DETERMINATION OF HYDRODYNAMIC PARAMETERS IN THE PAIVA CASTRO RESERVOIR USING ARTIFICIAL TRITIUM

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Abstract

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The Paiva Castro reservoir is used to supply about 67% of the total water consumed in the São Paulo metropolitan region. The reservoir contains about 32×10^6 m^3 and has a normal flow rate of about 30 m^3/s. A tracer experiment using 10 Ci (37×10^{10} Bq) of artificial tritium was performed in the reservoir. The results obtained were used to calibrate a mathematical model of tracer transport. The purpose of the experiment was to determine the mean transit time of water, mean water velocity, hydrodynamic dispersion, volume of active water in the reservoir, and possible losses of tracer into the stagnant zone. The mathematical model of tracer transport through the reservoir was calibrated using tritium concentration curves measured in different parts of the reservoir. It was anticipated that this calibrated model could be used to predict the movement of non-reactive pollutants through the reservoir in the case of an accident. The line injection, in four equally distributed points perpendicular to the flow direction, produced a homogeneous distribution of tracer mass at the entrance to the reservoir. The measurements of tritium concentrations in different cross-sections of the reservoir showed that about 45% of the tracer mass (up to the flow distance of about 4200 m) was transported through the right part of the reservoir. After 7100 m the tracer was equally distributed perpendicularly to the streamlines. The mean water velocity through the reservoir was 0.016 m/s and the dispersivity was 456 m. The volume of mobile water in the aquifer between the injection point and the outflow to the pumping station was found to be 13×10^6 m^3. Over the last 1000 m of flow path, about 15% of tracer mass was lost in a large, nearly stagnant zone in the southwest part of the reservoir.

1. INTRODUCTION

This paper presents a tracer experiment carried out in the Paiva Castro reservoir. The reservoir supplies drinking water for about 12 million inhabitants of the city of Sã Paulo, Brazil. This experiment was a part of the joint project between the Instituto de Pesquisas Energeticas e Nucleares (IPEN), Companhia de Saneamento Basico do Estado de São Paulo (SABESP) and the Nuclear Energy National Commission (CNEN). Financial support was provided by the IAEA under project number BRA/8/022.

The Paiva Castro reservoir is one of the final steps in the hydraulic complex entitled the Cantareira System, which provides 67% of the water consumed in the São Paulo metropolitan region. The main function of Paiva Castro reservoir is to collect and store water from other reservoirs for the Guarau water treatment station. The reservoir is located in the north region of São Paulo city. The storage dam was constructed in the Juqueri river. The reservoir runs from the east to the southwest, having a length of about 9.5 km. The depth varies from 2 m near the entrance to 12 m near the outflow to the pumping station. The reservoir contains approximately 32×10^6 m^3 of water and has an average flow rate of about 30 m^3/s. A map of the reservoir is shown in Fig. 1.

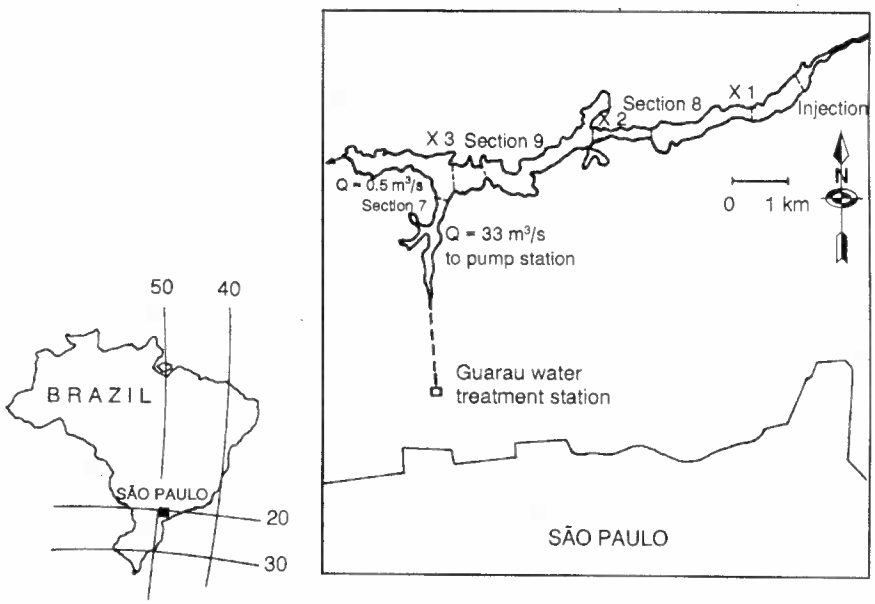

FIG. 1. Map of Paiva Castro reservoir showing its location within Brazil.

