

# State of knowledge of coastal aquifer management in South America

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**Abstract** A comparative analysis of the existing hydrogeological and management information from 15 coastal aquifers in South America was performed in order to obtain insight into common features of the sub-continent coastal zones. Some knowledge from other areas has been incorporated. There is a very variable degree of knowledge and management practice, ranging from almost no data and no action (the most common case), to sound conceptual models about aquifer behaviour and comprehensive management actions such as relocation of abstractions, pumping brackish groundwater, and aquifer vulnerability mapping. Some common features are: intensive groundwater exploitation; lack of characterization studies to support resource planning and management; lack of monitoring networks; and the need for raising awareness within society and its involvement in resource planning and management action programmes. Quality and quantity problems arising in heavily populated areas associated

with coastal aquifers in South America point to unsustainable groundwater development. The sustainable use of those aquifers must rely on adequate evaluation of aquifer characteristics and monitoring.

**Keywords** Coastal aquifers · South America · Conceptual models

## Introduction

South America has a wide variety of aquifer types, ranging from small aquifers of only local interest, although sometimes of crucial importance, to huge, barely known, slightly exploited, continental aquifers. Coastal aquifers are an important resource and play a key economic and social role in most countries, since most of the population and economic activity lies in coastal areas. Large cities like Buenos Aires (Argentina), Lima (Peru) or Santiago (Chile) rely largely on groundwater, but so too do many other smaller cities (like Mar del Plata in Argentina), towns and industrial areas. Groundwater is also important for water supply in rural areas devoid of other reliable water sources. Groundwater use in agriculture is not as dominant as in other areas of the world, but locally may be the key resource. Rebouças (1999) plotted areas with significant use of groundwater in South America by the end of the twentieth century, some of them lying in coastal areas. Although comprehensive data about groundwater use in South America coastal aquifers are not available, local estimations allow for extrapolation of relevant general information. Morris et al. (2003) report that in Argentina, Brazil and Colombia drinking water derived from groundwater ranges from 25 to 50%, while in Chile, Peru, Venezuela, Suriname and The Guyanas it ranges from 50 to 100%.

During the last 40 years, groundwater use for agriculture and industry has exponentially increased in developed and rapidly emergent economies. The process has not been accompanied by monitoring, controls and management action to avoid water pollution and depletion. A generalized consequence is groundwater quality deterioration, which is mostly a result of excessive exploitation, inadequate protection at the land surface and major changes in land use. In coastal aquifers increasing drawdowns often cause salinization.

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The goal of this paper is to present a general overview of the current situation in coastal aquifers in South America in terms of hydrogeological characteristics, main problems, studies, and management efforts that are being conducted, and also some future prospects. It was prepared on the basis of a comparative analysis on 15 coastal aquifers, selected on the basis of readily available published and personal information, and regional importance (Fig. 1). The work was conducted in the framework of the IGCP 519 UNESCO Project, which is still under way.

There is a widely differing degree of knowledge and management, ranging from almost no data and no action (the most common case, comprising a variety of aquifers like Ica in Peru, The Guyanas, Galapagos Islands in Ecuador and Easter Island in Chile), to sound conceptual models about aquifer behaviour and management practices, like relocation of abstractions, pumping brackish groundwater, or aquifer vulnerability mapping (which is the case in Mar del Plata, and Urabá Aquifer in Colombia). Some common features in terms of groundwater use, problems and management are: intensive exploitation (Morrosquillo and Santa Marta in Colombia, Mar del Plata and La Plata in Argentina, Raigón in Uruguay, and the northeastern coastal aquifers of Brazil); lack of characterization studies to support resource planning and management programmes; lack of monitoring networks and plans (all studied aquifers, with a few exceptions like Mar del Plata, Argentina and Recife, Brazil); and the need for raising the awareness and involvement of society in resource management, planning and action programmes. Quality and quantity problems arising in heavily populated areas associated with coastal aquifers in South America point to unsustainable groundwater development under present circumstances, but may be amenable and redressed. Although these may be considered worldwide problems, the comparison of selected coastal aquifers in South America is intended in the context of identifying the current state of knowledge and practices, weaknesses and challenges, to help in guiding sustainable groundwater management.

