Relative Risk Assessment of Disposal Alternatives in Southeast Florida

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The disposal of wastes into the environment results in many varied effects on the ecosystem, both beneficial and harmful to various populations. Disposal of treated municipal wastewater effluent in Southeast Florida often involves flows of water that are more than 200 million gallons per day (MGD) per plant, and associated mass loadings of other constituents. These loadings alter the flow of water, carbon, oxygen, nutrients, and other constituents through the ecosphere.

In considering the sustainability of alternatives for disposal of effluent, one important consideration is human and ecological health. The Florida Water Environment Association (FWEA) Utility Council contracted with the University of Miami to conduct a relative risk study of disposal options in Southeast Florida. In this research, indicators of the relative human health and ecological risks of available alternatives for disposal of treated municipal wastewater effluent were evaluated. The disposal alternatives considered in this research project included:

- injection wells
- ocean outfalls
- surficial aquifer recharge via canals and shallow wells

Prior to the study, little was known about the relative risks of such alternatives. Because of the complexity of potential exposure paths, time scales, and population characteristics, and because of the need to avoid site-specificity in the assessment, a predictive Bayesian assessment of relative risks of the various alternatives was undertaken.

Bayesian methods allow the explicit and rigorous integration of expert opinion and numeric data, in contrast with resampling methods (which have no subjective capability), and fuzzy logic methods (having limited numeric data capability). The generalized quantitative assessment presented was made possible through the use of a further extension of the approach termed predictive Bayesian methods, involving the use of unconditional probability distributions for potential human health and ecological losses. Such distributions represent both uncertainty (due to information limitations) and variability (due to natural random variation).

Resulting unconditional distributions become broader with decreasing levels of available information, giving estimates of risk directly and avoiding the arbitrary assumption of confidence limits. Because the distributions are broader in general, their means are typically larger than the corresponding mean frequencies of occurrence; therefore, these probabilities are termed believed probabilities and are not interpreted as frequencies.

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Research Methods

The study was titled "Comparative Assessment of Human And Ecological Impacts From Municipal Wastewater Disposal Methods In Southeast Florida." The research team members included:

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- David A. Chin, Ph.D., P.E., University of Miami
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Experience of the research team encompassed probabilistic risk analysis; wastewater process engineering; microbiological and chemical transport and modeling in groundwater, surface water, and marine waters; Floridan and Biscayne aquifer geology and hydrogeology; wastewater management and disposal; ocean outfall disposal; aquifer recharge disposal; injection-well disposal; and utility permitting and management.

Three meetings of the team were convened over the course of the project. At the first meeting, a conceptual model of the technological and environmental setting for wastewater disposal in Southeast Florida was constructed, including available wastewater-treatment technologies, water-quality regulations, hydrologic characteristics, and conventional and emerging wastewater constituents of concern.

At the second meeting, the analysis of collected water-quality data was presented, along with tree diagrams describing potential exposure pathways, and the conceptual model for the risk analysis was developed. Risk was defined for the assessment as the probability of violating a water-quality standard.

A modified Delphi elicitation of expert judgment concerning risks associated with the three disposal alternatives was then conducted electronically, based on data collected for the region, applicable published literature information, and the experience of the research team. A predictive Bayesian model was then constructed, based on the conceptual model developed previously, to probabilistically compute total relative risk for the three alternatives.

Information from the Delphi survey was used as input to the computer model. Initial results were presented at the third team meeting. The model and input were refined, based on a final iteration of the modified Delphi survey and review of results by the team, to develop final relative risk estimates. Risks were then characterized in a discussion of the tradeoffs involved.

Output of the probabilistic analysis included the believed number of days during which one or more violations of existing or assumed water-quality standards for arsenic, microbes, n-nitrosodimethylamine (NDMA), and total Kjeldahl nitrogen (TKN) would occur, for comparative purposes. Arsenic, microbes (Cryptosporidium parvum for surface water, rotavirus for groundwater), and NDMA were used as indicators of human health risks, and TKN was used as an ecological risk indicator.

