DEVELOPING AN EFFECTIVE COASTAL AQUIFER MANAGEMENT PROGRAM

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INTRODUCTION: THE PLANNING APPROACH

Coastal aquifers add a significant complication to the process of aquifer management, namely the potential for salt water intrusion to eventually render portions of the coastal aquifer unusable as a source of drinking water. For this reason, the planning process invariably relies even more on aquifer modelling than does an aquifer management plan for an inland aquifer. Figure 1 shows the recommended planning approach to coastal aquifer management. Although made up of familiar elements, it may appear to be in a somewhat unusual order. For example, the development of a database is placed early in the sequence. This has proven to be an important step in making data analysis more effective, and in providing the necessary input for groundwater modelling in later phases. There are also two steps that focus on problem analysis and developing an understanding of the cause of elevated chloride concentrations. The first step is shown as the development of a theory for the cause of intrusion, often called a "conceptual model". It is during this step that stakeholder opinions and information is collected. The list of problems and issues should be revisited after modelling and analysis to finalize the list prior to setting planning objectives. In this second step, problems perceived as important at the start of the study are confronted with the results of modelling and analysis.

Perhaps most important, however, is need to place modelling ahead of field studies. Preliminary modelling forces the planning team to develop an understanding of the data and a coherent theory of the mechanism of intrusion. This has been shown to significantly minimize the costs usually associated with extensive drilling and sampling by focusing the field study in areas most likely to yield important information. Once field studies have been completed, it is expected that the preliminary model will be updated to reflect the additional data, and that the conceptual model of the mechanism of intrusion will be refined and confirmed by the field results. The final elements of the planning sequence include the identification of solutions to the intrusion problem (as well as other problems that have been identified), and the evaluation of the management alternatives.

