

# MODELLING OF POLLUTANT TRANSPORT IN RIVER BENUE DOWNSTREAM OF YOLA, NIGERIA: AN ENGINEERING APPROACH

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## ABSTRACT

*This paper is aimed to study river pollution and pollutant propagation performed by using advective-dispersion equations and computer implementation for best management decisions. Sampling of water started from the headwaters of the river at Cameroon Mountains and at three other downstream reaches of Yola in cleaned pre-conditioned plastic bottles for analysis of both physical and chemical pollutant concentrations. The samples were analysed using Atomic Absorption Spectrophotometer (AAS 500) model. Mathematical model of mass balance equations of fluid flow were developed using Matlab tool to predict the flow pattern of these pollutants. The results indicate that most of the pollutant concentrations were above WHO (2007) permissible limits. However, Fe, Cu, Ni, and Cr exceeded recommended limits. The output of the model showed a one-dimensional non-uniform linear graph, and the estimated water flow velocity in the river was 0.66 m/s over a distance of 1.5 km in 15 minutes. The model was validated by comparing measured and predicted data which indicated a reasonable agreement in the shapes of pollutant flow curves.*

**Keywords:** Pollutants transport, River Benue, water velocity, dispersion, advection

## 1 INTRODUCTION

Recently, the general interest in preserving the quality of the environment has considerably increased. This is due to a need of ensuring the availability of resources for the next generations through sustainable development. In the field of surface waters, many problems are caused by pollutant releases. It was asserted that many rivers, especially those passing through inhabited areas are subjected to pollutant discharge; therefore, managers need reliable support tools for water quality assessment and to predict consequences of their decisions [1]. This issue can be addressed with the use of tools for computational estimation of in-stream pollutant concentrations, which is the main concern of this paper.

In this research, leachates containing pollutants released from decayed wastes dumpsites at Gwari vegetables market, Yola through open drainages and rainstorm runoff to River Benue via its floodplain was investigated, and the migration of these pollutants in the

river was modelled to determine how far they can travel within a specific given time; their velocities and direction of flows using the advective-dispersion equation (ADE), which is itself a partial differential equation (PDE) executed in Matlab environment and to focus on four different river reaches where different pollutants in terms of nutrients and heavy metal concentrations were taken into account. It is important to note that not all pollutants mix freely with water, majority of pollutants which are in true solution; colloidal solution or in suspension are carried along and mixed by the movement of water. The processes involved are advection and dispersion respectively [2]. Dispersion refers to the spreading of a pollutant from the source to the point of exposure [3].

Heavy metal pollutants are conservative in nature and their concentrations also mobilization depend on salinity, electrical conductivity and pH conditions; which vary along a given river. As a result, the metal may come out of the solution or even redissolve depending on the conditions along the channel [4]. Looking at the previous literature on the Benue River, it was noticed that only few water quality studies have been carried out until now. Some of them presented the state of water quality while others specified aspects related to the chemicals affecting the water [5]. None of these studies have anything to do with prediction of the Benue River water quality and the pollutant transport along the river reaches. Consequently, the formulation of a prediction tool for pollutant transport is of great interest for the environmental management in the Benue River Basin and also for other flowing surface water bodies in Nigeria. For the purpose of this analysis, the model was developed by deriving the one-dimensional mass balance equation with source and sinks terms; as such the main objective of this study is to model pollutant transport from decaying waste dumpsites at Gwari market to River Benue down its slope by means of methods and tools. Other objectives were organized as described further: (1) to develop mathematical model formulation that can adequately reflect the real dynamic and transport condition in River Benue reaches using Matlab tool; (2) to offer modelling support for a wide range of cases e.g., methods to describe river reaches, monitoring sites, river channel features and hydraulic characterization parameters of the river stretch; (3) to compile reliable field data on chemical concentrations and mass fluxes information.