## Hydrogeological and climatic features

The Hydrogeological Map of South America (PHI 1996) identifies four main coastal hydrogeological provinces: the Atlantic Coastal Province, the Andine-Pacific Coast Province, the Pantanal-Chaco-Pampean Province, and the Patagonia Province. The Atlantic Coastal Hydrogeological Province stretches intermittently along the Atlantic coast, from Uruguay in the south of the continent, up to the north through Brazil, The Guyanas, Venezuela and Colombia, and Colombian Pacific coast. This province comprises discontinuous aquifer bodies, generally little consolidated or unconsolidated, clastic Cenozoic sediments of alluvial, fluvio-marine and aeolian origin, with fair productivity. The Barreiras Group is an example, stretching through over 4000 km in the Brazilian eastern and northern coast, with sandy to clayey sandy sediments of fluvial origin and irregular hydrogeological characteristics (Lucena et al. 2004).

The Pacific coastal aquifers of Colombia, Ecuador, Peru and Chile belong to the Andine-Pacific Coast Hydrogeological Province, whose aquifers are generally small to medium in size, and are located in alluvial and sedimentary formations of continental detrital composition, with conglomerates and sandstones amid the prevailing bedrock formations.

The central coastal strip of Argentina belongs to the Pantanal-Chaco-Pampean Hydrogeological Province. It features a wide variety of hydrogeological conditions, ranging from aquitard to medium-high aquifer permeability. Aquifers are confined to unconfined in character, continuous or discontinuous, consisting mostly of variable grain size sands, silt and loess. The Argentinean southern coast corresponds to the Patagonia Hydrogeological Province, with frequent salinization processes in the aquifer units.

Most of the South American Pacific coastline, especially in Chile and southern Peru, and a considerable portion of the Atlantic coast consist of crystalline/volcanic bedrock units with low permeability, limiting groundwater use prospects. Of great relevance is the presence of major coastal aquifers advancing seaward into marine platforms, because they may contain large volumes of fresh and brackish groundwater recharged after the last glacial maximum (some 10,000 years BP). This is the case of the Amazon and Paranaíba Sedimentary basins in northern Brazil, the Maracaibo Basin in Venezuela, and The Guyanas (Suriname-Guyana Basin). In the northern Pacific coast there are important aquifers in areas with complex hydrogeological structure, following an Andine tectonic and structural setting.

Global oscillations of seawater level and isostatic movements have spectacular registers in the South American continent geological history, studied since the nineteenth century (Schwartz 2005). Certainly these phenomena have exerted a major influence on salinity patterns in the coastal aquifers, as pointed out by some previous studies. Guerra and Sial (2003) and Guerra et al. (2005) suggest a marked effect of sea-level changes on the formation of beach rocks, present along most of the Brazilian shoreline, and whose cementation and control of solubility-precipitation of matrix carbonates is exerted by salinity changes due to sea-level oscillations.

South American coastal zones present a great variety of climates, ranging from areas with extremely dry climates such as coastal Peru and northern Chile, with average annual rainfall of barely 4–40 mm, to continental and Caribbean Colombian humid tropical areas receiving more than 8,000 mm per year. In between those climates there are humid temperate zones in southern Chile, dry areas in Argentinean Patagonia and fairly humid subtropical, tropical and equatorial climates from Argentina to Venezuela.

## Overview of the state of knowledge and management

There are many coastal aquifers in South America which are barely known. The lack of adequate, if any, monitoring and the absence of at least one preliminary hydrogeological study, is a common situation. And for those aquifers



**Fig. 1** Map of South America with the different countries and its capital cities, showing the 15 studied coastal aquifers and other mentioned localities. The areas correspond to the four hydrogeological provinces

having some information, frequently this preliminary study is in internal reports of public entities or in limited-distribution academic documents, and are not easily obtainable.

The hydrogeological characteristics recognized in more than a dozen studied cases allowed for classification of three main types of groundwater bodies: (1) large coastal aquifers of regional importance; (2) small clastic aquifers of local interest; and (3) aquifers in islands. Though the adjectives “large” and “small” are

relative and bear ambiguity, the classification is appropriate for the objectives of the article because small aquifers of local interest and insular aquifers, especially in small islands, usually face more acute salinity problems and stresses, and literature is more abundant. For large, poorly known aquifers, which cover large areas of Brazil, southern Argentina and the Pacific coast, management measures are far from being materialized since even their limits, potential and exploitation are unclear.

