The Use of Risk for Permitting Groundwater Programs

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A critical issue facing most utilities is the protection and maintenance of a safe, reliable water supply for current and future customers so that growth and development can continue. The term "sustainability" is often used to describe the long-term, safe yield of a resource and includes the impacts of competing and/or future users of the resource. Since major capital investments have been or will be made to adequately treat a specific source, measures to protect the resource are paramount to ensure sustainability of the water supplies.

Saltwater intrusion is one result of development in urban areas, since the water table generally is lowered to allow development to occur, permitting the saltwater front to move inland. Where water supplies exist in coastal aquifer systems, inland saltwater can threaten water supplies and investments in infrastructure. The use of salinity barriers to retard such movement is one tool that may be helpful to utilities with this predicament. Growth and development have been rapid in warm climates, often in areas most prone to drought conditions. Where water demands generally exceed availability (at least for certain portions of the year), groundwater injection projects can provide a mechanism that negates the need for interbasin water transfers and large pipelines to transfer water from one location to another, or impoundment areas where much of the water may evaporate.

Because of limited water supplies, there is a move toward using waters of impaired (or less than pristine), quality to supplement existing water supplies. The use of reclaimed wastewater has become an attractive, economically viable choice in some areas, but proposals to use reclaimed wastewater have met with significant resistance from the public and the regulatory community. Concerns center around the risk of health effects to the public should these impaired waters be recovered in water-supply wells at a later point in time.

The "risks" of such reuse projects are generally associated with heavy metals, organic products like pesticides and solvents, and microbiological contaminants. Risk analyses are touted as a solution to a number of regulatory problems. For purposes of this article, the term "risk" is defined as the probability of occurrence of an infection as a result of withdrawal of a contaminant introduced into the aquifer by an injection project. The U.S. Environmental Protection Agency (EPA) has defined acceptable risk for drinking water as 10^{-4} per year.

The Florida Department of Environmental Protection has indicated that its major public-health concerns about injection programs involve microbiological constituents in wastewater. Since South Florida aquifers contain many naturally occurring bacteria, differentiating between the natural and introduced bacteria would be impossible because they are generally the same species and most are not unique to either environment; however, viruses present an entirely different scenario.

In EPA studies, disease outbreaks have been found to result from viruses found in human excretions in wastewater. Few dose-response curves are available for viruses or other pathogens, so conducting a risk assessment for pathogens assumes that some form of dose-response function and an indicator organism to model can be selected.

For the present investigation, predictive Bayesian methods were used to create a dose-response model that yielded useful information on the public-health response of humans to microorganisms while remaining conservative. *Rotavirus* was selected from a series of potential indicator organisms for use in modeling subsurface conditions because of its persistence, its low threshold dose required for infection, and its significant numbers in wastewater.

Because viral dose-response information is limited, predictive Bayesian methods are useful since a predictive distribution evolves in shape in response to data. Evolving shape is an advantage for a distribution when there is theoretical or empirical basis for the form of the distribution because risk can be assessed from any level of available information. An appropriate, mathematically rigorous risk assessment can be constructed from knowledge of the underlying dose-response relationships created with the predictive Bayesian methods.

The purpose of this article is to develop a mechanism whereby the distances required to reach the desired risk factor for these projects can be defined. It was assumed that any distance in excess of that required to obtain the defined risk level does not pose a concern that would prevent installation and operation of a project that was subjected to the risk assessment. Comparisons to other methods were made using *rotavirus* as a test of the model's veracity–the reference dose methods used by the EPA, the Benchmark dose methods devised by Crump (1985), and the methods utilized by Haas, et al (1999).

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Regulations and Associated Permitting Problems

One mission of the EPA is to protect all potential drinking-water aquifers. Under the auspices of general health protection, the federal government has the ultimate authority to accept or reject permits for innovative groundwater strategies based on their success or failure to meet the primary drinking-water standards. The EPA's authority to govern underground injection programs results from the Underground Injection Control (UIC) Program promulgated in 1981, pursuant to the Safe Drinking Water Act. These regulations are aimed at regulating waste disposal via underground injection and are clearly focused on the injection of hazardous materials. As part of the delegation of programs during the Reagan administration, the federal government subsequently delegated the UIC Program to most of the state governments. Thirty-four states currently have primacy for implementing full underground injection control programs.