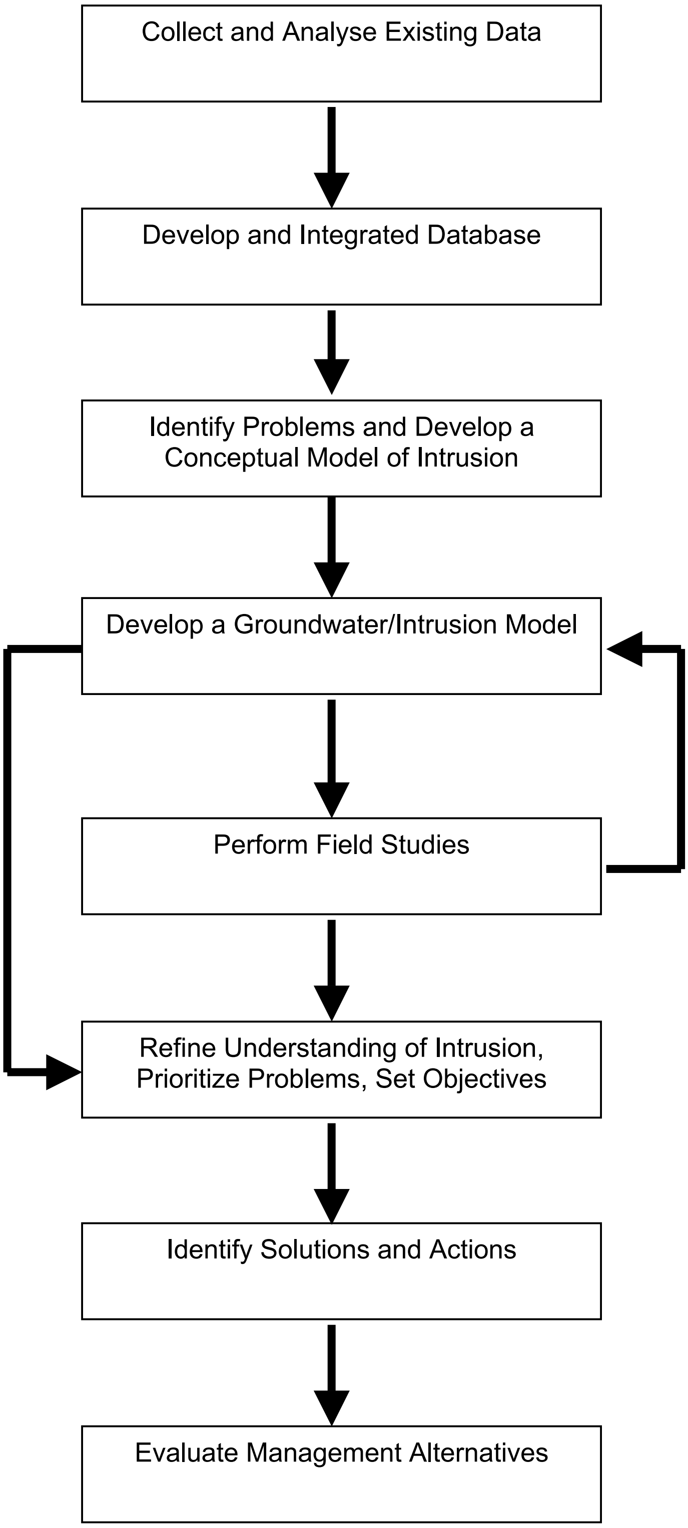

Figure 1 *Study Approach for Coastal Aquifer Management*

EXISTING DATA COLLECTION AND ANALYSIS

The first step in comprehensive coastal aquifer planning is to collect sufficient data to adequately define and understand the coastal aquifer system, its pumping stresses, and its associated salt water problems. Existing data on aquifer heads and chloride concentrations in coastal wells should be reviewed. Usually data are sparse, with too few data points to adequately characterize or fully understand the current status of the aquifers with regard to salt water intrusion. All physical or chemical data from supply wells or monitoring wells should be reviewed. Even non-technical, anecdotal information, such as a report from a private well that was shut down due to chlorides, can provide invaluable clues to timing and direction of intrusion.

By examining and contouring heads along the coast, areas where offshore "mining" of fresh water can often be recognized. Heads in the fresh water aquifers may be below sea level, yet the wells continue to provide fresh water. Examples of this situation can be seen on Long Island in the deep, confined Lloyd Aquifer, and in Georgia and Florida, where suppliers take water from the confined Floridan Aquifer. Coastal suppliers can often withdraw water from wells under these conditions for many years, even decades, before the offshore supply of fresh water is exhausted.

INTEGRATED DATABASE

Given the complexity of analysis required for coastal aquifer studies, one of the most important elements in the overall planning approach is adequate database development and application. Data must be organized early in the planning process, and in such a way that it can be analyzed spatially, in three dimensions, as well as temporally. The long-term nature of interface movement requires that data from as far back as possible be collected. The only way to make the data available for analysis and modelling is to develop an integrated database/geographic information system (GIS). This critical and often neglected step of integrated database design allows users and modellers to analyze and query data, and places the data in a consistent format for model pre- and post-processing.

Data elements and map coverages in the GIS/database needed for coastal aquifer management include:

- Well information (depth, location, aquifer designation)
- Historic and projected pumping information (linked to the well information)
- Chloride sampling data (dated, linked to well locations)
- Water level data (dated, linked to well locations and chloride concentration)
- Surface map features (roads, streams, well locations, topographic features)
- Aquifer properties: hydrogeologic parameters and map coverages (e.g. transmissivity or hydraulic conductivity data and contours, aquifer/aquitard thickness data and map contours, other parameters (specific yield, storativity)
- Recharge estimates, mapped as contours if spatial variation is expected
- Maps of estimated present interface locations and depths

Unlike the calibration of a typical groundwater model in a fresh water aquifer, the response time of the fresh water/salt water interface to changed pressure distribution (rise in sea level, increased pumping, altered recharge) in a coastal system might well be decades, or in some cases even a century or more. Estimates of historical pumping usually have to be made over a period of many decades. One of the most challenging aspects of developing the conceptual model is the estimate of the natural position of the interface prior to pumping, and a determination of whether the pre-development position was in equilibrium, or is still responding to a change in sea level.

Once the data have been put into a database/GIS system, initial analysis can be carried out prior to modelling. Common analytical steps include examining:

- Water quality trend and spatial analyses
- Pumping analyses: seasonal, annual, monthly
- Water level and aquifer head mapping
- Chloride concentration and trend mapping
- Water demand projections

IDENTIFY PROBLEM AND DEVELOP A CONCEPTUAL MODEL

Once available data and information have been collected and reviewed, a conceptual model of the mechanism of intrusion must be formed as a working hypothesis for further study. Intrusion generally can be categorized into one or more of several types of intrusion: horizontal and upward movement of the interface, downward leakage of brackish or salt water from surface water, or salt water upconing beneath a well field.