## **2 METHODOLOGY**

### **2.1 Description of Study Site**

Gwari International vegetables market which attracts vegetables from neighbouring countries such as Cameroon, Niger and Chad Republics is located at Northwestern part of the Greater City of Jimeta-Yola, Nigeria; where farmers, traders, and customers meet to sell and buy different varieties of vegetables for their consumption. The study site consists of River Benue itself (Fig. 1), is the major tributary to Niger River [7]. It traverses and drains Jimeta-Yola city and surrounding areas. It started from Sassa-Mbersi Mountains in Northern Republic of Cameroon at about 132 m and traverses through Lagdo Reservoir with a 40 m high Dam built across it where it passes through Garoua, then flows westward to Yola in Northeast part of Nigeria and finally empties into River Niger at confluence, Lokoja in Kogi State where they flow through the lower Niger Delta basin and drains directly into the North Atlantic Ocean. It has both major and minor tributaries. While (Fig. 2) consists of the market, decaying vegetable

waste dumpsites, open drainages and rainstorm runoffs that help to convey leachate pollutants in form of nutrients and heavy metals from these dumpsites into River Benue channel located at an average of 1.5 Kilometers down the slope of these dumpsites. The vegetables market covers an area of approximately 93,290.36 m<sup>2</sup> and lies between Latitudes 9°16' and 9°17'N; Longitudes 12°25' and 12°30'E. The landscape is a low sloping area with an elevation of 150 m above Mean Sea Level with varying aquifer potentials [6].

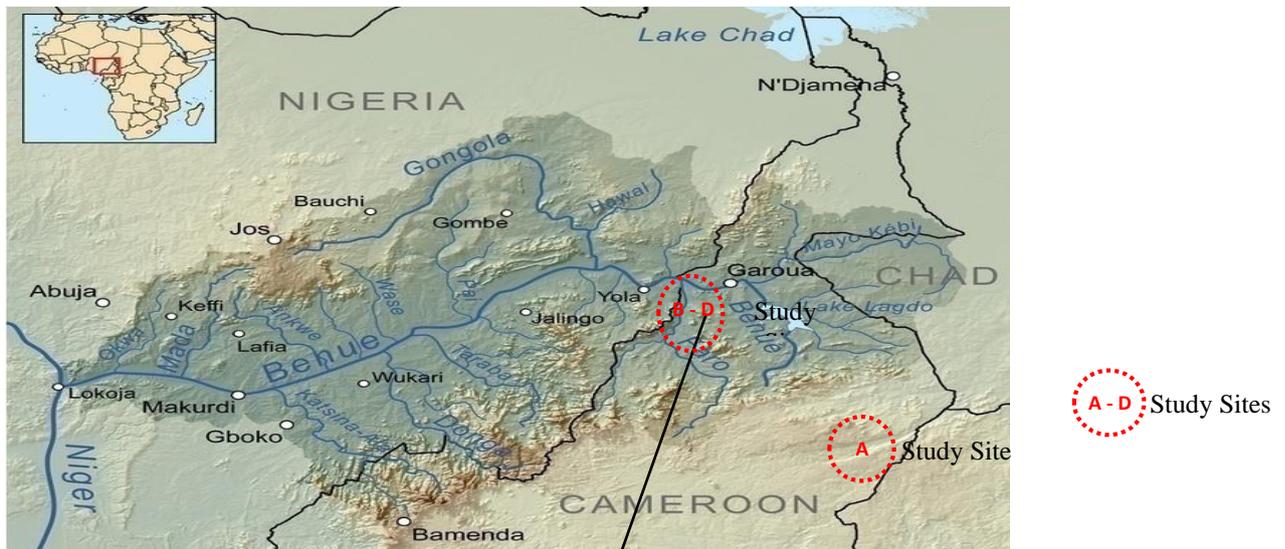


Figure 1. Earth Imagery Map of River Benue channel from the Headwater in Cameroon to River Niger in Nigeria