The compound NDMA was selected to represent nitrosamines, an emerging class of carcinogens that has been found in wastewater effluent. NDMA is considered carcinogenic at extremely low doses. Believed violation days are shown in **Table 1 and 2.** These numbers were larger than the expected number of days on which violations would be expected to occur because they reflected uncertainty in addition to inherent variability. Also, they were based upon the following multiple assumptions:

1. Rapid vertical migration to the Upper Floridan Aquifer from deep injection wells in the Lower Floridan Aquifer was assumed, although evidence of effluent in the Upper Floridan near injection wells in Miami-Dade County could have been related to construction problems. This assumption is equivalent to assuming that the Floridan Aquifer will be "impacted" with water of generally much lower dissolved solids and inorganics, yet higher organics and nutrients, than native water of the aquifer. The assumption of rapid vertical migration to the upper Floridan was equivalent to assuming a violation of the USDW with 100-percent probability. This probability of violation was not computed and is not reflected in the numbers in **Table 3.**
2. ASR wells were assumed located one mile from effluent injection wells. The regulations provide for closer spacing, but in practice, the one-mile spacing is likely too close. It was further assumed that, as water is withdrawn from potable and non-potable ASR wells, salinity would be monitored and withdrawals would stop if elevated levels were detected.
3. Because marine raw water for drinking was assumed to receive RO treatment, human consumption risks were driven by accidental ocean-water ingestion by bathers at the beach, as indicated by the probability of violating marine surface-water standards at the beach. In general, surface-water standards are comparable to drinking-water standards, though consumption of surface water in South Florida is probably three orders of magnitude less than consumption of drinking water. Because specific surface-water standards do not exist in Florida for NDMA and Cryptosporidium parvum, standards were assumed based on California action levels (NDMA) and published dose-response data (Cryptosporidium parvum). Assumed standards were adjusted by a factor of 1,000 to account for the fact that ocean water is ingested only accidentally in small quantities relative to drinking water. Because a specific surface-water standard does exist for arsenic in Florida, this standard was not adjusted, in keeping with the definition of risk assumed for the project; therefore, results for arsenic may be less indicative of actual human health risks.

Alternative Disposal Methods	Mean Believed Violation Days In 30 Years[1]		
	Arsenic	Microbial[2]	NDMA
Deep Well Injection	1	0.1	0.5
Ocean Outfall	10	50	30
Surficial Aquifer Recharge	0.3	5	40

1. [1]*Results reflect input developed on a relative basis, and should not be evaluated individually.*
2. [2]*rotavirus for groundwater nodes; Cryptosporidium parvum for surface-water nodes*

Table 1: Comparison of Human Health Risk Indicators for Three Discharge Alternatives

Alternative Disposal Methods	Mean Believed Violation Days In 30 Years[1]
	TKN
Deep Well Injection	10
Ocean Outfall	40
Surficial Aquifer Recharge	100

[1]*Results reflect input developed on a relative basis and should not be evaluated individually.*

Table 2. Comparison of an Ecological Risk Indicator for Three Discharge Alternatives

4. Levels of treatment assumed to be received by discharged effluent and treated drinking water varied according to regulatory requirements; only effluent released to surficial aquifers was assumed to receive AWT. Surficial aquifer recharge (SAR) was assessed at lower risk than ocean outfalls for Cryptosporidium parvum, because (a) the filtration step included in AWT treatment preceding SAR provides efficient removal of cryptosporidium parvum, and (b) persistent onshore winds could result in inadequate dilution of ocean outfall plumes at the shore. These assessed risks and others evaluated in the study depended upon the level of treatment assumed. Consideration of costs, including those of treatment, was outside the scope of this study.

Evaluation of water-quality parameters of both the effluent and the receiving waters indicates that many constituents found in the effluent were below those found in the receiving waters. Constituents found in higher concentrations in effluent included cyanide, nitrogen, phosphorous, color, odor, foaming agents, total trihalomethanes (Thms), biochemical oxygen demand (BOD), and total coliform count. In addition, treated effluents were somewhat higher in temperature and lower in pH, on average.

Of note and based on wastewater effluent analyses obtained, on average the treated effluents met both primary and secondary standards for drinking water, with the exceptions of primary standards for antimony and total coliform and secondary standards for color, odor, TDS, and foaming agents.

Buoyancy of the injected effluent due to its lower salinity is a driving force for vertical migration, and effluent associated with two existing wells has been found at middle elevations within the Floridan Aquifer. Horizontal dispersion within the Floridan Aquifer and Boulder Zone are uncertain; however, migration through the Hawthorne Layer to the Biscayne Aquifer is considered unlikely.

