GROUNDWATER RESOURCES FOR SUSTAINABLE DEVELOPMENT OF THE LAKE CHAD BASIN. THE CHARI-LOGONE STUDY AREA

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Abstract

The lake Chad basin is an inland drainage system extending over an area of about 2,355, 000 km^2. situated in the eastern part of the Sahel region of Africa, and its active basin constitutes and important freshwater resource for the neighbouring countries. The surface area of the lake varies considerably with the amount of annual rainfall and run-off, and it is the fourth largest lake in Africa. In 1960s, the lake extension was 25,000 km^2; presently it has been reduced to about 2,000 km^2. According to literature, water balance in the lake shows a close interaction between rainfall, evaporation, lateral inflow and groundwater. The Chari Logone system is the most important water supply to the lake supplying over 92% of the inflow into lake Chad. In 1997 and within the framework of UNESCO-PHI and the BMZ financial support, a project on the management of groundwater resources in the Chari-Logone catchment started with the following objectives:

-knowledge and quantification of water recharge in the underlying aquifers under three climatic scenarios (medium, dry an humid)

-evaluation of aquifer recharge from floodplains and surface water

-proposal of management systems through a simulation model

-proposal of regulatory issues for aquifer protection

The project has carried out a new wells inventory and several sampling campaigns for quantity and quality groundwater characterisation and recharge evaluation and a groundwater modelling is now on-going for water management proposal

1 INTRODUCTION

The studied region is located SW of Chad, extending over 96.000 km^2 from forested savannah in the South to spiny shrubbed savannah in the North. The study area considered is located in the Lake Chad basin –South of the lake-, between coordinates 8º 12’ and 12º 02’ N latitude and 14º 06’ and 18º 45’ It is primarily located in Chad, extending from N’Djamena to the north and Doba and Sarh to the south. It also extends along the floodplains of Wasa in (Cameroon). Population is primarily rural and is about 6,5 million inhabitants.

The plain relief is formed by clayey soils in the North and laterite deposits in the South, which become periodically flooded from July to December.

The region's climate is characterized by high special variability, conditioned by the tropical continental air mass (The Harmattan) and the marine equatorial air mass (the Monsoon). As a result, the North of Djamena has a semi-arid climate while the south is humid. Annual rainfall oscillates between 400-600 mm.yr to more than 1,000 mm.yr. Most of the rainfall occurs between April and October. Average temperature varies between 33ºC and 24ªC. The Chari and Logone rivers are responsible of 95% of inflow to lake Chad. The flat topography of the area is responsible for the formation of floodplains from July to December.

The present study characterises the groundwater hydrology of the existing aquifers in the area in a generalist hydrogeological approach. A special emphasis has been placed on the upper aquifer characterisation, which basically sustains the region, and the generation of a numerical groundwater flow model. Special emphasis has being made to evaluate and quantify water recharge under dry, moderate and wet periods. With the objective of improving the geological, hydraulic and hydrochemical knowledge of the aquifer system, 7 new wells were dug and another 10 old wells were rehabilitated within the framework of project 507/RAF/45 (Mpondo and Saleh, 2000).