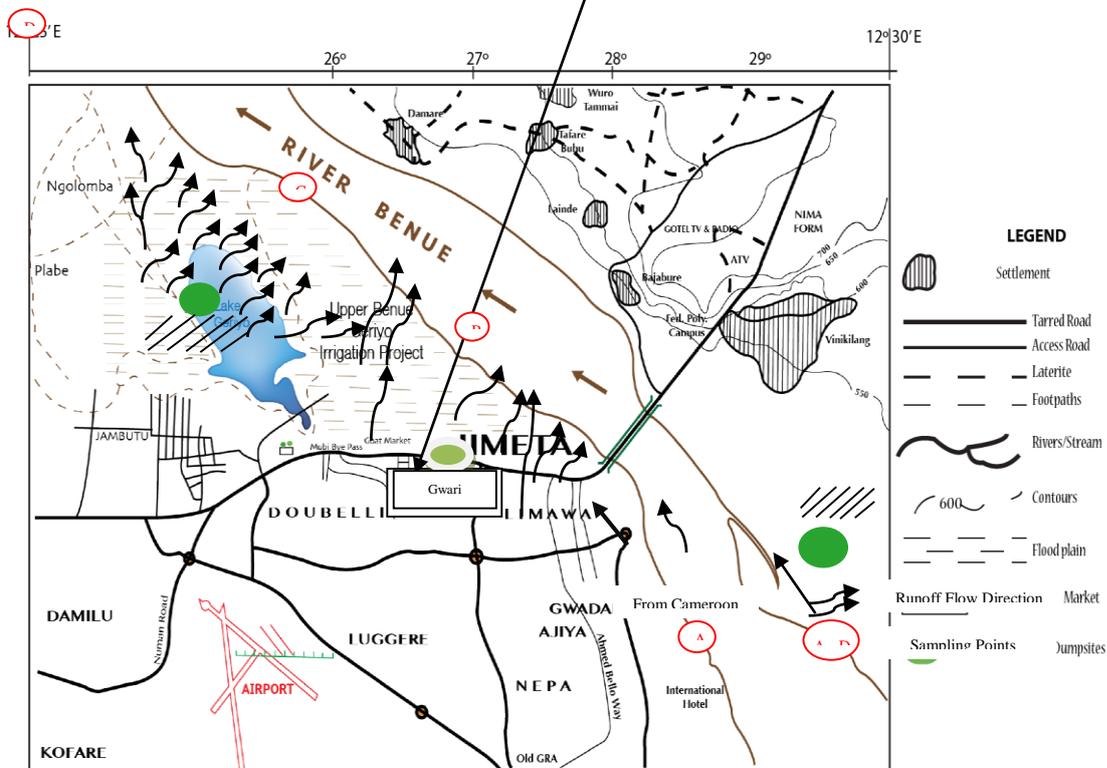


Figure 2. Topographical Map of Study site showing River Benue, Flood plain, Gwari Market Dumpsites, and Runoff Flow Direction

## 2.2 Sampling and Laboratory Analysis of Pollutant Concentrations

The water sampling stretched over a distance of 1.5 km covering the research area where the effect of pollution from decayed vegetable waste dumpsites is greatly felt. Water samples were collected at three locations (B-D): upper stream, the middle, and the lower stream at interval of 500 m to 1.5 km mark. Water samples were also collected from the source of this river (A) in the Northern part of Cameroon. At each sampling point, water sample was collected at a depth of 5 – 10cm below the surface in separate pre-conditioned and acid rinsed clean polyethylene sampling bottles of 1 litre with screw cap covers; soaked overnight with diluted hydrochloric acid and rinsed twice before filling the bottles. The collected samples were filtered using vacuum pump and 0.22 micro size string filters then acidified with concentrated nitric acid to a pH below 2.0 to minimize precipitation and adsorption on container walls. For the determination of total heavy metals in the samples extraction, a procedure as described in [8] was followed. Heavy metal concentrations were determined in acidified filtrate water samples by the use of Atomic Absorption Spectrophotometer (AAS 500). Other conventional pollutants in the water samples were also determined.

## 2.3 Mathematical Model Formulation

The Fickian advection-dispersion approach employed in this paper was based on the convective-dispersive mass transport in the running waters. The mathematical tool is the fundamental advection-dispersion equation (ADE) for pollutant transport in surface waters. Pollutant transport model developed in the framework of this study was also based on one-dimensional (1D) form of ADE because most rivers in practice are considered as horizontal linear networks of segments or volume elements, especially for long, narrow and shallow rivers. River Benue runs a course of 1402km; therefore, a 1D transport model is appropriate for this study because it is a flowing not a stagnant water bodies where a 3D transport model is used. For longitudinal direction which takes into account pollutant sources and sinks along with its transport can be described by the principle of mass conservation and Fick's Law as follows: (SI units are used).