The acceptance or rejection of a permit is based on meeting or failing federal primary drinking-water standards, plus other standards incorporated by individual states. The states often incorporate secondary drinking-water standards into the permit process. In many cases the difficulty arises not with meeting the primary standards but with meeting the secondary standards, whereby the proposed injectate is of "lesser quality" as defined by one or more secondary water-quality parameters not found in the native water. Despite regulatory concerns to the

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contrary, microbiological constituents are not a major factor in the UIC program; the common constituents of concern with the utilization of raw or reclaimed water are total organic carbon and nitrate.

Because violation of any water-quality standards may lead to the potential abandonment of a project, the EPA has established an aquifer-exemption process. An aquifer exemption is required if a primary standard is not met. It may be either a major or a minor exemption.

A major aquifer exemption is required if the proposed injection zone has total dissolved solids (TDS) of less than 3,000 mg/L. Such aquifer zones are designated as potential potable water supplies. All major aquifer exemptions must be issued by the EPA in Washington. To date, no major aquifer exemption has been issued.

Minor aquifer exemptions have occurred on a limited basis when the proposed injection zone contains total dissolved solids between 3,000 mg/L and 10,000 mg/L. Limited aquifer exemptions are shorter processes than minor aquifer exemptions and are oriented toward raw-water ASR and reclaimed-water applications. Rules designed for limited aquifer exemptions for innovative groundwater technologies are still in draft stages. These changes are more oriented to technical issues, where the original intent of the Safe Drinking Water Act is queried.

The Florida rules mimic and expand the federal rules. In addition, factors that might impact injection wells using waters of impaired quality are scattered through other portions of the Florida Administrative Code. These include requirements for the use of various qualities of reclaimed water (in the reuse rules), water-quality standards, anti-degradation rules and reasonable assurance criteria. Despite the added regulations, a significant regulatory issue remains concerning whether the water-quality standards should be measured at the wellhead or at the USDW.

In addition to the state's rules on reuse, injection wells, indirect potable reuse, and reasonable assurance, there are also local wellhead protection rules that may create conflicts for a proposed injection program. The protection of public water-supply wells through a wellhead protection program is considered an important component of comprehensive state groundwater protection programs.

The legal basis for wellhead protection programs is contained within the implementation of the 1986 amendments to the Safe Drinking Water Act. Florida, like many other states, promulgated minimal rules that delegate specific implementation of the wellhead (or source-water) protection program to regional water management districts and/or counties. This practice creates varying degrees of regulation.

Summary Of Regulatory Issues With Salinity Barriers

The Hollywood Salinity Barrier Pilot Project includes issues from a variety of regulations that overlap and, in some cases, may conflict or provide no guidance at all. **Figure 1** illustrates this issue:

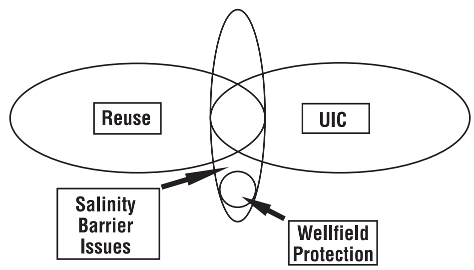

Figure 1: Permit Rule Overlap

- Recent rule changes permit the use of treated, reclaimed wastewater to create freshwater barriers to impede landward or upward migration of saltwater into Class F-I, G-I, or G-II groundwaters, which would apply to the proposed project.
- A setback distance of 1,000 feet must be maintained between the injection well and potable water-supply wells.
- The injection system must be designed and operated to preclude movement of the injected reclaimed water into potable water-supply wells or the subsequent withdrawal of reclaimed water at the potable water-supply wells.

The city's position on this issue has been consistent: Indirect potable reuse of water is an unacceptable outcome of a salinity barrier program, in part because it would diminish the success of the salinity barrier itself.