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The purpose of the current experiment was to use tritium as a tracer to obtain information about:

(1) The hydrodynamics of Paiva Castro reservoir, including determination of the mean transit time of water through the reservoir and the detection of the main flow path within the reservoir. Consequently, from the known volumetric flow rate, the volume of water in the reservoir could be determined.
(2) The contaminant transport of non-reactive pollutants, including the determination of flow velocity and dispersivity at the flow path between the entrance to the reservoir and the outflow to the pumping station.

The injection sites and all sampling points are shown in Fig. 1. The injection of 10 Ci[1] tritium was performed on 10 August 1993. The volumetric flow rate of water through the reservoir was 28 m^3/s. The tracer was divided into four 10 mL glass bottles and injected simultaneously in four places at the reservoir cross-section (Injection in Fig. 1). It was assumed that this injection produced a line injection with the homogeneous distribution of a tracer perpendicular to the flow direction. Initially it was intended to inject tracer directly to the Juqueri river at the entrance to the reservoir. However, due to the fact that at that very spot there is a small water pumping station for the city of Mairipora the injection was performed 350 m downstream. The water samples were collected in five cross-sections:

(1) In Sections X1 (1000 m downstream), X2 (4200 m downstream) and X3 (7100 m downstream) to detect the tracer distribution across the reservoir;
(2) Continuously in sections: Section 8 (3200 m downstream), Section 9 (6600 m downstream), and Section 7 (7600 m downstream). In the last two sections, the water samples were collected from four places perpendicular to the flow direction and at three depths. Samples were mixed together to obtain an integrated representative sample for the whole cross-section.

2. RESULTS AND MODELLING

2.1. Tracer distribution in the reservoir

It was assumed that the mass of tracer transported along different flow paths was directly proportional to the water velocities on these paths and that the differences in the flow velocities were not too great. The measurements of tracer concentrations in Sections X1, X2 and X3 are summarized in Tables I–III. The length of Section X1, situated about 1000 m from the injection point, was 250 m.

[1] 1 Ci = 3.7×10^{10} Bq.

TABLE I. TRITIUM CONCENTRATIONS MEASURED 25 HOURS AFTER INJECTION IN THE CROSS-SECTION X1

Y (m)	25	50	75	100	125	150	175	200	225
C (TU)	855	818	681	333	550	436	372	526	582

X = 1000 m, bottom depth 3 m at a depth of 2 m. Y = distance from the right border.

TABLE II. TRITIUM CONCENTRATIONS MEASURED 75 HOURS AFTER INJECTION IN THE CROSS-SECTION X2

Y = 40 m		Y = 125 m		Y = 200 m	
H = 2 m	249 TU	H = 2 m	154 TU	H = 2 m	124 TU
H = 4 m	225 TU	H = 4 m	158 TU	H = 4 m	174 TU
H = 8 m	172 TU	H = 7 m	138 TU	H = 6 m	136 TU

X = 4200 m, bottom at a depth between 7.5 and 9 m at three depths (H). Y = distance from the right border.

TABLE III. TRITIUM CONCENTRATIONS MEASURED 125 HOURS AFTER INJECTION IN THE CROSS-SECTION X3

Y = 65 m		Y = 200 m		Y = 335 m	
H = 2 m	235 TU	H = 2 m	264 TU	H = 2 m	256 TU
H = 4 m	239 TU	H = 4 m	276 TU	H = 4 m	276 TU
H = 8 m	271 TU	H = 8 m	244 TU	H = 8 m	266 TU

X = 7100 m, bottom at a depth of 8.5–10 m at three depths (H). Y = distance from the right border.