$$\frac{\partial c}{\partial t} = \frac{\partial(cV_x)}{\partial x} + \frac{\partial}{\partial x} \left( D_x \frac{\partial c}{\partial x} \right) + S_s \pm S_t \quad (1)$$

$$\text{and,} \quad \frac{\partial C}{\partial t} + \frac{1}{A} \frac{\partial}{\partial x} (AUC) - \frac{1}{A} \frac{\partial}{\partial x} \left( AD_x \frac{\partial C}{\partial x} \right) = R_x + q_r \quad (2)$$

The evolution of pollutant concentration  $c$  (mg/L) in time  $t$  (s) along the river  $x$  (m) is influenced by the convective velocity of water  $V_x$  (m/s), which carried the pollutants downstream, and by the longitudinal dispersion coefficient  $D_x$  ( $m^2/s$ ), which is responsible for the pollutant spreading all over the river channel.  $S_s$  (mg/L) stands for pollutant sources e.g. dumpsites, and  $S_t$  (mg/L) represents pollutant transformations during transport.  $D_x$  stands for the combined effect of diffusion (mixing produced by the Brownian motion and turbulences), dispersion coefficient (spreading enhanced by variations of velocity across the stream),  $A$  = cross-sectional flow area perpendicular to the flow,  $U$  = cross-sectional velocity,  $R_x$  = rate of

reaction of pollutants,  $q_r$  = rate of external addition of effluent,  $\partial c$  = change in concentration,  $\partial x$  = change in direction [9].

The mass balance and dispersion governing equations (1) and (2) were derived with assumptions given as follows [10]:

- i. The velocity across the river section is uniform while the water level is horizontal.
- ii. Small streamline curvature and vertical accelerations are negligible; hence the pressure is hydro-static.
- iii. The effect of boundary conditions is accounted for through laws analogous to those used for steady state flow.
- iv. The average bed slope is small so that the angle it makes with the horizontal can be replaced by unity.

The dispersion coefficient  $D_x$  was determined by considering the source/sink term in equation (1).

$$D_x = 64.K_1.n.\left(\frac{Q}{A}\right)H^{5/6} \quad (3)$$

Where  $Q$  = volumetric discharge ( $m^3/s$ ),  $H$  = hydraulic depth,  $n$  = Manning's friction coefficient, and  $K_1$  = an empirical coefficient. Equations (1), (2), and (3) form the mathematical basis for this model. The fundamental aspects of these equations that relate to pollutant transport in rivers, its modelling support, and parameters are discussed below.

### 3 RESULTS AND DISCUSSION

#### 3.1 Analysis of Heavy Metals and other Pollution Parameters in Water Samples

The results of heavy metals analysis in water samples collected from River Benue in Yola and Cameroon Mountains where the river took its source are presented in Table 1. From the results, all Zn, Cu and Mn values fall below the maximum permitted limits of 3.0 mg/l, 1.0 mg/l, and 0.5 mg/l. But all Fe concentration levels exceeded the stipulated limit of 1.0 mg/l by far; Cd was not detected in samples A and B while samples C and D were above the reference level of 0.003 mg/l. Pb was not detected in all the samples, but all values of Ni were above the permissible standard value of 0.02 mg/l which can lead to possible carcinogenic cases in the environment. Cr concentration values were all above the desired limit of 0.05 mg/l, while Co levels in the four samples fall below the threshold reference value of 0.1 mg/l. The presence of  $NO_3^-$  values in the river was also below the permitted limit of 50 mg/l and pH values recorded were within the tolerance limit of 6.5 - 8.5; only sample C was acidic. This implies that for consumption, it can be hazardous to human health and favours corrosion of pipelines used for irrigation.

Table 1. Results of Analysis of Water Samples from River Benue at Yola and Cameroon in (mg/L)

Samples	Zn	Cu	Mn	Fe	Cd	Pb	Ni	Cr	Co	NO3	pH	Turb. (NTU)
A	0.46	0.21	0.023	24.6	0	0	0.052	0.253	0.049	10.5	8.29	315
B	0.31	0.23	0.066	19.33	0	0	0.061	0.096	0.048	10.5	7.8	158
C	0	0.09	0	1.78	0.009	0	0.082	0.071	0.039	7	6.46	7.53
D	1.107	0.77	0.023	13.06	0.004	0	0.053	0.081	0.044	7	7.84	171
WHO (2007)	3	1	0.5	1	0.003	0.01	0.02	0.05	0.1	50	6.5-8.5	5

A – Water sample collected from Cameroun Mountains, the source of River Benue;

B – Water sample was collected at 500 m away from under the bridge at Yola; (wstream)

C – Water sample as collected at 1000 m away from the bridge (downn stream);

D – Water sample collected at 1500 m from the bridge (downstream).