Florida regulatory requirements include the following elements:

- The injection wells must lie outside the 210-day travel-time zone defined by Broward County's wellhead protection zone, as demonstrated through computer modeling.
- Class V, Group 2 groundwater standards apply to the project.
- A zone of discharge is permitted, but the zone of discharge may not extend into zones having TDS concentrations less than 1,000 mg/L.
- The injection wells must be more than 1,000 feet from any public water-supply well.
- Water quality of the receiving water dictates treatment requirements.
- Primary water-quality standards must be met at the wellhead.
- Secondary water-quality standards must be met at the edge of the zone of discharge.
- The regulatory concept of "reasonable assurance" must be demonstrated.

Issues that are unclear in the regulations include:

- Class of the aquifer—injection is proposed into the Biscayne aquifer, but only in a portion of the aquifer that is not permittable for potable water-supply purposes, and where the TDS exceeds 10,000 mg/L.
- The classification of the aquifer determines the level of treatment required: advanced secondary, principal, or full treatment. For Hollywood, the latter two are likely to be too expensive for a demonstration project.
- How the quality of the receiving water should be determined (aquifer water quality changes with depth over a relatively small horizon).
- What constitutes the regulatory concept of "reasonable assurance?"

The permittability of any injection project involves acquiring sufficient information to answer these questions to the satisfaction of the permit writers. Lack of clarity means other methods must be pursued to resolve the permitting dilemma. Risk assessments have been touted as one solution. Constructing an appropriate risk assessment, however, is a much larger problem than might be anticipated.

Risk Issues

The proposed use of waters of impaired quality to supplement existing water supplies often meets with resistance caused by concern from the public and the regulatory community about the risk of effects on the public should these impaired waters be recovered in water-supply wells at a later time. The perceived "risks" of such reuse projects generally involve:

- Microbiological constituents
- Heavy metals
- Organics, solvents and synthetic compounds

Heavy metals are not perceived by the regulators as being able to move very far in the aquifer system, and so are not perceived to be a major public health risk. Likewise, the movement of organics varies considerably, depending on the weight of the substance and the activity that naturally occurring groundwater microorganisms in the aquifer will exert toward organic decay, so they are not perceived to pose much public health risk. Small quantities of organics (such as would be injected) generally serve as a food source in the aquifer for the naturally occurring bacteria, and thus quantities would decrease with time and distance. Where such compounds might be found, dose-response relationships for organics are readily available on the EPA's IRIS Web site.

Discussion of the issue with state regulators in Florida revealed that they perceive the biggest risk of the salinity barrier project to be the possibility of contamination of potable aquifer systems with potentially pathogenic organisms found in domestic wastewater effluent. In part, this concern occurs because groundwater has traditionally been considered safe for consumption without treatment, a belief that is not be justified given current knowledge of groundwater quality.

A risk assessment of the hazards posed by pathogenic organisms provides a valuable tool for evaluating the potential effect on the public from waters that contain, or may contain, such organisms. The risk assessment can be used in the development of standards of practice and protocols for injection-well usage, as well as the public benefit of using potentially contaminated waters for public purposes.

Despite the presence of pathogens, risk-assessment tools have been used only to a limited extent for judging risks of waterborne pathogens. *Shigella* and *Salmonella* are the two bacteria of greatest concern among health professionals, but virus survival can be much longer in groundwater. Application of reclaimed wastewater that may contain viruses, coupled with the potential for viruses to persist for long periods of time, has led to the recognition that viruses may increase the likelihood of groundwater-related illnesses if aquifer recharge programs are located in or near aquifer systems used by potable water-supply wells (Yates, et al, 1985).

The significant number of waterborne *rotaviruses* excreted by infected people and the number of infections worldwide each year indicate potentially large health impacts. As result of the prevalence of the organism and low infectious dose, *rotavirus* was chosen as a surrogate to model the risks.

It is difficult to test for bacteria and viruses quickly, or to identify the strains, so identification or quantification of a specific, acceptable risk seems more achievable. To this end, the risk assessment included the following:

1. Discussion of how dose-response data for microbiological species is developed
2. Manipulation of the existing data
3. Use of principles of information theory
4. Delineation of available data for the species in question
5. Delineation of available data for similar species
6. Determination of probable underlying dosage distribution

Since the significance of viruses as agents of waterborne disease in this country is just now being recognized, injection-project risk assessments should focus on how long viruses may remain viable in the ground and how far they travel (Yates, et al, 1987).