Developing a well founded, conceptual model of the cause and mechanism usually involves the interpretation of existing data, the development and use of a preliminary groundwater model, and the collection of additional data through field programs. In some cases the cause is obvious. In others, a considerable effort is required to pin down the exact mechanism causing the intrusion.

COMPUTER MODELLING

Although much insight can be gained from the process of collecting and analyzing the data, only through modelling of the mechanism of salt water intrusion can the plausibility of the conceptual model be tested, and a deeper understanding of the mechanism of intrusion be gained. Modelling lies at the heart of the planning process, and interacts with all other activities, as shown in Figure 2. For this reason, it is recommended that a preliminary salt water intrusion model be developed before additional field studies are carried out to collect more data. This is recommended for a number of reasons:

- Models will provide significant insight into the potential mechanism of intrusion, and is the best tool for integrating and interpreting the data.
- Models will provide clear guidance on the need for additional data, the type of data needed, and the most critical locations and depths to collect data.
- Models are the best tool for investigating and testing assumptions (e.g. assumptions of recharge, of interface location, etc.), developing and testing intrusion theories, and gaining an understanding of the sensitivity of the coastal aquifer system to changes in its hydrologic components (e.g. aquifer/aquitard structure, hydraulic conductivity, specific yield, etc.).
- Models are excellent visualization tools, providing the necessary graphic software to provide fully 3-dimensional visualization of the aquifer system. Current modelling software packages now offer practical capabilities to zoom, pan, cut cross-sections through any part of the modelled area, contour heads or chloride concentrations in plan view or cross-section, show interface locations, and display point data in plan and cross-section.

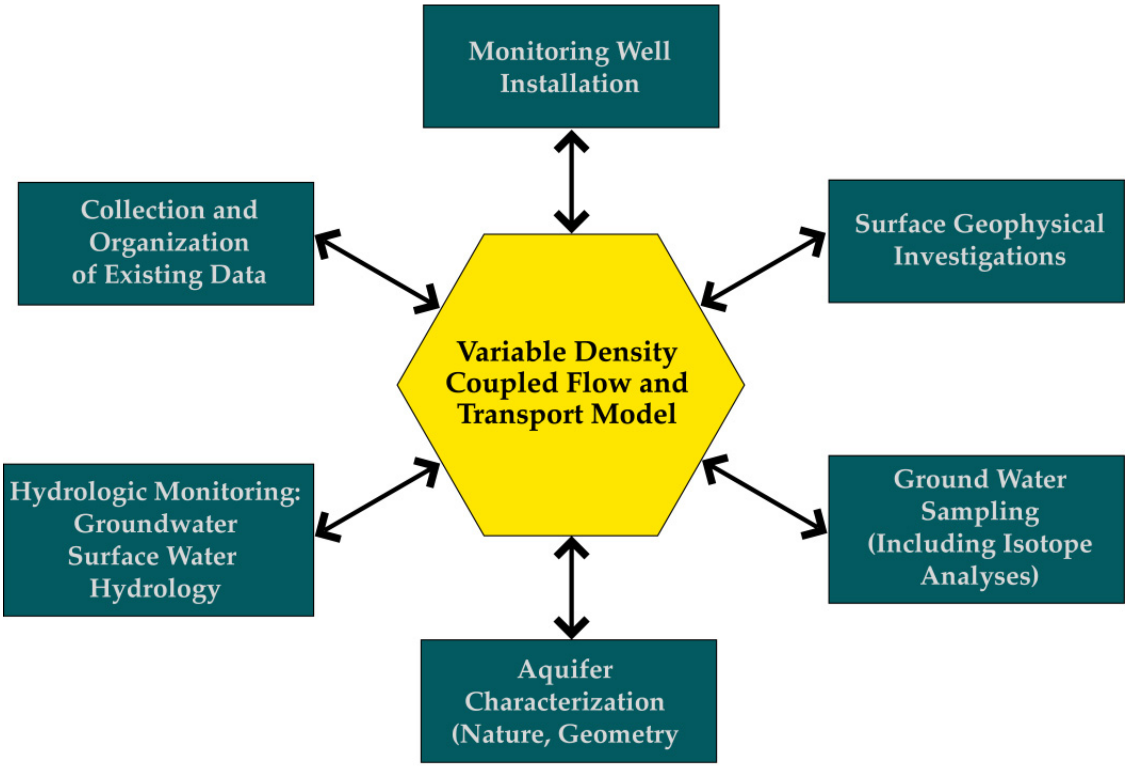

Figure 2 *Modelling Role in Coastal Aquifer Management*

Selecting the correct model depends on setting clear and unambiguous modelling objectives. In many practical studies, modelling objectives could be to:

- Determine the cause of existing chloride contamination and the mechanism behind the contamination (lateral intrusion, upconing, downward leakage, etc.)
- Estimate the present, offshore location of the interface
- Assess if the interface was stable prior to pumping
- Determine the potential for intrusion or accelerated intrusion based on current pumping or future projected pumping
- Estimate expected time of impact for specific well locations based on various pumping scenarios
- Develop estimates of pumping rate versus rate of interface movement as part of a cost/benefit analysis of alternative water supply sources
- Test various approaches to mitigating, halting, or reversing intrusion

The modelling objectives, available budget, and the scale of the problem will be the primary factors in selecting an appropriate modelling approach.

In the past 8 to 10 years, successful applications of fully three-dimensional models of salt water intrusion, effective use of available analytical approximations of salt water upconing, and the use of particle tracking contaminant transport models have been combined to provide very effective planning and permitting tools for coastal water suppliers and regulatory agencies. These tools are particularly effective when fully integrated as a set of interrelated models.

Three dimensional, sharp interface salt water intrusion models, or coupled flow and transport models are both effective tools to analyze the long-term sustainability of coastal wells in a regional context. These models can:

- provide insight into the horizontal advance of wedges of salt water under the influence of both sea level rise and coastal pumping

- help estimate the rate at which fresh water is being withdrawn from offshore sources
- help estimate the rate and timing of the salt water advancer, provided that some information is available on the location of the offshore interface

Models can help answer important questions about the long-term viability of coastal well fields, and can help formulate plans for alternative sources or assess the need for treatment of brackish water.

In analyzing upconing of salt water, the existence of salt water in aquifers below the pumping wells is usually already documented. In this situation, it is important to calculate the maximum sustainable pumping rate that still avoids salt water upconing, or to calculate the timing of eventual upconing and the expected levels of chlorides in the wells. There are numerous, analytical solutions to the salt water upconing problem that can provide insight into the problem, albeit with important simplifying assumptions (see Motz, 1992; Schmorak and Mercado, 1969). Sharp interface models, fluid density-dependent flow, and coupled flow and transport models are useful in simulating this situation in more complex hydrogeologic environments.

Single phase contaminant transport models are very useful in analyzing the interaction between brackish surface water and groundwater where brackish surface water could be drawn downward toward pumping centres from canals, bays, or tidal creeks and rivers. In this case, the brackish water often has a density not significantly different from that of the groundwater. Advective transport and dispersion then become the primary mechanism of transport towards the well, a situation that can be effectively and efficiently simulated by particle tracking codes.

If concentration gradients are important, then fluid density-dependent ground water flow models, or coupled flow and transport models can be applied. Fluid density dependent models or coupled flow and transport models allow the effect on groundwater flow of fluid density gradients associated with solute concentration gradients to be incorporated into model simulations. The main applications are in studies of seawater intrusion where dispersion of salt into the fresh water zone needs to be quantified and mapped.

One note on model calibration must be made. Salt water intrusion models often suffer from insufficient data to provide true “calibration and verification”. Data gaps include a lack of data on the natural or equilibrium position of the interface, on whether the interface was in fact in equilibrium prior to pumping, on the current location and rate of movement, on the thickness of the salt water wedge and the degree of diffusion in the transition zone, and on the history of intrusion (location, timing). This should not be a reason to forego modelling. Even with limited data, it is usually possible to test the “reasonableness” of the model results and learn a great deal about the coastal aquifer system.

FIELD STUDIES

Having developed a preliminary model based on existing data, the gaps and inadequacy of the data is often apparent. At this point, field studies can be carried out to fill the most important data gaps. The design of a field study is very site specific and may have several components.