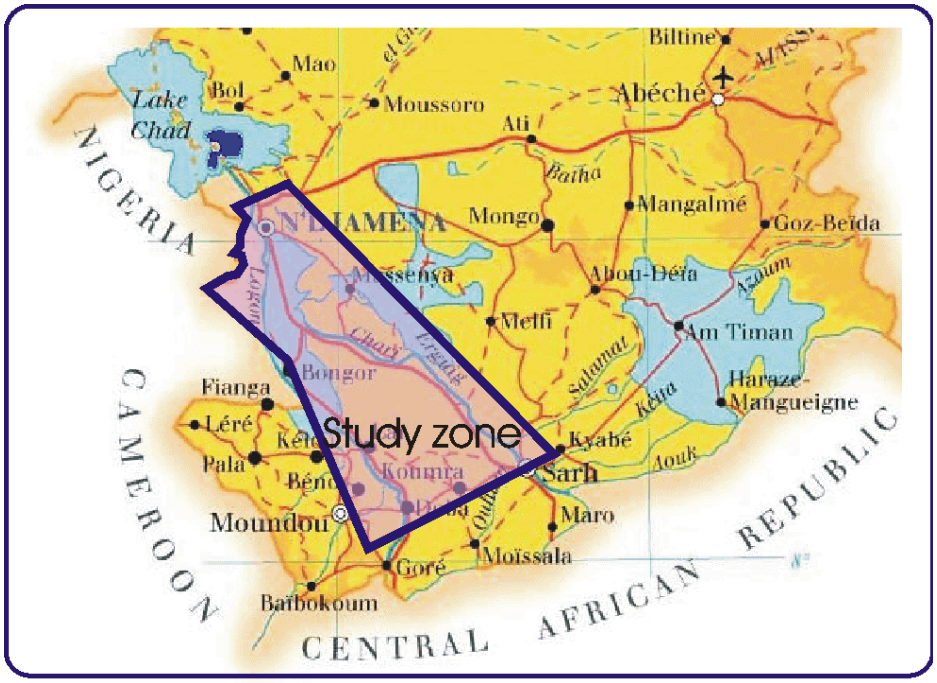

Figure 1. Geographic location of the study area (Almagro, 2002).

2 GEOLOGICAL SETTING

The project area is located in the graben region of Chad, which predate the Upper Jurassic period. Depth to Precambrian bedrock (granite, migmatite, gneiss, schist, etc) increases towards the west, where it is found at a depth of more than 1000 m. In N'Djamena, the Precambrian bedrock is at a depth of 550 m, as determined by geophysical methods.

The stratigraphic sequence, which fills the Chad graben is constituted by sediments of Precambrian age, Mesozoic deposits (Cretaceous), Cenozoic deposits (Oligocene–Miocene and Pliocene) and Quaternary deposits. Only the Tertiary and Quaternary deposits in the study area are of hydrogeological interest, and a special emphasis is placed on their description

The principal event of the Mesozoic period, in the region, is the formation of the Chad graben, covered with alternating sequences of sands and clays deposited in a freshwater environment.

The sedimentation of the lower Cretaceous was predominantly continental, while .the upper Cretaceous have two facies composed by , fine and coarse sands, with traces of clay (the eastern part of the Doba and Salamat grabens) and reddish and grey clays, located in the Doba graben.

The Tertiary formations (Oligocene-Miocene) present in the project area are all of continental origin. The sediments which cover series of the upper Cretaceous and which have a special importance in the project are referred to, in this report, as *Terminal Continental*. *Terminal Continental* are made up of heterogeneous sandy sediments, clayey sandstones and sandy clays outcropping to the South of the region (Sarh, Doba, Moundou).

The Lower Pliocene is constituted by sandy deposits of reddish colour; the thickness may reach up to 200m. The middle Pliocene deposits, up to 30 m, are of clayey lacustrine origin with some sand episodes, and the upper Pliocene are made up of strata of clays with sand intercalation; they may reach up to 300 mm thickness

The Quaternary deposits are of continental origin and fill the open grabens. They are made up of fluvio–lacustrine sands, fluvio-deltaic and eolian deposits, and kaolinite clays or clays from neoformation.. The lower Pleistocene corresponds to the coarse sandy deposits that cover the clayey Pliocene sediments towards the centre of the Chad graben. In the southern third of the area it corresponds to the clayey sediments of the *Terminal Continental* (Schneider, 1989). The middle Pleistocene deposits in the region are related to wet episodes and to European glaciation, and are made up of sands, sandstones, clays and diatomites. The upper Pleistocene is made up of weathered lacustrines, and in an arid environment, made up of clays, diatomite, gypsum and sands. The Holocene, is prepresented by a humid period (Lower) during which where relatively extensive lakes formed in inter-dune spaces (Mpondo, and Saleh, 2000). In the middle Holocene a vast lake with a surface area of 350,000 km^2 was formed, in Chad (Schneider, 1989).

3 GROUNDWATER HYDROLOGY OF THE AQUIFER SYSTEM

In the region three aquifers have been identified (Fig. 2):

-The upper aquifer, which behaves as phreatic and semi-confined, extends throughout the entire project area and consists of Quaternary and Terminal Continental deposits.

-The intermediate aquifer, corresponding to the Lower Pliocene deposits, which extends from Bongor (on the 10^{th} parallel) to the North, confined by the upper and intermediate Pliocene clays.