Development of the Risk-Assessment Method

The benefit of Bayesian methods in risk assessment is that it integrates subjective information rigorously with available numeric data in the assessment. Advantages of the Bayesian approach include (Press, 1983):

- Practical experience and subjectivity can be accounted for explicitly.
- Uncertainty is factored into the analysis and the CDF.
- Confidence intervals are small.
- It can be applied where objective methods are required, while using vague prior data.
- Hypotheses can be tested without predetermining the outcome.
- Forecasts are accurate; errors are small if reasonable subjective information can be elicited.

Previous application of Bayesian inference to dose-response estimation has focused on development of probability distributions for parameters of the dose response function. Results are expressed as such and assumption of arbitrary confidence levels is required for the application of this approach.

Predictive Bayesian methods are an extension of traditional Bayesian approaches, in which unconditional distributions for the quantity of interest are found by integration over probabilities of parameters of the distribution for the quantity of interest. The result is a distribution that becomes broader with decreasing levels of available information. These probabilities then incorporate both uncertainty and variability in the quantity of interest, and have been termed "believed probabilities." The approach has not previously been applied to dose-response assessment, although the literature suggests this as an appropriate application (Englehardt, 1995).

The absolute or unconditional probability density function p(x) on X is the underlying distribution found through curve-fitting. Its form, as defined by Aitcheson and Dunmore (1975), is:

$$p(x) = \int p(x \mid \theta)p(\theta)d\theta$$

where $p(x)$ and $p(q)$ are completely different and independent functions, and the function $p(q)$ is the prior distribution. The Bayesian approach assumes that while the true value of q is unknown, there are probabilities that can be assigned for a series of possible values of q. More precisely, it is assumed that $p(q)$ is a density function.

The posterior distribution incorporates observations from x into the sample space S. The outcome of the observations conveys additional information about the true content of S through a series of informed assumptions. The basis for the information obtained is the influence of the proper distribution, and the attachment of same to the possible distributions for x. Updating the plausibility in light of the observations of the prior, using Bayes notation, leads to the posterior probability function:

$$p(\theta \mid x) = \frac{p(\theta)p(x \mid \theta)}{p(x)}$$

where $p(x)$ can shown to be equal to 1.

The information so far derived permits a plausible assessment of the outcome of the future observations. The interest in the results or conclusions from the prior information means that as new information is gathered, the predictive function can be refined. This is the benefit of the Bayesian approach: Given uncertainty about a density function $p(y \mid q)$, some data can be deduced from the assessment of $p(q \mid x)$ over q when the experimental results of x are known (Aitcheson and Dunmore, 1975). This function is:

$$p(y \mid x) = \int p(y \mid \theta)p(\theta \mid x)d\theta$$

where the function $p(y \mid x)$ is the predictive density function. Solving for the CDF of this function yields a dose-response curve that was applied to the concentration contour results of a contaminant-transport groundwater model. Introducing uncertainty into the groundwater further improves the results (variability in concentration injected, transmissivity, leakance, etc,)

The use of predictive Bayesian methods for the dose-response relationships in determining the potential risks associated with groundwater injection programs has not been pursued previously, but the limited data and use of subjective data made the Bayesian methods an attractive avenue to investigate.

Comparisons were made to other methods using *rotavirus*–the reference dose methods used by the EPA, the Benchmark dose methods devised by Crump (1984), or the methods utilized by Haas, et al (1999). The limitation of the first two methods is that they have never been applied to, nor especially intended for, biological species. The Haas model is designed for biological species and offers the best comparison to Bayesian methods. It relies on having real data and does not

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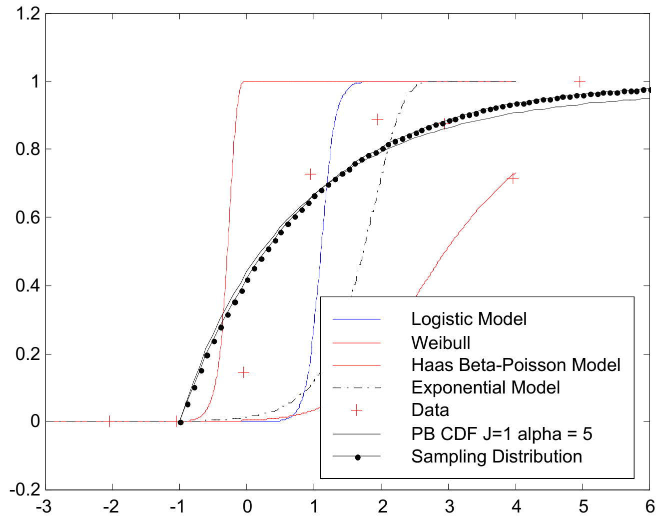