Well drilling, water level readings and chloride sampling

The most direct approach (and often the most expensive) is to drill monitoring wells, preferably with the ability to measure chlorides at several depths. Drilling program objectives are commonly stated as:

- Providing sufficient coverage to accurately determine head distribution in the coastal area of interest
- Collecting chloride concentrations to map the interface location
- Gathering geological data to confirm or refute the initial conceptual model of the aquifer system and the mechanism of intrusion
- Providing a permanent salt water intrusion monitoring system. This should be enhanced by using PVC casing in the monitoring wells to allow downhole focused electromagnetic induction borehole geophysics to measure the thickness of the salt water wedge

In looking at chloride concentration results, it must be remembered that concentrations often change in the horizontal direction, with concentrations increasing towards the shore, but also in the vertical directions, with concentrations increasing with increasing depth. Care should be taken in mapping chloride distribution to account for variations in the depth of the sampling points.

One other consideration often overlooked is to correct mapped contours of aquifer heads for chloride concentration. Full seawater often has a specific weight of between 1.2 and 1.3, as opposed to fresh water, at 1.0. Thus a head of mean sea level with a chloride content of 19,000 ppm measured at a depth of 80 feet has an equivalent fresh water head of 2 feet. In mapping the head contours near the coast, heads should be converted to equivalent fresh water heads.

Chloride Balances and Ion/Isotope Fingerprints

A chloride balance (estimating the mass of chloride from each potential source, and comparing it to the mass measured in the aquifer of concern) is another useful field study that can help in the investigation of potential sources of contamination. In many coastal aquifers, the only source of chloride contamination of the aquifer is salt water intrusion. In such cases, chloride balances serve no real purpose. In certain cases, however, the collection of data and the modelling might reveal several potential sources (e.g. lateral intrusion of seawater, brackish water from inland sources, recharge of concentrated wastewater from septic system, sewage infiltration, and agricultural irrigation water, upconing of deep brines from the underlying aquifer).

When faced with multiple potential sources, developing a chloride balance can yield significant insight into the relative importance of each source. Sampling and developing diagrams of the relative concentrations of ions in the water of each potential source can help to ‘fingerprint’ each sources.

Surface Geophysical studies

One proven survey approach is the use of Time Domain Electromagnetic (TDEM) soundings. This technique is effective because electrical resistivity is highly influenced by the salinity of the ground water, providing clear contrast between zones of fresh water and zones of salt water. In general, TDEM has proven to have excellent vertical and lateral resolution for mapping interfaces characterized by resistivity contrasts, and can reach depths of between 500 and 1000 feet, depending on the availability of open space at the surface.

Downhole focused induction logging

Focused-induction logging of boreholes uses an electromagnetic emitter coil that induces current loops within the surrounding formation to generate a secondary electromagnetic field. The intensity of the secondary field received by the receiver coil is proportional to the formation conductivity (Stumm, 1993). Salt water, in place of fresh water, significantly alters the conductivity, and is usually easily recognized in the downhole log of the well. The log provides an excellent indicator of the exact depth of the transition from fresh water to salt water in the well.

Offshore Drilling and Seismic Studies

In some cases, offshore drilling and/or seismic studies can be used to establish the offshore interface location and depth, and to identify areas where confining units protecting underlying aquifers may have been eroded by ancestral rivers, thus providing a relatively quick pathway through which seawater can enter the underlying aquifer system.

Refine and Prioritize Problems and Set Objectives

Once the analyses and modelling have been carried out, a more definitive understanding of the problem and a refined conceptual model are usually the result. The conceptual model and understanding of the problem will have been either verified or further refined by the field studies. To move towards a set of solutions, however, the problems need to be turned into a clear set of planning objectives.

The model can provide a practical tool with which to understand the severity and time scale of the problem and to present a clear set of potential planning objectives to a stakeholder group. Examples of possible model results might be:

- The current pumping does not cause significant movement of the interface.
- The interface is already onshore, and relatively stable with regard to further onshore movement. The intrusion is an upconing problem beneath specific wells. The cone might be unstable, and chlorides could enter the well above a certain critical pumping rate in a matter of days or weeks. Alternatively, the interface depth might be such that upcoming might eventually take place, however, the process could take 5 to 10 years.
- The interface is at an unknown, offshore location. Pumping is significant and will move the interface onshore and impact wells, however, eventual impacts through horizontal interface movement might take decades.
- The interface is onshore and adequately mapped, and is continuing to move toward pumping wells, and impacts can be expected in a number of years.