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H = 8 m	266 TU

. Y = distance from the right

The water samples were taken at 25 m intervals and at the same depth of 2 m. The tritium concentrations observed are shown in Table I. Considering three main parts of this cross-section it was observed that, up to a flow distance of 1000 m, the greatest velocity was near the right hand border. Consequently about 46% of tracer was transported in that part of the reservoir. Approximately 25% of the tracer mass was transported in the centre part and 29% at the left side of the reservoir. The length of Section X2, situated about 4200 m from the injection line, was the same as that of Section X1 (250 m). The water samples were taken from three locations (40 m from the left and right sides and in the middle) and from three depths (Table II). Data suggested that at this distance, the water flow velocity was the greatest at the right side (42% of tracer mass) and water velocities in the centre and left parts of the reservoir were nearly the same (29 and 28%, respectively). In Section X3, which had a length of 400 m and was located at a distance of 7100 m from the injection line, the tracer concentrations found at three places (65 m from the left and right sides and in the middle) were very similar. This observation suggested that the water transport at this distance was equally distributed perpendicular to the flow direction. Simply put, the mean flow velocities at 7100 m were the same along the whole cross-section.

2.2. Tracer concentration curves as a function of time

The tracer concentrations were measured as a function of time at three distances from the injection line. Tritium concentrations reached maximum values of 1620 TU in Section 8 (X = 3200 m), 461 TU in Section 9 (X = 6600 m) and 305 TU in Section 7 (X = 7600 m) after 15, 74 and 108 h, respectively. The natural background tritium content in Paiva Castro reservoir was 20 TU. All three tracer concentration curves found in different sections of reservoir are presented in Figs 2–4. The tracer mass recovery found in Sections 8 and 9 was nearly 100%, whereas only about 85% of tracer mass was recovered in Section 7. This suggested that the loss of tracer mass at the flow distance of 1000 m was attributable to transversal dispersion and diffusion into the southwest part of the aquifer.

2.3. Mathematical modelling

Well known dispersion models [1] can be used to describe tracer transport in aquatic systems. If the tracer is homogeneously distributed along the whole cross-section perpendicular to the flow direction then the transverse dispersion (horizontal and vertical) does not influence tracer transport. Thus, transport can be considered as one dimensional. Assuming that the tracer losses due to diffusion into stagnant zones or evaporation can be approximated as a first order kinetic irreversible reaction, the transport equation has the following form [2]:

$$D_L \frac{\partial^2 C}{\partial x^2} - \nu \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} + \omega C \qquad (1)$$

where C is the concentration of tracer, x is the flow distance, D_L is the dispersion coefficient, t is the time variable and ω is the reaction rate constant. The solution to the above equation for the instantaneous injection of the mass of tracer M, is given by [2, 3]:

$$C(t) = \frac{M}{Qt_0\sqrt{4\pi P_D (t/t_0)^3}} \exp\left\{-\frac{[1-(t/t_0)]^2}{4P_D(t/t_0)} - \omega t\right\} \quad (2)$$

with

$$t_0 = V/Q = x/v \quad (3)$$

being the mean transit time of water through the reservoir and V the volume of mobile water in the reservoir between injection and the place of detection, Q the volumetric flow rate through the reservoir. P_D is the 'dispersion parameter' equal to:

$$P_D = D_L/(vx) = \alpha_L/x \quad (4)$$

where α_L is the dispersivity.

The above model has three parameters (t_0, P_D, ω). These parameters must be obtained by model calibration, specifically by fitting Eq. (2) to the experimental data.