Figure 2: Comparison of Haas Models and Predictive Bayesian Model

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permit the incorporation of new data as it is acquired. Also, subjective data is not used with the same veracity as in Bayesian methods. The results of the Bayesian model are conservative compared to the other methods (**see Figure 2**).

City of Hollywood Pilot Project

Hollywood pursued the salinity-barrier pilot program with the idea that by injecting excess reclaimed water into the Biscayne Aquifer to mitigate saltwater intrusion problems, vast quantities of freshwater in the Biscayne Aquifer, currently at risk of saltwater intrusion, would be protected. A successful long-term program may also restore some old wells to viable status and possible use. In addition, disposing of reclaimed water via a salinity barrier is significantly less expensive than installing retail/residential reuse irrigation, requiring far fewer pipelines, less engineering, and much less disruption to area residents.

The aim is not to recover any of the water injected, since this would be counter to the salinity barrier's stability; therefore, the city does not intend to provide the significant and often duplicative treatment regimes employed at Water Factory 21 in California. In Florida, the resources are not yet so scarce that this amount of money spent on treatment is acceptable, especially since many utilities are moving to membranes for potable treatment.

This need for lesser treatment is further suggested because the flow of water under the city of Hollywood is southeastward. Preliminary modeling indicated that 12 inches of head would be created at the coastal injection wells and that water would not migrate to the water-supply wells located four miles to the west.

Given this finding, two series of monitoring wells and two injection wells were constructed. The purpose of the first set of monitoring wells was to better define the location of the saltwater front and to obtain core samples. The significant finding was that the profile was very clear and consistent and that the vertical distance between the 3,000 and 10,000 mg/L TDS lines was less than 10 feet in all cases. As a result, the team decided that injection into the 10,000 mg/L TDS water would accomplish the objectives easily, lessen the regulatory burden on the city, and allow the natural buoyancy of the reclaimed water to exert pressure on the saltwater front.

The second set of monitoring wells was drilled at the same time as the two 12-inch injection wells. Two zones were monitored: 165-200 feet and about 90 feet. The injection horizon was established at 135 to 160 feet below land surface, in 10,000 plus mg/L TDS water. The wells were logged and used to define geologic parameters. Injection tests indicated that transmissivity of the aquifer is very high and that injection of over 1.5 MGD of treated wastewater was possible.

Upon completion of the injection testing, groundwater modeling was conducted. The groundwater model yielded contours of the injectate movement. Solving contaminant transport equations for this concentration yielded a three-dimensional ellipsoid of constituent concentrations. Once the contours were applied to the predictive CDF for *rotavirus*, it was determined that there was minimal risk to the city's wellfields from the injection program.

The initial results of the risk model are shown in **Figure 3**, using a predictive Bayesian dose-response relationship for *rotavirus*. This figure indicates that the viruses do not pose a threat to the potable water-supply wells, since the viral content of the water resulting from the effects of dispersion and decay would not allow the presence of significant quantities to be present in the wells, even if the water were to move upgradient (which it would not). Since the wellfield is upgradient, the wells are not at risk from the injection program.

Because of the difficulty in delineating the permit requirements resulting from the aquifer classification, the predictive Bayesian risk-assessment tool may be utilized to demonstrate the viability of the project. This, however, raises a whole new issue: how to integrate a very mathematically complex analysis of risk into the current regulatory framework. The rules provide little guidance and the integration of the reasonable assurance criteria is still unknown, but because uncertainty is included in the model and conservatism is built into the dose-response function, the resulting risk-assessment model would appear to incorporate enough uncertainty to meet the reasonable-assurance criterion.