The classification is not intended to portray genetic aspects. The aquifers evaluated in the present article, though, allow for an insight of the groundwater management situation in South America, measures undertaken, perspectives and legal framework.

### **Large-extension coastal aquifers**

Most coastal aquifers that cover a large extent in South America lie within coastal sedimentary basins. They are geographically discontinuous and occur mainly associated with forearc depositional basins in the Pacific coast and with passive margin basins in the Atlantic coast. Intra-cratonic platforms and continental basins also touch and cross the present coastline so they may constitute coastal aquifers as well. There is a wide range of depositional environments, types of sedimentation and lithological types, leading to numerous aquifer units. Such units are: (1) multilayered-like detrital coastal aquifers of sandy or clayey silts and carbonate banks such as in Buenos Aires province, Argentina, a good example of which is Mar del Plata (Bocanegra et al. 1993; Bocanegra and Custodio 1995); (2) unconfined to confined sandstone aquifers, sometimes hundreds of meters thick with clayey and calcareous horizons such as in coastal areas of Brazil (Demetrio and Oliveira 2004), The Guyanas and Suriname (Groen et al. 2000); and (3) detritic alluvial aquifers with variable depth with confined sands and gravels such as in Peru, as the Ica aquifer (Tovar Pacheco et al. 2006).

The main common feature for these aquifer areas is competition for land and water between urban, industrial and agricultural uses, particularly in the more populated metropolitan areas. Regardless of their lithology and dimensions, of the local climate and the existence or not of significant surface water sources, groundwater in these areas is usually the cheaper, most secure and better quality source for water demanding activities. Low-income populations are the primary users of groundwater resources whenever they meet minimum requirements for consumption, even if sometimes the groundwater contains solutes in excess of drinking water quality standards. The main problems found in the aquifers in Argentina (La Plata and Mar del Plata), Brazil (Recife, Fortaleza, Maceió), Peru (Máncora aquifer) and Uruguay (Raigón aquifer) are intensive exploitation, salinization (either by lateral marine intrusion or by upconing from deeper saline layers), and anthropogenic pollution. The problems are even more acute in aquifers located in highly populated areas, as is the case with the coastal systems of sand bars and lagoons of southeastern Brazil, extending down to northeastern Uruguay as the Chuy/Chui aquifer (Almagro et al. 1998; Almagro and Custodio 2004).

### **Small clastic aquifers of local interest**

Small aquifers have sometimes great importance in local terms, acting as a strategic water reservoir of great economic and social relevance. These aquifers usually

occur in shallow sand dunes and beach deposits interlayered with lagoon finer sediments such as in the eastern Rio de Janeiro State, Brazil, in the Buenos Aires province, Argentina, and in silty-sandy loessic sediments in La Paloma aquifer, Uruguay. The Colombian coast presents some small aquifers of local interest, like the alluvial deposits underlain by a deep, 200 m thick sedimentary sequence in Urubá (Cossio and Vargas 1995), the shallow unconfined alluvial terraces formed by gravels and sands (30 m thick in the Santa Marta aquifer), and the fine quartz sands, gravels and granules with clay interbeddings in the Morrosquillo aquifer.

The studied small aquifers include some socially and economically very important water bodies, like the north-eastern Brazilian aquifers (Fortaleza, Maceió and Recife), Rio de Janeiro Eastern coastal aquifers, La Paloma aquifer (Uruguay), La Plata aquifer (Argentina) and Santa Marta and Urubá aquifers in Colombia; they all show various degrees of information and management, but almost all of them have been studied for hydrodynamics, groundwater quality and aquifer vulnerability. Also, aquifer management programmes like using treated waste-water for irrigation, control of pumping, artificial recharge (e.g. Rodriguez et al. 1994), joint use of groundwater and surface water (e.g. Silva and Pizani 2003), or groundwater treatment for specific contaminants, were carried out or have been considered in some of them.

### **Coastal aquifers in small islands**

The small dimensions of these aquifers make it difficult to define the aquifer boundaries, mainly due to intensive groundwater exploitation, which is mostly for supply for tourism. As intensive exploitation usually mobilizes water from large volumes of terrain, in the case of small aquifers the groundwater drawn comes not only from the expected aquifers but also from adjacent formations.