-The deep aquifer, corresponding to the Terminal Continental deposits, present from Bongor to the north, separated from the intermediate aquifer by clay facies.

It should be noted that there are local perched aquifers of limited extent and storage capacity to the north of Chari, located at depths of up to 20m. According to Schneider (1989) they developed as clay lenses intercepted infiltrating rainwater and in places river water (the Chari River in Bousso Goneri, Djemena Gide and Guelengdeng)

3.1 Upper aquifer

Quaternary deposits

The Quaternary aquifer consists of formations made up of eolian sands of the upper Pleistocene and of fluvial sands of the lower Pleistocene. The thickness of the deposits is highly variable and there are diverse inter-stratifications of clay lenses (Fig. 2). The frequency of occurrence of clay lenses increases towards the centre of the project area (Bongor and Goueye Loura. The thickness of the Quaternary sediments increases towards the centre of the basin, reaching almost

190 m to the northeast of lake Chad. The alluvial deposits that accompany surface water streams in the south of the region are also associated with the Quaternary.

The fluvial and eolian Quaternary deposits, are exploited in the region by wells, which in general do not exceed 60 m, and have specific flow rates around 1 to 5 $m^3/h/m$. Transmissivity values are in the order of hundreds of m^2/d values from Schneider (1989) and the pumping test being carried out in Guedeleng. The basement of the superficial aquifer is Pleistocene.

The upper limit of the Quaternary sands, dips towards the north. It reaches depths of 30 m in Bousso, depths of 60 m near N'Djamena to the centre of the region, and depths of 150 m to the north of lake Chad.

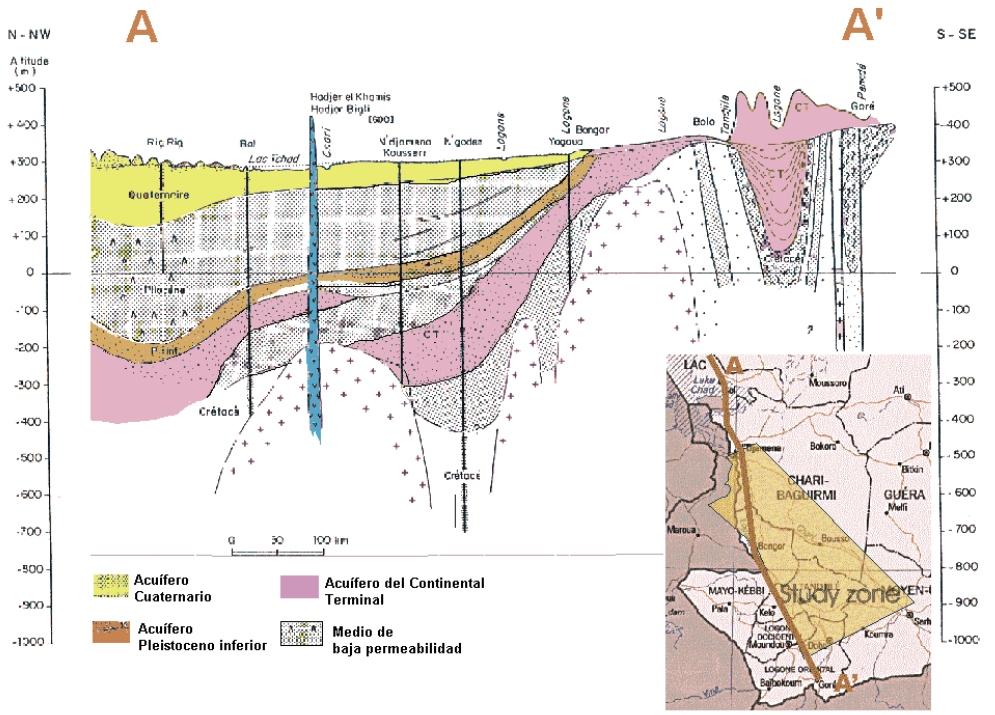

Figure 2. Cross section of the study area showing the existing aquifers (after Schneider, 1989).