Reverse osmosis is generally required to treat the brackish water of the Floridan Aquifer before it is used for drinking, which virtually eliminates risk to potable-water supplies in the Floridan Aquifer; however, the risk driver for injection wells appeared to be the route by which treated wastewater effluent could potentially reach surface waters via migration to a potable or nonpotable aquifer storage and recovery (ASR) well.

Aquifer Storage and Recovery (ASR) Wells

The research team assessed the risks associated with the discharge of nonpotable ASR water to canals without treatment to be higher than those associated with discharge of water from potable ASR wells to distribution systems following chlorination and

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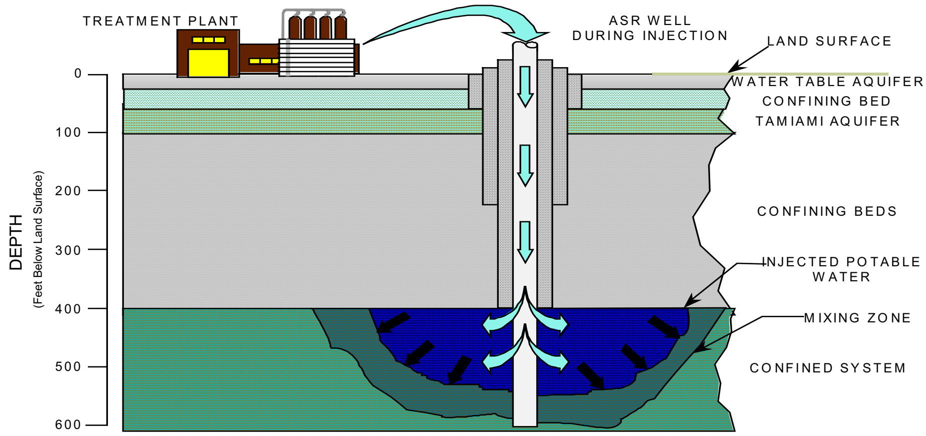

Figure 1: Schematic Diagram of Injection into an Aquifer Storage and Recovery System for Brackish-Water Aquifers.

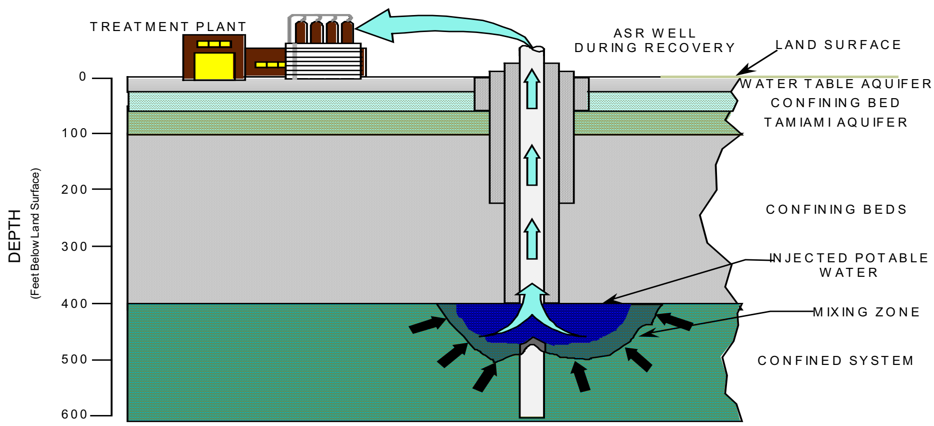

Figure 2: Schematic Diagram of Withdrawal from an Aquifer Storage and Recovery System for Brackish-Water Aquifers.

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blending. ASR wells have been recently proposed and employed as an alternative for managing water supplies in Florida. Such wells are formed by injecting freshwater into the Upper Floridan Aquifer during wet or low-demand seasons, with subsequent withdrawal to meet demand for potable water, natural-system flows, or aquifer-level maintenance at other times of the year. **Figures 1 and 2** depict the process.

ASR wells store water in a bubble within the brackish Florida Aquifer. Potable ASR water is generally treated before injection and receives only chlorination upon withdrawal before distribution; however, withdrawals from the well are monitored for salinity, and pumping ceases if elevated salinity is detected.

Nonpotable ASR water is intended to be released in large volumes to receiving canals during the dry season as part of the Everglades restoration efforts, as well as for raw-water supplies at treatment plants.