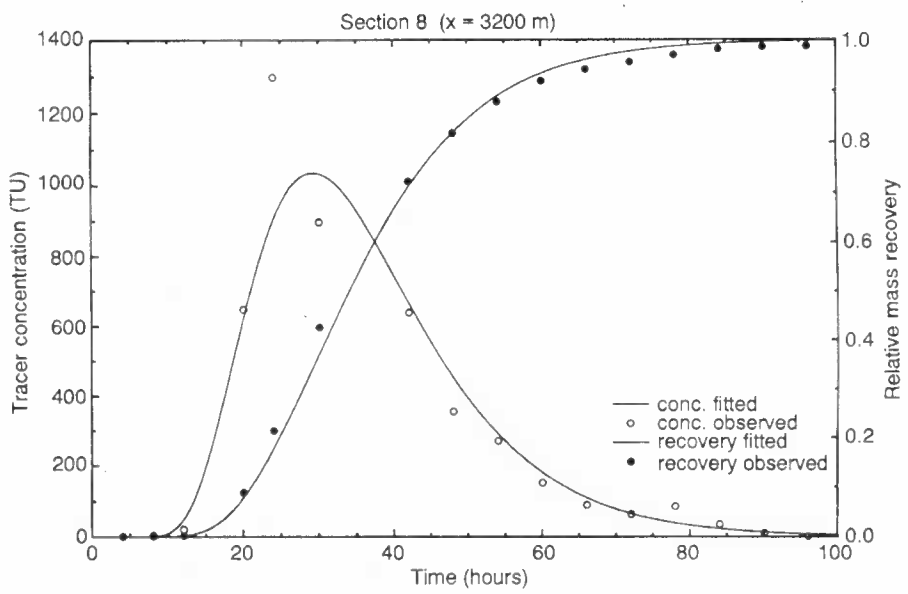

FIG. 2. Best fits of the model to tracer concentration and recovery curves obtained in Section 8 (x = 3200 m).

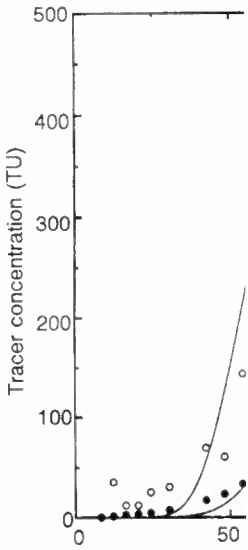

FIG. 3. Best fits of the
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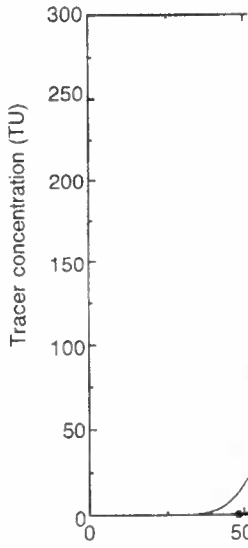

FIG. 4. Best fits of th
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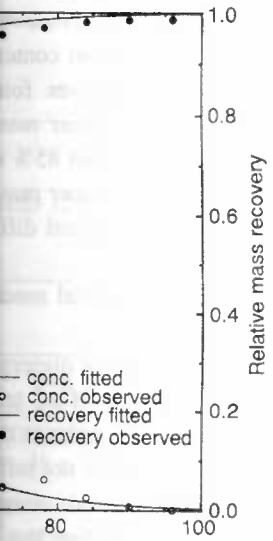

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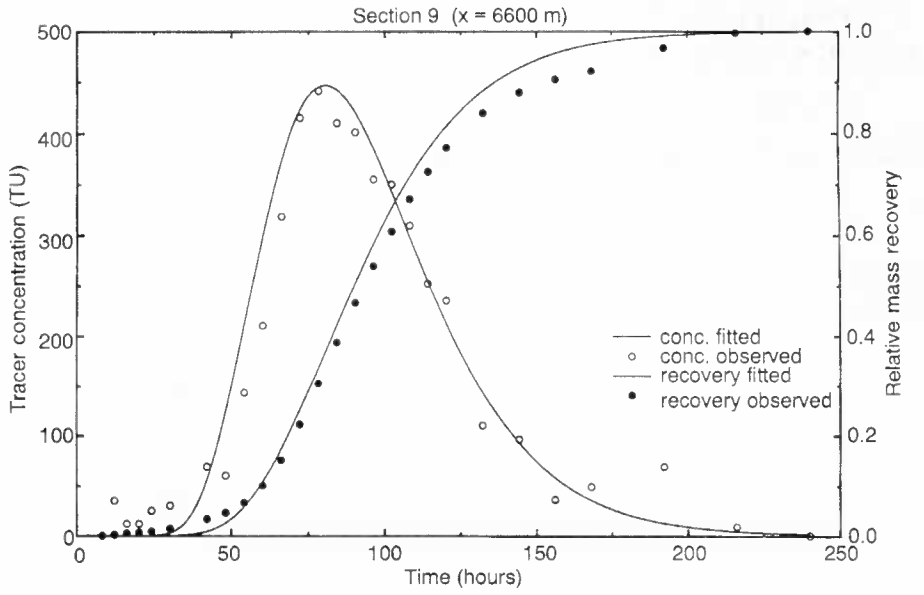