Aquifer in Terminal Continental deposits

Between the cities of Bongor – Bousso and the crystalline massif in the Central African Republic the superficial aquifer is in Terminal Continental deposits except for a narrow fringe which is in Lower Pliocene deposits. It consists of a sandstones, clays and conglomerates, with a certain generalised hydraulic behaviour. To the southeast of the project area, near Salamat, the contact between the Quaternary and the Terminal Continental deposits is between 10 and 15 m depth. In the extreme east of the Salamat graben, the crystalline basement is at a depth of 181 m and the contact between the Quaternary and the Terminal Continental occurs at a depth of 32 m. Greatest transmisivity occurs in the Koros area and Mayo Kebbi region (1500-5000 m^2/d)

3.2 Intermediate aquifer

It behaves as a confined aquifer system and consists of a succession of sands, silts and clays, which extend over the northern half of the study area from the city of Bongor. Its upper limit is formed by thick layers of middle and upper Pliocene clays, which separate it from the sands of

the upper aquifer. Its base is made up of Terminal Continental clays and clayey sandstones. The upper limit is found at a depths from 60-270 m .The thickness of the layer of aquifer sands of the lower Pliocene, varies from 35 to 90 m to the north of lake Chad .To the north of the project area, there is confined groundwater flow coming in from Nigeria, with artesian characteristics beneath lake Chad

3.3 Deep aquifer

In the project area, the deep aquifer is in *Terminal Continental* deposits, which extend from the crystalline massif in the south of the region to the north, increasing in depth as far as the city of N'Djamena In general this system consists, basically, of sandy deposits with a thickness of approximately 100 m, reaching as much as 600 m in the rifts. The upper part is the most productive with a thickness of 40 to 60 m of sands, overlying a clay lens of more than 250 m with intercalations of continental sandstone.

In the region of the Koros (Doba, Kome and Damalla) to the South, oil well drillings have determined the presence of thick sandy layers at a depth from surface of less than 400 m. Wells that penetrate between 50 and 100 m of these sands have a production of 200 m^3/h. This zone forms the recharge area of the deep aquifer.

The specific flow rate from wells in the Terminal Continental deposits are less than 1.2 m^3/h/m and diminish to the east of the region, while those that exploit the intermediate aquifer reach values of 10 m^3/h/m. The scarcity of data pertaining to the lower aquifer prohibits establishing its hydrogeological characterisation

4 PIEZOMETRIC SURFACE

Upper aquifer

In general, the upper aquifer shows N – NE direction, from the high-lying areas of the south, towards the east of lake Chad (Fig. 3). The southern margin of lake Chad acts as a discharging area to the upper aquifer, as does the Chari River. In its entirety lake Chad acts as a temporary reservoir that intercepts laterally, retards and redistributes the groundwater flow of the superficial aquifer. The Logone River also feeds the upper aquifer through its riverbed and delivers water to the aquifer from the floodplains that cause it to overflow. Rainy periods where rainfall deficiencies occur have been recorded, which result in continuous drawdown of the piezometric surface, as is the case of the plain of Bir Louri where the piezometric surface has dropped 2,5 m in 20 years.

In the framework of project 507/RAF/45 two campaigns of measurements of piezometric heads have been conducted, one in 1998 and another in 1999. When compared there appears to be a tendency towards recuperation of head levels towards the end of the 1990's**,** this behaviour is explained by the fact that the rains of 1997 to 1999 provoked some of the largest floods for many years, both in extent and duration. The oscillations of the piezometric surface reflect the seasonal contribution of rainfall and surface water contributions. In Douguia, the piezometric oscillations can reach 3,60 m between November and July.