Examples of these aquifers are the vulcanites, dominantly basalts in the oceanic Easter Island (Isla de Pascua), Chile, where the 160 km<sup>2</sup> aquifer is formed by a thin freshwater lens around the island (Herrera and Custodio 2008; Herrera et al. 2004), and the aquifer of Santa Cruz Island (Galapagos Archipelago), where population growth and extreme water shortage have led to sophisticated geophysical studies that allowed mapping of previously unknown and important suspended aquifers, as well as the island saltwater wedge (d'Ozouville et al. 2008). On the other hand, the karstic aquifer on limestone and consolidated calcareous silts of Isla San Andrés, Colombia (INGEOMINAS, unpublished report, 1993), with 25 km<sup>2</sup> extent, is considered prone to increasing permeability due to enhanced calcite dissolution due to the freshwater-saltwater interface position disruption by pumping. This may provoke land sinks caused by caves collapsing, which is a serious hazard in urban and peri-urban areas.

Coastal aquifers in small islands display common features: high water demand; intensive groundwater exploitation; marine intrusion; and lack of resource planning and management policies. In a few cases there are studies, even if incomplete, that support some ground-

water management. This is the case of Itamaracá island aquifer (near Recife, Brazil), where a hydrogeological zoning of the aquifer (delineation of the aquifer system with the definition of hydraulically distinct zones) was carried out as an important tool to visualize areas of similar groundwater exploitation, contributing to a more rational planning of aquifer development, as it helps to indicate available volumes of groundwater (Demetrio and Oliveira 2004). Information on the 15 selected aquifers for this comparative study is summarized in Table 1.

Even within a single aquifer, conditions are frequently highly variable in terms of hydrogeological characteristics, pumping rates, and management actions. Detailed information is usually scarce, but one may focus on some typical systems in the continent and their common problems for the following discussion.

## Discussion and concluding remarks

In South America coastal areas, the use of groundwater resources is irregularly distributed throughout the continent. It is sometimes spatially concentrated, with groundwater abstraction used to satisfy local needs of the populations or the touristic developments, which is the case in Mar del Plata, Argentina (Bocanegra et al. 1993), Recife and Maceió (Brazil) (Montenegro et al. 2006; Nobre et al. 2007), for example. This produces marine intrusion and significant depression of piezometric levels. Additional problems are salinization caused by irrigation return flows and groundwater contamination due to lack of sewerage systems and leaching of urban waste disposal areas. Other scarcely inhabited coastal areas have not yet experienced major problems related to groundwater abstraction, as in vast areas of the Brazilian eastern coast, most of the Pacific coast (Chile, Peru) and southern Argentina. Those relatively unaffected areas occur due to (1) geological causes: coastal aquifers relatively isolated from marine influence due to topographical and structural/stratigraphic setting, like in the southern Pacific coast, and (2) demographic causes: scarce population, as in northern Brazil and most of the Southern Cone.

The studies conducted in most of the analyzed aquifers include hydrogeological and hydrochemical characterization, assessment of the vulnerability, monitoring and in some cases also modelling. It is noticeable that some of those efforts are not part of systematic government policies but of localized and restricted academic outcomes, seldom supported economically and rarely followed by management actions, like in Maceió and Rio de Janeiro aquifers in Brazil (Silva-Filho et al. 2009; Silva and Pizani 2003; Nobre et al. 2007).

The legal framework in the studied South American countries has a hierarchic regulation structure, at municipal, state/provincial and national levels. This leads to sometimes conflicting action programmes, laws and norms that sometimes hinder more effective actions in aquifer management. As an example, current Brazilian environmental and water resources legal rules were implemented approximately a

decade ago and, in addition to conflicting subjects, still lack a regulation to enforce policies. Nevertheless, groundwater level and quality monitoring plans (Recife, Brazil), regulation of new well drilling (most countries and aquifers), artificial recharge, hydraulic barriers (Mar del Plata, Argentina), environmental education plans of inhabitants (Colombia) or maintenance of sewerage networks to prevent leakage, are some of the identified measures already undertaken in the aquifers.