Assumptions of the team members regarding the future levels of operational control and treatment to be required before and after ASR withdrawals undoubtedly affected these judgments and are considered to affect the risks associated with contamination of ASR wells from injection wells.

Regulations regarding monitoring and operation of such releases had not been determined at the time of the study. Potentially exposed populations include potable-water consumers, users of nonpotable water for irrigation, consumers of vegetables irrigated with nonpotable water, and consumers of fish caught in canals receiving water from nonpotable ASR wells.

The use of ASR technology can decrease the cost of municipal water treatment by allowing the use of excess treatment-plant capacity during the wet, low-demand seasons (June-October) for treatment of water and injection into potable ASR wells. Water can then be withdrawn when full treatment-plant capacity is required by system demands.

Withdrawals are disinfected and blended with newly treated water before distribution. Excess stored water can be used as a reserve supply in case of high demand, drought, or treatment-plant failure, allowing water-treatment plants to be sized for average, rather than high, seasonal demands, thus saving capital infrastructure costs. Miami-Dade County is also experimenting with a system for storing raw groundwater. Retrieved water will then be treated at the existing water-treatment plants and distributed.

ASR systems involving injection of freshwater into saltwater aquifer systems will incur some loss of freshwater due to mixing with native waters. Such mixed water will not be recoverable without treatment to remove dissolved solids (chlorides). It has been estimated that as much as 300 to 500 million gallons may be lost from a single well, and more from a field of ASR wells. After this loss, 70- to 100-percent recovery of injected water has been estimated.

ASR system efficiency and success are determined largely by aquifer characteristics, including hydraulic gradient, transmissivity, static head, storage coefficient/effective porosity of the aquifer, salinity, and confinement and structure of the aquifer, including fractures, facies changes and stratigraphy of the system. Hydraulic gradient, transmissivity, and structure of the aquifer affect speed and direction of movement of the bubble. High transmissivity and gradient favor migration of the bubble. Incomplete confinement, or intersecting fractures, may allow injected water to migrate away from the well. The differential density of the waters will also affect separation of the bubble from native waters.

Conclusions from the Study

In general, the collected data did not indicate significant health concerns associated with the injection of treated effluent. Of the measured constituents with specific toxicity or infectivity, only antimony and total coliforms were higher in the effluent with respect to both ambient water and regulatory drinking-water standards. In light of the assumptions used, generalized scenarios represented, and uncertainties reflected, the risk assessment results shown in Tables 1 and 2 can be evaluated only on a relative basis.

Relative, or comparative, risks were defined as the ratio of believed violation days (that is, the mean of the believed probability distribution for violation days) for injection-well disposal to those for each of the alternatives, and are shown in **Table 3**. Results are considered significant in terms of orders of magnitude only.

In addition, results should not be compared among constituents. For example, arsenic risks are expected to be lower than other risks because average arsenic concentrations in the effluent samples analyzed were lower than either existing or proposed surface-water and drinking-water standards, in contrast with other constituents selected for assessment. The relative risks of arsenic are shown to be comparable among discharge alternatives as expected (see **Table 3**).

In general, injection wells were assessed to represent lower health and ecological risks, assuming potential changes in Floridan Aquifer water quality in the vicinity of injection wells. Further, while there are no zero-risk options, all discharge alternatives evaluated are permitted under current regulations, though revised rules have been proposed for injection-well disposal. The maximum risks associated with the injection-well disposal option were associated with potential migration of effluent to ASR wells in the vicinity of injection.

Despite ASR wells having the greatest risk and being used for comparative purposes, all the assessed risks were low because of the geologic isolation and lack of ecological features within the aquifer, and because it was assumed that any contamination of ASR wells would be detected during operational withdrawals and that withdrawals would then stop.

In general, flows of human and ecological emissions affect the ecosystem in many ways. Large-scale regional treatment facilities in Miami-Dade, Broward, and Palm Beach counties, along with a number of smaller plants, routinely dispose of over several hundred million gallons per day. Risk indicators evaluated in this study were lower, in general, for injection-well disposal because of natural barriers between the injection point and population centers; however, all wastewater discharges of this magnitude impact hydrologic and chemical cycling.