FIG. 3. Best fits of the model to tracer concentration and recovery curves obtained in Section 9 (x = 6600 m).

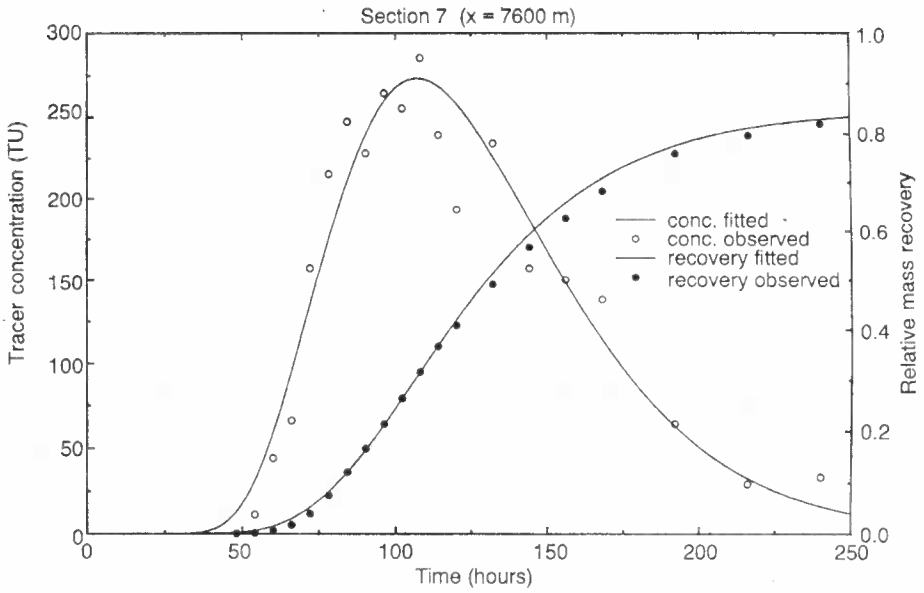

FIG. 4. Best fits of the model to tracer concentration and recovery curves obtained in Section 7 (x = 7600 m).

From the known flow distance x = L, the mean water velocity in the reservoir (at the flow distance L) can be determined from t_0 and P_D using Eqs (3) and (4):

$$v = L/t_0 \tag{5}$$

and dispersivity α_L

$$\alpha_L = P_D L \tag{6}$$

Additionally, from Eq. (3) the volume of water in the reservoir can be estimated from the known flow rate Q:

$$V = Qt_0 \tag{7}$$

From the known surface area of the part of the reservoir between the injection and detection lines, A, the average depth of the reservoir, H_b, can be determined:

$$H_b = V/A \tag{8}$$

If the depth of the reservoir can be determined from independent measurements, the calculated parameter (8) can be used to validate the model.

According to Refs [2, 4], in the tracer experiments performed in the close systems it is useful to determine the relative tracer mass recovery R, defined as follows:

$$R(t) = Q \int_0^t C(t)\,dt/M \tag{9}$$

The form of the function (5) can also be helpful for determining the model of exchange reactions [2]. Additionally, R (t = ∞) provides the necessary information about the tracer losses along the flow path between injection and detection lines.

2.4. Results of modelling

Model parameters were obtained by applying a fitting procedure based on the least squares method. The results of modelling at three detection points (Sections 7, 8 and 9) are summarized in Table IV. To verify the quality of fitting, these parameters were used to calculate the tracer recovery curves, Eq. (9). These curves agreed very well with the experimental recoveries. The best fit curves (tracer concentration and recovery) are shown in Figs 2–4. Up to flow distance of x = 6600 m (Section 9) tracer losses were not observed and the model calculations were performed with $\omega = 0$. The mean water velocities, dispersivities, volumes of water and the average depths of the reservoir were calculated from the fitting parameters. The results are summarized in Table V.