The comparative study performed regarding 15 coastal aquifers in South America revealed the following common needs in terms of groundwater use and management in the systems:

- Management of intensive exploitation
- More characterization studies to support planning and management programmes
- Groundwater monitoring
- Increased awareness of society and its involvement in resource management, planning and actions

Furthermore, the accomplished analysis reinforces that controlled management actions, beyond economic investments, depend upon:

- The characteristics of the system
- Public and institutional participation (society, stakeholders)

International integration could improve promotion of sustainable management in endangered coastal aquifers.

The aquifers that have proved to have fewer management actions are usually those in which there is a low level of knowledge regarding their geometry, dynamics and hydrogeology, something that happens in less developed countries and regions of South America (e.g. northern Brazil or Ecuador), but also in less inhabited areas (extreme southern Argentina and Chile). Conversely, aquifers that are well known, regularly monitored, and to which modern and more sophisticated techniques have been applied (such as hydrogeochemical and isotopic techniques, flow and transport modelling, evaluation of marine intrusion and contamination risk assessment), usually present various management strategies, as is the case of the aquifer of Mar del Plata, Argentina. Common actions in those more developed regions include remediation by artificial recharge, decrease and relocation of extractions, and even procedures to modify the dynamics of saltwater–freshwater relations by means of freshwater injection and extraction of saltwater. In some cases, legal and regulatory activities to protect groundwater resources are scarce or nonexistent, whereas in other cases they constitute the support of an effective management plan. In general, there is a strong correlation between economic and human development and aquifer-problem awareness and management. This is very clearly seen for the case of urban and periurban aquifers, which have the largest availability of aquifer studies and management actions, as in the case of Mar del Plata, Argentina.

It was noticed that, in general, an effective intervention of institutions that congregate and successfully represent