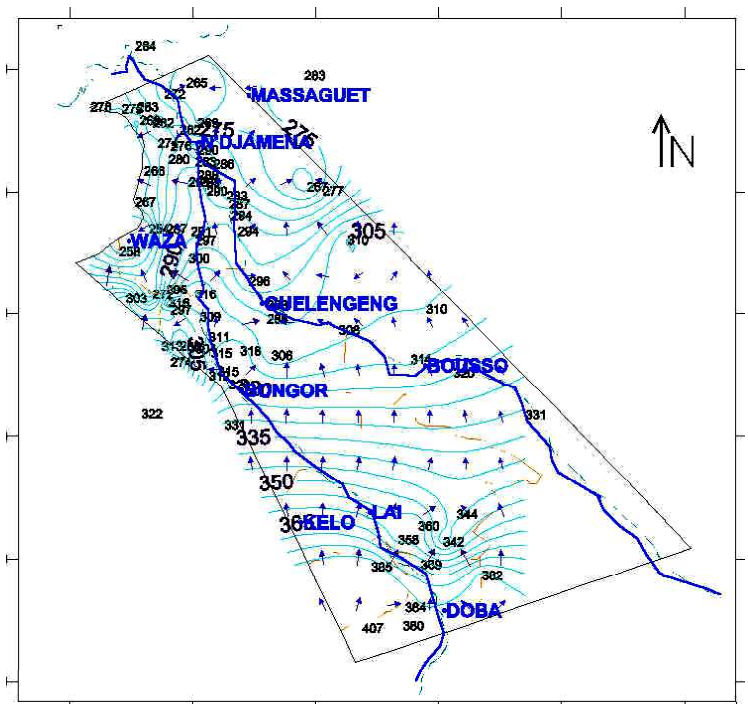

Figure 3. Piezometric level of the upper aquifer (Almagro, 2002)

5 WATER BALANCE

Various hydraulic balances have been conducted in the study area, assuming three characteristic periods: dry, intermediate and wet. The year 1984 is taken as representative of a dry year, 1989 of an intermediate year and 1994 of a wet year (data from both the N'Djamena and Sarh meteorological stations). However, validation of the results from this study is made impossible due to the lack of available histograms. The lack of piezometric head levels also inhibits establishing variations in storage of the region's aquifer.

In the north of the project area the predominant sources of recharge are contributions from the sandy beds of the surface water sources, which far outweigh the contributions from precipitation events, as minimal infiltration occurs. In contrast, to the south of the 12th latitude, rainfall exceeds 1100 mm/year and both the slope and the nature of surface materials favour rainwater as the major source of recharge. The influence of rainwater on recharge is only observed in areas in which eolian sands cover the surface, and where the depth to piezometric surface is less than 15 m with respect to the land surface (BRGM, 1994).

The lateral discharge of the upper aquifer was determined based on the piezometry of the year 1999, a value that had to be assumed constant in the hydrological balances of 1984, 1989 and 1994.

In the arid zones, certain factors characteristic of regions where soil and air humidity are very low should be considered. A strong decrease in humidity can provoke considerable evaporation from depth across the unsaturated zone. This phenomenon, called exfiltration, has been quantified in the unsaturated zone by means of O^{18} and H^{2+} isotopic balances. Rates were estimated for a sandy medium, where rates of 1 to 900 mm/year for depths of 10 m to 0.25m respectively were calculated (BRGM, 1993).

Table 1. General results of the balance of the upper aquifer (average year).

Recharge by rainfall in the southern zone (Sarh	30 hm3/yr	*Lateral discharge of the aquifer*	70 hm3/yr
Recharge by rainfall in the northern zone (N'Djamena	55 hm3/yr	*Pumping extractions*	34 hm3/yr
Lateral inflows to the aquifer	10,6 hm3/yr	. *Phenomenon of exfiltration*	40 hm^3/yr
Vertical inflows from the Lower Pliocene aquifer	*73* hm3/yr		
Total recharge	***169* hm3/yr**	***Total discharge***	***141* hm^3/yr**

6 CHEMICAL CHARACTERISTICS OF WATER

The hydrochemical characterization of the region has been based on the analysis of water samples from two groundwater sampling-campaigns conducted within the framework of the present project. The campaigns were conducted between May and August 1998, and between January and May 1999; at the end of the dry season, at the end of the wet season. In each chemical sampling campaign the following 'in-situ' determinations have been done: Temperature, Electrical conductivity, pH, Total alkalinity, Nitrates (colorimetry)

A total of 100 and 114 water samples were analysed in the first and second campaign. Major ions were determined in the Laboratory of Applied and Exact Sciences in N'Djamena. In addition, 75 samples were analysed for ^{18}O and Deuterium determination and 58 for the determination of Tritium. Isotope analyses were conducted in the IAEA, in Vienna.

Upper aquifer

Water of the upper aquifer is a calcium/sodium bicarbonate type of low mineralisation, with a dry residue of less than 500 mg/l. The electrical conductivities in the south central region are in the order of 150 µS/cm increasing towards the north, to average values of 350 µS/cm and which exceed 900 µS/cm to the north of N'Djamena. The high conductivity values to the North are associated with higher concentrations of recharge water due to greater evaporation of flood rainwater and due to the hydrolysis of calcium carbonates present in the fine sediments that cover the aquifer in the northern part of the region. In the eastern part of the region, the chemistry reflects the absence of flood areas, resulting in the fact that waters of this area have a higher mineralisation.