The water flow velocity decreased with the flow distance. This was as expected because the cross-sectional area increased in the direction of outflow. The dispersivity increased with the flow distance. The mean transport parameters for the flow

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TABLE IV. MODEL PARAMETERS OBTAINED BY CALIBRATING THE MODEL TO THE TRITIUM CONCENTRATION CURVES MEASURED AS A FUNCTION OF TIME

Detection point	L (m)	t_0 (h)	P_D (-)	ω (h^{-1})
Section 8	3200	36.5	0.075	0
Section 9	6600	94.5	0.055	0
Section 7	7600	130.0	0.059	0.0013

TABLE V. TRANSPORT AND HYDRAULIC PARAMETERS OBTAINED FROM THE FITTING PARAMETERS BY KNOWN MEAN VOLUMETRIC FLOW RATE THROUGH THE RESERVOIR (Q = 28 m^3/s) AND SURFACE AREAS OF THE RESERVOIR A (BETWEEN INJECTION AND DETECTION POINTS)

Detection point	L (m)	A (m^2)	v (m/s)	α_L (m)	V (m^3)	H (m)
Section 8	3200	1.14×10^6	0.024	240	3.68×10^6	3.3
Section 9	6600	1.56×10^6	0.019	363	9.53×10^6	6.1
Section 7	7600	1.71×10^6	0.016	456	1.31×10^7	7.6

distance of 7600 m were: water velocity $v = 0.016$ m/s; dispersivity $\alpha_L = 456$ m; and the first order irreversible kinetic reaction rate constant $\omega = 0.0013\ h^{-1}$. These parameters can be used to predict the transport of non-reactive pollutants through the Paiva Castro reservoir. By applying the convolution integral to any initial concentration $C_{inp}(t)$, the concentration of contaminant in the outflow to the pumping station $C_{out}(t)$, can be calculated as follows:

$$C_{out}(t) = \int_0^\infty C_{inp}(t - \tau)\, g(\tau)\, d\tau \qquad (10)$$

where

$$g(\tau) = \text{Eq. (2) } Q/M \qquad (11)$$

The volume of water found between injection and detection lines was approximately $V = 13 \times 10^6\ m^3$. The channel between Section 7 and the pumping station contained about $2.5 \times 10^6\ m^3$ of water whereas about $0.3 \times 10^6\ m^3$ of water was stored in the initial part of aquifer between the Juqueri river inflow and injection line.

Taking these values into account, the volume of active water in the Paiva Castro reservoir was estimated to be about $V = 16 \times 10^6$ m^3 of water. This suggested that about 14 to 16×10^6 m^3 of water was stored in the southwest part of the reservoir (west of Section X3 in Fig. 1). This volume corresponds to about 50% of the total water stored. As a result, 50% of water in the reservoir was considered to be inactive (quasi stagnant) under the hydraulic conditions existing during the experiment.

As expected, the average depth of reservoir determined using a mathematical model increased from 3.3 m at the flow distance of 3200 m to 7.6 m at the flow distance of 7600 m (Table V).

3. CONCLUSIONS

Mathematical modelling of the experimental data yielded the transport and hydraulic parameters needed to assess the effects of non-reactive contaminant transport through the reservoir. The transport parameters and the model used can be applied to predict the movement of non-reactive contaminants through the Paiva Castro reservoir, thus providing the water authority with a much needed tool to prepare remedial measures and manage the water supply. The volume of water found to be active under the experimental conditions was about 50% of the total water stored in the reservoir. The loss of tracer mass by diffusion, transverse dispersion and a small volumetric flow rate (0.5 m^3/s) into the quasi stagnant zone situated in the southwest was relatively small (15%). The average depths of the reservoir, calculated for the different parts of reservoir, agreed with direct measurements. These determinations validated the mathematical model in the system under the conditions investigated.

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Abstract

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