It is important to actively engage the technical advisory committees or other stakeholder groups in the planning process to gain consensus on the nature and severity of the intrusion problem, and to develop a set of operational planning objectives.

Some examples may help to clarify this point.

- It might be found that mining of offshore fresh water is occurring. A decision must be made whether this is acceptable for the present, or whether the goal is to halt or even reverse intrusion.
- It might be determined that the interface is presently very close to pumping wells, and that present coastal pumping is close to the sustainable yield. One objective might be to reduce pumping and halt all further intrusion. Alternatively, if water is scarce, this might not be a viable objective, and the objective might be to maximize the aquifer yield by finding the most productive rate and distribution of wells to extract the most water without causing direct impacts to wells.

IDENTIFY SOLUTIONS

Once the planning objectives have been identified, potential means to mitigating intrusion can be investigated. Examples of potential solutions include:

- Demand Management: essentially lowering the demand for water to reduce pumping stress on the aquifer
- Non-potable water reuse: another method is to reduce demand by replacing potable water with treated wastewater for irritation or other “grey water uses”.
- Injection Barriers: a hydraulic barrier is created by injecting water to form a narrow zone in which the freshwater gradient is towards the sea. This prevents intrusion of seawater into unaffected portions of the aquifer system.
- Extraction Barriers: a seldom used solution that creates a hydraulic barrier by extracting saline water near the interface to lower heads and protect wells further inland.
- Tapping alternative aquifers: aquifers located either below or above the impacted aquifer can sometimes provide alternative sources and relieve pumping stress on the impacted aquifer.
- Well Relocation: relocating wells to areas of higher fresh water head or areas less susceptible to intrusion. Relocation can also be used to reduce the intensity of pumping in an area and spread out the pumping cone of depression, making the head gradients less steep.
- Plugging abandoned wells: in some cases, older abandoned wells are left in place and can provide a conduit for leaking salt water from saline aquifers into fresh aquifers.
- Modified Pumping Rates: in situations where the well is subject to periodic increases in salinity due to upconing, a modified pumping schedule (lower constant rate or an on-off sequence that allows the well heads to recover) can sometimes alleviate the problem.

- Pumping Caps: restrictions on pumping rates or the placement of new wells can be applied in sensitive areas to protect against additional intrusion.
- Physical Barrier: physical barriers such as slurry walls or sheet piles have been tried in small scale, shallow intrusion situations to protect a well.
- Scavenger Wells: wells specifically designed for extracting fresh water while preventing the upconing of saline water through hydrodynamic stabilization of the saline-freshwater interface. Wells are actually installed in the saline part of the aquifer to reduce heads by pumping and wasting the saline water. This can slow or stop the movement of salt water towards the fresh wells.
- Controlled Intrusion: mining trapped offshore fresh water for use, with adequate planning for alternative supplies when the source is depleted.
- Intrusion with treatment: salt water intrusion could be tolerated at certain concentrations, with treatment to remove the salinity before use for public supply. This could range from Reverse Osmosis treatment of brackish water to full desalination plants using groundwater.
- Conjunctive Use: the coordinated use of surface water supplies and storage with groundwater supplies and storage to offset excessive reliance on groundwater.
- Aquifer Storage and Recovery: the treatment and storage of potable surface water in the saline aquifer for later extraction and use.

EVALUATE MANAGEMENT ALTERNATIVES

An increasingly important aspect of coastal aquifer planning involves the selection of alternative solutions, all of which involve tradeoffs. The selection should be based on a thorough evaluation of competing alternatives in an organized, comprehensive, and defensible manner. Multi-criteria evaluation techniques have proven to bean excellent decision support tool for evaluating water resource management alternatives.

Much research has been done over the last decades on multi-criteria evaluation techniques with the aim of developing simple, understandable, yet effective decision support tools. Approaches include simple weighted summation matrix techniques, concordance-discordance analysis, GIS overlay techniques, and mixed data multi-criteria techniques. All attempt to include economic, environmental, social, technical, political, and other considerations within the decision making process.

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