**Table 1** Main aspects of the studied aquifers (Fig. 1). For table legend and layout, see footnote

| Studied aquifers and their aspects <sup>a</sup> |   |
|---|---|
| 1.  | Fortaleza coastal aquifer, NNE Brazil   |
|   | • Holocene and Pleistocene sand dunes, 10–25 m thick/Barreiras Formation, 60 m thick  |
|   | • Intensive development   |
|   | • Monitoring. Water Resources State Secretariat management project  |
| 2.  | Recife coastal plain (Cabo, Beberibe, Boa Viagem aquifers). ENE Brazil  |
|   | • 112 km <sup>2</sup> . Cabo aquifer 90 m thick, sandstones, siltstones, mudstones, semiconfined. Beberibe aquifer 100 m thick, sandstones and clayish layers. Boa Viagem aquifer 40 m thick, sand, silt, clay, unconfined  |
|   | • Intensive development, piezometric drawdown, marine intrusion, pollution, influence from estuarine and mangrove areas with respect to water quality   |
|   | • Regulation of well drilling, well ownership, water use and artificial recharge, and protection of wellhead against contamination. A regulation act was issued for the Recife Metropolitan Area (including 13 towns), but it is essentially applied in the coastal plain |
| 3.  | Maceió coastal aquifer, E Brazil  |
|   | • Alagoas sedimentary basin, 20–500 m thick, Quaternary sands and gravels. Barreiras and Marituba formations. Poço formation, Quaternary  |
|   | • Intensive development, marine intrusion   |
|   | • Introduction of water rights (2001)   |
| 4.  | Eastern Rio de Janeiro State coastal aquifers, E Brazil   |
|   | • Shallow sandy dune and beach deposits; interbedded fine lagoon sediments  |
|   | • Intensive development; lack of sewerage systems; small, easily salinizable aquifers   |
|   | • Environmental education of local inhabitants, importation of surface water  |
| 5.  | Paloma aquifer, Rocha, E Uruguay  |
|   | • 120 km <sup>2</sup> , 30–150 m thick, sandy-sandy loessic sediments, fine sandy textures  |
|   | • Marine intrusion, groundwater pollution by agriculture, high dissolved iron   |
|   | • No pumping in winter. Aeration to precipitate iron  |
| 6.  | Raigón aquifer, S Uruguay   |
|   | • 1800 km <sup>2</sup> , 10–30 m thick, fine sands and gravels, conglomeratic lenses, clay layers   |
|   | • Intensive development, poor sewerage system, pollution from chemical plants   |
|   | • Monitoring, land use plan   |
| 7.  | La Plata coastal aquifer, E-Central Argentina   |
|   | • 100 km <sup>2</sup> ; Upper aquifer 25–45 m thick; Lower aquifer 15–25 m thick. Sandy to clayey silts, carbonate banks  |
|   | • Intensive development, marine intrusion, agricultural and livestock farming pollution   |
|   | • Environmental education of local inhabitants. Unification of urban water supply   |
| 8.  | Mar del Plata coastal aquifer. E Argentina  |
|   | • 900 km <sup>2</sup> , 70–100 m thick, silty-sandy sediments with fine-grained sandy textures. Graven and horst bedrock  |
|   | • Intensive development, marine intrusion, urban and agricultural pollution   |
|   | • Municipal water plan. Coastal extraction barrier  |
| 9.  | Bahía Blanca industrial area coastal aquifer. SE Argentina  |
|   | • Upper aquifer: 15–30 m thick, coastal lagoon and salt marsh deposits. Lower aquifer: 100–200 m thick, loess and silt, cemented by carbonate   |
|   | • Differential subsidence, damage to buildings, groundwater contamination by industry   |
|   | • Monitoring, environmental education of local inhabitants  |
| 10.   | Easter Island (Isla de Pascua), S Pacific Ocean, Chile  |
|   | • 166 km <sup>2</sup> . Vulcanites, dominantly basalts  |
|   | • Thin freshwater lens around the island; salinization of coastal wells. No springs, no surface water   |
|   | • Spreading the wells, placing wells far from the shore   |
| 11.   | Máncora coastal aquifer, W Perú   |
|   | • Alluvial aquifer, variable thickness, confined sands and gravels  |
|   | • Rapidly increasing groundwater salinity. Risk of enhancement by future tourism development  |
|   | • Unification of urban water supply   |
| 12.   | Urabá aquifer. Eje Bananero, N Colombia   |
|   | • 288 km <sup>2</sup> , 25–200 m thick, alluvial deposits on a sedimentary sequence   |
|   | • Intensive development, marine intrusion   |
|   | • Introduction of concessions and well permits. Monitoring  |
| 13.   | Morrosquillo aquifer, N Colombia  |
|   | • 310 km <sup>2</sup> , 65–80 m thick, fine quartz sands, fine gravels and gravels, clay interlayers  |
|   | • Intensive development, septic tanks, pollution by agrochemicals   |
|   | • Land use control through municipal plans  |
| 14.   | Santa Marta aquifer, N Colombia   |
|   | • 48 km <sup>2</sup> , 32 m thick (average), sand and gravel alluvial terraces, unconfined  |
|   | • Intensive development, marine intrusion, pollution by sewage effluent   |
|   | • Structure to enhance river recharge; induced infiltration through wells   |
| 15.   | San Andrés island, N Colombia   |
|   | • 25 km <sup>2</sup> , 100–150 m thick, karstified limestones, consolidated carbonated silts  |
|   | • Intensive development, marine intrusion, high water demand, lack of planning  |
|   | • Environment management policies, control of abstractions  |

<sup>a</sup> Table legend and layout:

No. Aquifer denomination, location, country

- Main hydrogeological characteristics
- Main problems
- Management actions

the users and the civil society is a necessary step for proposing and implementing adequate management strategies. Nonetheless, this approach also requires important efforts to build technical knowledge and credibility. The greatest challenge in coastal areas is the lack of awareness of most decision makers and users regarding the negative impact of aquifer over-exploitation and contamination, while proper management is needed to preserve an important freshwater source producing clear social benefits.

Most references and examples refer to urban water supply in coastal areas, where there is more information, even if it is in internal reports. However, there are also aquifers such as the Ica coastal aquifer in Peru, which support important intensive agricultural developments in danger of being affected by marine water intrusion. Awareness on the problem is appearing in large farming areas.

Another important deficiency is the lack of financial resources for scientific research. This is mostly necessary in order to generate and implement alternatives of sustainable management of coastal aquifers. International cooperation could help to improve the current situation of coastal areas in the South American continent and thus promote sustainable management of endangered coastal ecosystems. Efficient water-management policies would help to dramatically reduce the impairment of groundwater systems due to marine intrusion, and consequently the present degradation risks for biodiversity, human population and economic development in coastal areas.

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