All results obtained were compared with the World Health Organisation Drinking Water Quality Standard [11] indicated in Table 1.

### 3.2 Model Implementation

$f(c, x)$  represent  $(y)$ ; where;  $c$  = concentration of pollutants (mg/l), and  $x$  = distance travelled in water (m). The values of the model input parameters are:  $c$  = [1, 2, 5, 6] in mg/l;  $x$  = [300, 500, 1000, 1500] in meters;  $S$  = 0.03, slope of area;  $t$  = [5, 10, 20, 30] in minutes;  $D_x$  = 0.5 (coefficient of dispersion); Water discharge = 450 m<sup>3</sup>/s; Width of river = 900 m; Hydraulic depth of river = 5 m at time of study; Manning's coefficient = 0.035

The application of this method to the governing equations of the present model and differentiation; accounting for the fact that the limits of derivation are functions of spatial distance and time in Matlab yields the following working solutions:

$$\frac{\partial c}{\partial t} = D_x V \frac{\partial}{\partial x} \left( \frac{\partial c}{\partial x} \right) + S \quad (1)$$

$$y = D_x V * \text{diff}(\text{diff}(c, x), x) + S - \text{diff}(c, t)$$

From the model, the pollutants changed direction of flow at 500 m, 1000 m, and 1500 m marks. It took contaminants 5 minutes to travel a distance of 500 m and 15 minutes to travel a distance of 1.5 km down the river indicated in (Fig. 3) at a velocity of 0.66m/s. The simulation showed pollutants' concentration levels at different distances with respect to time. The implication of change in direction is that there was dilution of pollutants as a result of contact with upper and lower water parcels at those points and mixing of pollutants with sediments as sinks due to deposition effects.