In particular, flows of water, carbon, oxygen, nutrients, and many life-sensitive constituents of lesser concentration through the ecosphere are affected and should be considered in further studies. For example, indirect and direct effects on freshwater and chemical releases to estuarine environments should be considered in the context of previous substantial alterations in such flows through large-scale drainage in South Florida, and in the context of the current Everglades restoration.

It is also conceivable that in Southeast Florida, where outfalls lie within the influence of the Gulfstream, ocean outfall disposal contributes positively to the marine environment through the return of nutrients and organic matter. For example, it can be noted that no evidence of benthic accumulation of secondary effluent particles has been detected in the vicinity of the Southeast Florida outfalls.

Alternative Disposal Methods	**Relative Mean Believed Violation Days In 30 Years[1] (days/days)**			
	Arsenic	**Microbial (rotavirus or *Cryptosporidium parvum***	**NDMA**	**TKN**
Injection Well/Ocean Outfall	10^{-1}	10^{-3}	10^{-2}	10^{-1}
Injection Well/Surficial Aquifer Recharge	10^{0}	10^{-2}	10^{-2}	10^{-1}

[1]*Higher values represent higher potential frequency of, and/or higher uncertainty in the probability of, violating surface- and drinking-water standards given current treatment requirements, for a generalized scenario in Southeast Florida. Values less than one indicate a lower believed risk of violating standards for injection-well disposal relative to the alternative.*

Table 3: Relative Risk Indicators for Three Disposal Alternatives

It was not possible to conduct a quantitative assessment of risks associated with pharmaceutically active substances (PASs), because such compounds are still being identified chemically, concentrations in treated and natural waters are largely unknown, and environmental fates are uncertain. Currently these substances are not monitored, but such chemicals are being found in concentrations not recognized previously. Because of the widespread use of birth control, hormone replacement and other hormonally active drugs, and the lack of removal of PASs in conventional wastewater treatment, the potential risks associated with these compounds require significant further study.

Most direct evidence of toxicity is in the form of animal data; evidence in humans is currently limited. Additional data regarding effects of exposure in animals and humans are needed. Statistical pilot monitoring programs should be implemented on a broad scale as a basis for future policy development.

Further questions include treatment technologies for removal and the effects of natural processes such as microbial degradation, adsorption, dilution, and photochemical reactivity on the fate of PASs in the surface and subsurface environment. Estrogens may be useful as an indicator in future risk assessments because the compounds and their health effects are measurable.

In addition to PASs, the team felt that potential risks of blue-green algae and their toxins related to the discharge of treated wastewater effluent, also outside the scope of the current project, also deserve further study. Information on blue-green algae toxicity in Florida is limited at present, but several species of freshwater or freshwater-estuarine cyanobacteria, or blue-green algae, which produce cyanotoxins, occur in Florida waters.

Of samples collected in recent monitoring studies of recreational and surface drinking-water supplies in Florida with algal blooms, approximately half showed significant levels of blue-green algae, all of which were positively identified to contain blue-green algal toxins found to be lethal in mice. Because such algae are nitrogen-fixing, growth rate is independent of TKN levels but growth is enhanced with phosphorus concentration.

Even following AWT treatment, concentrations of phosphorus in wastewater effluent are two orders of magnitude greater than in natural South Florida surface waters. Further, cyanotoxins are not well removed in conventional flocculation and filtration, so blue-green algae may be a factor in the risks associated with the choice of wastewater discharge alternative that was not evaluated in this study.

There are important limitations to the results in this report. Some of these are related to the broad scope and generalized nature of the assessment, the currently limited implementation and regulation of ASR technology, uncertainties associated with emerging wastewater constituents of concern such as NDMA and PASs, and associated assumptions for the assessment.

The definition of risk as the probability of violation of a standard allowed a broad assessment based on limited available information; however, the definition limits the interpretation of results. In particular, numbers of exposed individuals were not explicitly compared. Further, the assessment was based on professional judgment, using current data for the region, applicable published literature information, and the experience of the team.

The results reported represent the first quantitative assessment of wastewater discharge risks of such scope and are therefore considered a starting point rather than an end. Nevertheless, the results are considered important for water-management planning

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and as a basis for further studies.

Cooperation with investigators in a similar and imminent study supported by the U.S. Environmental Protection Agency is planned, and the approach taken may represent an example for future assessments. It is recommended that in future studies, the number of individual risk events which expert teams are asked to assess be reduced through preliminary screening to more narrowly focus attention on significant risk events.

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