Conclusions

The use of reclaimed wastewater has become an attractive, economically viable

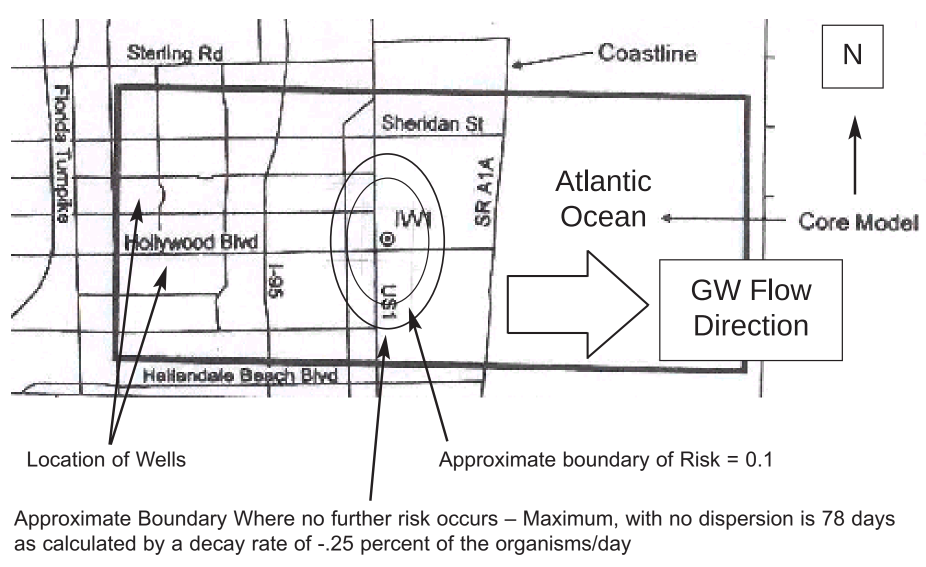

Figure 3: Rotavirus Risk Contours for Hollywood Salinity Barrier Project

choice in some areas of the United States (Florida, Arizona, California, and Nevada are examples). Unfortunately, the difficulty in permitting these projects at reasonable cost and effort without undue regulatory burden may prevent utilities from moving forward. In reviewing the correspondence on the city of Hollywood's project, several items are immediately apparent:

- The current rules do not establish fully the requirements for permitting the project.
- New rules have been developed to improve the situation, but the rules are still subject to significant interpretation by the permit writers.
- On innovative projects, permit writers will be much more conservative in their interpretation of the rules and require significantly more information from the permittee, including more sampling, monitoring, and modeling, than might be expected for more traditional projects.
- Within the regulatory agencies, there may be conflicts between the goals of the agency administration and the rules and procedures used by permit writers at the local level. For the salinity barrier, certain permit writers were wary of the entire concept, while the administration was very supportive of the efforts and wanted to find a solution allowing permits to be issued. The agency administration did not understand why the permit writers did not issue the permit and as a result, at certain junctures much time was spent defending positions instead of solving problems.
- Extensive permit conditions weaken support of local elected officials who want results and do not see them when permits are not issued.
- Multiple agencies giving permits compounds the problem.

This investigation was undertaken to develop a mechanism whereby the distances required to reach a defined risk factor for these projects can be defined. It is assumed that any distance in excess of that required to obtain the defined risk number does not pose a concern that would prevent its installation and operation. Groundwater modeling yields contours of the movement of the injected fluids. Assuming conservative tracers (no decay), the contours can be applied to a risk model as defined above. The contours will provide a relative risk probability from the contour.

Because the definition of reasonable assurance remains vague in the Florida rules, the use of risk-assessment tools may be a solution to the permitting problem; however, the ability to review the modeling may be equally limited. The dose-response model developed to determine the level of health risk posed by injection projects is very mathematically intensive and requires advanced mathematical understanding. Use of dose-response models using limited information and information-theory techniques is required.

The information obtained from the Hollywood salinity-barrier project has been of industry-wide benefit, although the project is not complete at this time. The risk-assessment methodology is well developed and the ability to transfer the technology to other jurisdictions and applications now exists. The results of the project provide an opportunity for utilities to conserve and protect local water sources, and appreciably increase the amount of reclaimed water that Southeast Florida utilities can use to provide a significant benefit at an affordable cost.

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