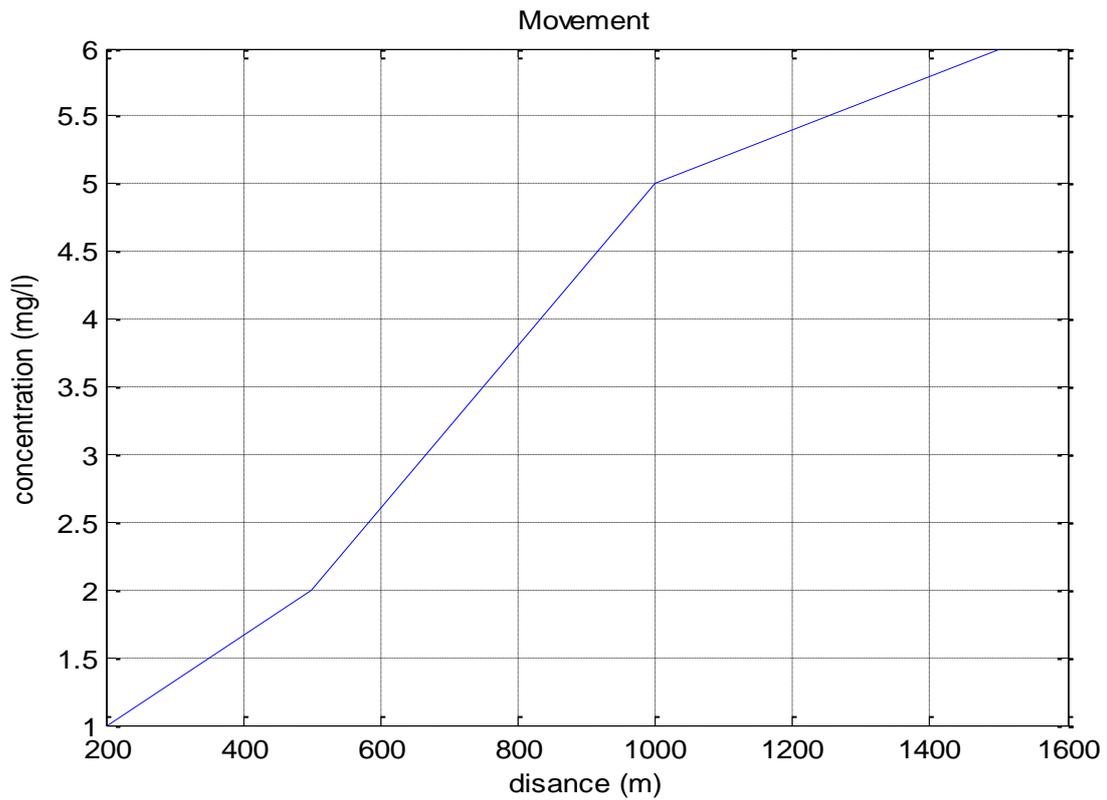


Figure 3: One-Dimensional Flow Model Predicting the Pollutants Transport in River Benue

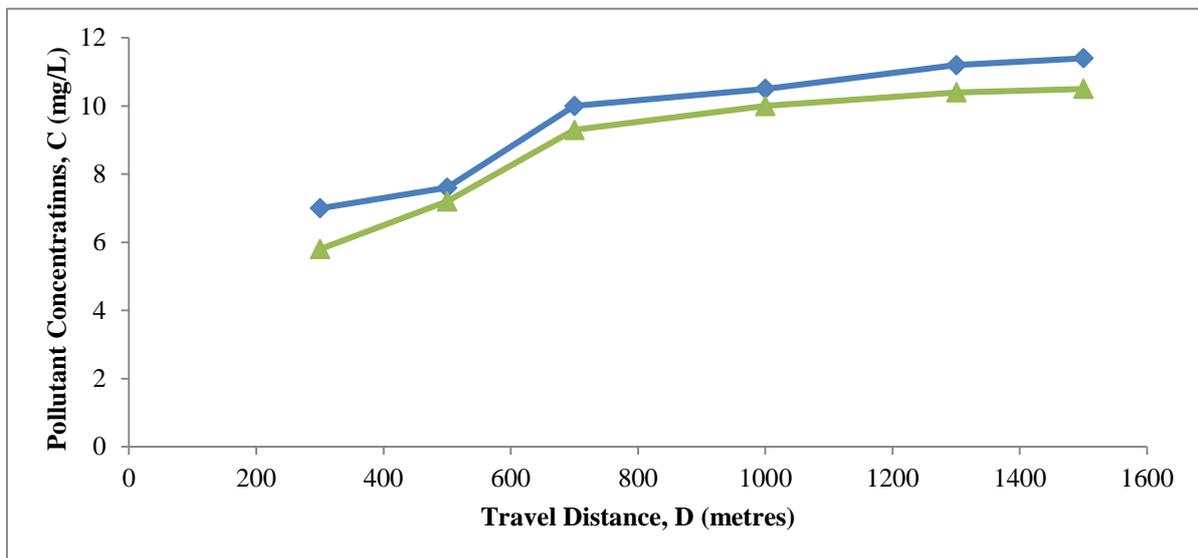


Figure 4: Observed ( $y_2$ ) Vs Simulated ( $y_1$ ) Pollutant Concentration Curves Downstream

Validation of the model was performed by comparing the measured (green) and predicted (blue) concentration curves which showed reasonable agreement in the general shapes of the curves (Fig. 4). Inspection of the simulated pollutant concentrations ( $y_1$ ) indicated

that the model over estimated observed natural values ( $y_2$ ), especially at peak values. The observed and simulated curves have somehow close identical flow pattern. This explained why most rivers in practice are considered as horizontal non-linear networks of segments or volume elements, especially for long, narrow and shallow rivers. It further buttressed the fact that a one-dimensional transport model is appropriate to this river under study.

#### 4 CONCLUSION

A mass balance mathematical model was used for predicting pollutant transport in River Benue of Yola with the help of a user friendly Matlab package; and analysis of chemical contaminants was performed in the laboratory. Most of the heavy metal concentrations discovered were above the international requirements and the model simulated a one-dimensional non uniform linear flow pattern of pollutants with an estimated velocity of 0.66m/s through a distance of 1.5 kilometers down the river. The model was validated using the experimental data and simulated concentration data which indicated good agreement in the shapes of the concentration curves. These findings can help to curb pollution problems and take correct management decisions on the Benue River more especially during emergency water pollution cases along the river.

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