initial/desktop analysis of the operation of Jebba dam for different number of units in use along with the historical flow are shown in Table 3. The corresponding reliability, resilience and vulnerability are given in Table 4. The results of simulation of the operations at Jebba dam using optimized release values and monthly and annual sequences of generated flows are shown in Tables 5 and 6 respectively. The reliability, resilience and vulnerability for the two flow scenarios are shown in Tables 7 and 8.

Table 3: Failure Events Using Historical Inflow Data and Required Turbine release for various number of units from desktop analysis

	6 Units	5 Units	4 Units	3 Units	2 Units	1 Unit
Number of Failure Events	7	8	10	21	20	2
Total number of Failure	328	324	306	249	133	2

Table 4: Reliability, Resilience and Vulnerability from Desktop Analysis

	Reliability	Res_1	Res_2	$Vul_1(Mm^3)$	$Vul_2(Mm^3)$
6units	0.024	0.021	0.01	180690.96	452054.49
5units	0.036	0.025	0.01	117326.32	354765.97
4units	0.089	0.033	0.01	61614.02	257477.45
3 units	0.259	0.084	0.028	15021.21	100978.54
2 units	0.604	0.150	0.023	4360.57	36539.12
1 unit	0.994	1	1	33.775	44.92

Table 5: Simulation Results Using Monthly Forecasted Inflows With optimized releases

Number of months Of flows used	Total number Of failures	Number of Failure events	Average number Of failures per Event
336	137	40	3.42
360	163	58	2.81
600	218	81	2.69
900	298	110	2.71

Table 6: Simulation Results Using Annual Forecasted Inflows with optimized releases

Years of Flows used	Total number Of failures	Number of Failure events	Average number Of failures per Event
28	15	4	3.75
50	19	5	3.80
100	38	9	4.22
200	72	19	3.78
500	115	43	2.67

Table 7: Reliability, Resilience and Vulnerability based on Monthly Forecasted Inflows and optimized releases

Months	**Reliability**	**Res_1**	**Res_2**	**$Vul_1(Mm^3)$**	**$Vul_2(Mm^3)$**
336	0.592	0.292	0.091	3298.19	14187.83
360	0.547	0.356	0.100	2614.99	10580.77
600	0.637	0.371	0.125	2113.11	9933.87
900	0.669	0.369	0.125	2157.05	10347.14

Table 8: Reliability, Resilience and Vulnerability based on Forecasted Annual Inflows and optimized releases

Years	**Reliability**	**Res_1**	**Res_2**	**$Vul_1(Mm^3)$**	**$Vul_2(Mm^3)$**
50	0.620	0.263	0.125	37774.32	82108.66
100	0.620	0.237	0.100	42722.02	99603.34
200	0.640	0.263	0.100	27994.16	99603.34
500	0.770	0.374	0.125	15008.11	90603.34

DISCUSSION OF RESULTS

The optimal solution with the total annual energy generation of 1705547 MWH was obtained. The results revealed that the maximum release of 3474.83 Mm^3 was recorded in the month of October to generate a significant energy of 219505.00 MWH compared to the minimum release in the month of April with generated energy of 60776.74 MWH. It is obvious that the peak discharge at the Jebba dam from both historical data and the optimal solution is in the month of October, which means that the dam will be more reliable in the month of October than any other month as it will have more water which can be used to run more units to generate power.

The results on the number of failures and number of failure events for different number of units at the Jebba dam indicate that the duration spent by the system in an unsatisfactory state is more when the number of units in used is more than two. This shows that the station will perform well and look less vulnerable with less than 3 units of turbines in use. The results in Table 4 can be interpreted to mean that the firm power from the dam is about 90 MW. This is because only one unit has 99% reliability. This means that one unit can run all year round and deliver 90 MW, while other units are on standby. Also two units can run 60% of the time or 7 -8 months in a year to deliver 180 MW continuously. Use of three or more units will lead to failure as the system will not be able to provide the water needed to run the units.

The results also show that the duration spent by the system in an unsatisfactory state for both monthly and annual forecasted inflows series increases proportionately with length of data used for the simulation. However the average number of failures per failure event was between 3 and 4. This few number of failures will occur when the operation of the dam is based on the optimized schedule of releases.

Furthermore, the system is found to be less reliable, spends more time to recover and more vulnerable when used with three units or more but it shows an improved reliability, with a good recovery time and less vulnerable when used with three units or less. The increase in the reliability will increase the resilience and make the system less vulnerable. The highest reliability of 66.9% using optimized release on a long term was obtained along with a resilience of 0.369 and a vulnerability of 2157.05 Mm^3. This means that 374.64 MW of the total installed capacity of Jebba dam can be achieved in the long run and 2157.05 Mm^3 will be a deficit release for that period. There is no significant difference between the reliability, resilience and vulnerability for the annual forecasted inflows series used with optimized release except for the 500 years sequence with an improved value of 77% for the reliability as well less vulnerable amount of deficit release.

CONCLUSION

The study has shown that the three criteria evaluated changed significantly with the number of units in operation. It is so evident that use of the historical inflow data produced a very low reliability value of 0.024 when all the six units are put to use for 24 hours daily and all year round. However, their reliability values increase sharply from 0.089 when used with four units to 0.259 when used with 3units. Interestingly, the reliability obtained for two units or less is quite high. It can be concluded that the performance of the system can be improved by adopting the optimized release pattern obtained in this study. This is so because the simulation over long term showed that the reliability would not be less than 60% and may reach 80 %. This shows that the station as a whole can contribute significant energy to the national grid and its operations guidelines should be updated by real time analysis. The Jebba reservoir response to failure is very poor with higher units in operation but improve steadily with the decrease in the number of units in operation. However, it was observed that the system is more resilient with the increase in the reliability but severe damage is caused when the system fails to respond quickly to the failure.

From the study, it is so obvious that from the hydrological perspective and assuming other factors are constants, Jebba dam cannot satisfactorily and adequately cater for all the six units to run simultaneously for 24 hours a day. It is more advisable to stick with just two or three units and keep the others on standby. If there is need to increase the number of units to be used, then hours of operation will also be reduced.

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