The predominance of recharge waters from the Logone and Chari rivers, near their channels is reflected in the fact that one sees an increase in sodium concentration of the groundwater the further the monitoring stations are from the rivers.

To the west of N'Djamena, the water becomes a sodium bicarbonate type, and has the highest concentrations of ions of the region. This western zone is also the area with the greatest thickness of Quaternary deposits. At the centre of the region, in Bousso and Bongor the water of the upper aquifer is particularly poorly mineralised, with dry residue of less than 100 mg/l, due to lixiviation of deposits from a wetter a period of the Pleistocene.

Aquifers adjacent to the upper aquifer (Lower Pliocene, Terminal Continental and crystalline bedrock)

The hydrochemistry of the Lower Pliocene aquifer is characterised by a sodium bicarbonate water type of high mineralisation, with electrical conductivities between 600 and 800 µS/cm and which increase in direct proportion to the depth of the aquifer. The pH however diminishes with depth oscillating between 6.7 and 7.4. The temperature of the water is elevated and varies between 36 and 41ºC.

The mineralisation of the *Terminal Continental* aquifer increases towards the North of the project area, going from a sodium/calcium bicarbonate water type with a conductivity in the order of 150 μS/cm to a strongly sodium bicarbonate water type with conductivities of more than 1200 μS/cm.

Due to the dearth of chemical analysis in the south of the study area the analysis given by Schneider (1989) for the region of the Koros is used. In the study by Schneider (1989) the water of the upper aquifer (*Terminal Continental*) is characterised as one of low mineralisation, with a dry residue lower than 100 mg/l, it is of a calcium bicarbonate to sodium calcite water type with elevated acidity and corrosiveness. The low content of chlorides in the upper aquifer, with an average of 2 mg/l, is indicative of the continental origin of this water. The greatest concentrations of this ion are near the city of N'Djamena, with values of up to 80 mg/l. In general, the water of the upper aquifer has a neutral to basic character in particular along the Chari and Logone river systems and in clay regions where the possible existence of fossils could add to the carbonate content, making the system more basic.

The temperature of the water of the lower aquifer is affected by the geo-thermal gradient and varies from 29ºC in the south of the region to 46ºC in the north. The water of this aquifer is strongly basic, with pH values greater than 8.0. To the west of N'Djamena, in the Kousseri well, evidence of sulphate reduction was recorded. The high concentrations in Na^+, HCO_3^- and SO_4^{2-} of the water are associated with arid phenomena during different periods of the Miocene and of the Pliocene.

7 MODELLING OF THE STUDY AREA

In the mathematical model two aquifers are considered:

a) The upper aquifer: the quaternary deposits.

   This is considered as a phreatic aquifer. Its upper part is the topographic surface and its bottom the thick layers of middle and upper Pliocene clays.

b) The lower aquifer: the lower Pliocene and the terminal continental deposits.

This is considered as a confined aquifer. Its upper part is the bottom of the thick layers of middle and upper Piocene clays. Its bottom is the Cretaceous, Primary and Continental Terminal formations.

For the sake of simplicity, as a first approach, these two aquifers have been simulated independently, using only a bi-dimensional layer for each one. The water charges are considered constant in depth for each aquifer. This simple approach is consistent with the data showing that depth flows are irrelevant against the lateral flows between formations or against the connection of the upper aquifer with the atmosphere.

This model is implemented with the Visual Modflow software, which uses a finite difference approach to simulate groundwater hydrodynamics'. In this case a telescopic grid has been used, focusing to have a more detailed grid on the areas with higher piezometrics gradients. The limits of the model are defined from the whole Chad lake basin.

In this preliminary simulation phase, one of the main objectives was to identify and to quantify the main factors for the piezometric levels in the aquifers. This has been obtained with a sensitivity analysis on stationary conditions. Later on, a calibration phase on transitory conditions has been developed.

In the near future, a quasi-three dimensional model is going to be developed, trying to analyse deeper the connections in between the different formations.

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