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Environmental Protection
Agency

Relative Risk Assessment of Management Options for Treated Wastewater in South Florida

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Executive Summary

WASTEWATER CHALLENGES IN SOUTH FLORIDA

Every day, more than 1.5 billion gallons of wastewater leave municipal treatment facilities in Florida bound for reuse or disposal. Municipalities in South Florida rely less on discharges to surface waters and more on reuse, ocean discharge and deep-well injection. For example, in Miami-Dade County, for every three gallons of wastewater generated, one gallon is treated and sent to deep underground saltwater formations. The other two gallons are piped out to the ocean, three and a half miles offshore. In dry-weather conditions in Pinellas County, for every three gallons of wastewater generated, all three gallons are reclaimed to golf courses, parks, and lawns after high-level treatment and disinfection. However, the Pinellas area receives on average forty-eight inches of rain annually, and deep-well disposal is heavily relied on as the backup during wet weather.

Each municipality in South Florida is faced with its own particular challenges to ensure, safe reuse and disposal of wastewater, safe drinking water and a healthy environment for its 5.8 million residents. Local municipalities are struggling to make sound wastewater management decisions, taking into account the often overwhelming complexities and the range of technical issues associated with different reuse and disposal options.

The State is strongly committed to protecting its surface waters, such as lakes, rivers, streams, wetlands, estuaries, and the ocean. It is equally committed to protecting the highly permeable aquifer systems that provide 94% of the area's drinking water. A major challenge to protecting water resources is Florida's growing population and the accompanying need for safe drinking water, safe reclaimed water reuse, and safe wastewater disposal.

The Environmental Protection Agency (EPA) has established minimum requirements for Class I municipal wells and other underground injection activities through a series of Underground Injection Control (UIC) regulations at Code of Federal Regulations (CFR) Title 40 Parts 144-147, developed under the authority of the Safe Drinking Water Act. These regulations ensure that Class I municipal wells will not endanger USDWs by prohibiting the movement of any contaminant into Underground Sources of Drinking Water (USDW).

On July 7, 2000, EPA proposed revisions to the UIC regulations that would allow continued wastewater injection by existing Class I municipal wells that have caused or may cause movement of contaminants into USDWs in specific areas of Florida (65 FR 42234). Continued injection would be allowed only if owners or operators meet certain requirements that provide adequate protection for USDWs. In the alternative, if new requirements are not promulgated, owners and/or operators of wells targeted by the proposal would be required to close their wells and adopt different wastewater disposal practices, which could consist of surface water disposal, ocean outfall, and/or reuse. Use of these alternative disposal practices would likely require the construction of systems for advanced wastewater treatment, nutrient removal, and high-level disinfection.

CONGRESSIONAL MANDATE FOR RELATIVE RISK ASSESSMENT

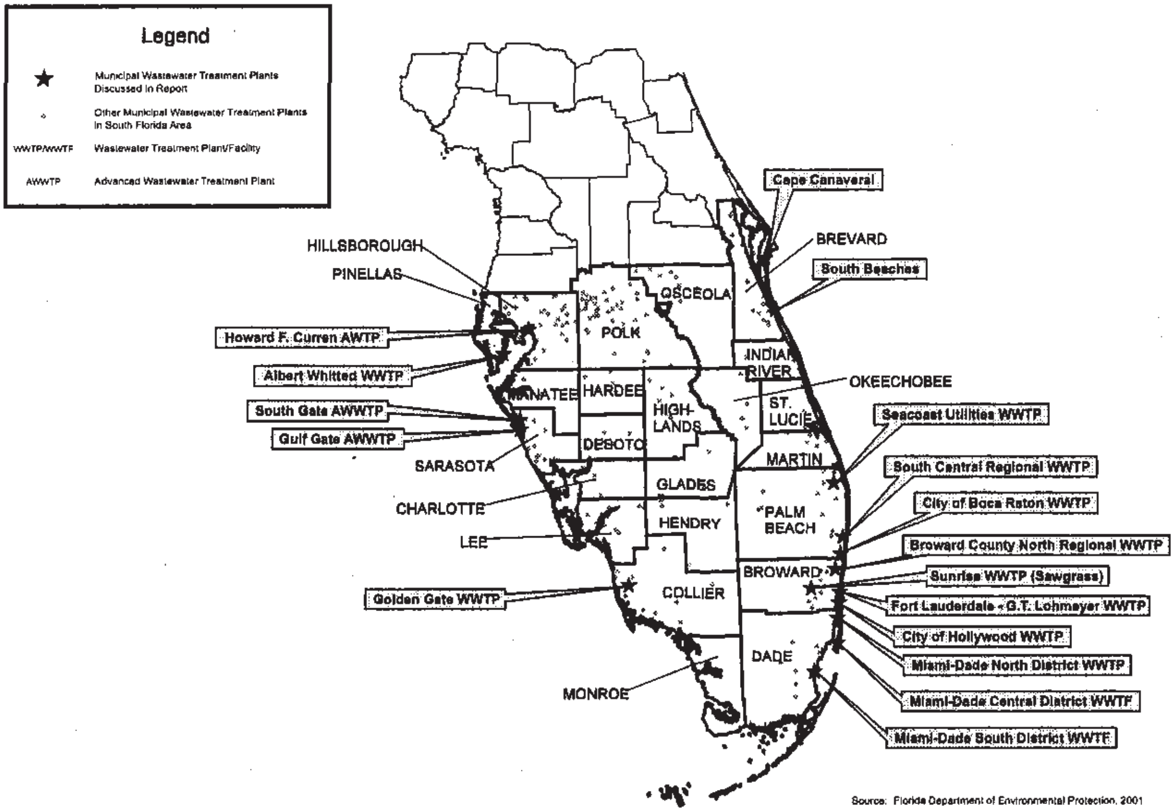
EPA, as directed by congressional language in its fiscal year 2000 appropriation, prepared the relative risk assessment presented in this report:

> *Within available funds, the conferees direct EPA to conduct a relative risk assessment of deep well injection, ocean disposal, surface discharge, and aquifer recharge of treated effluent in South Florida, in close cooperation with the Florida Department of Environmental Protection [DEP] and South Florida municipal water utilities.*

Congress directed EPA to conduct this assessment because wastewater injected into deep wells had moved from where it was supposed to be confined to areas where it is prohibited. Congress directed EPA to conduct the relative risk assessment to shed light on the risks posed by fluid movement from deep injection and relate those risks to risks posed by treated effluent from other wastewater management options.

MUNICIPAL WASTEWATER TREATMENT OPTIONS IN SOUTH FLORIDA

To capture all counties with deep-well injection, the South Florida area considered in the relative risk assessment extends south from a line drawn from the northern end of Brevard County on the east coast to the northern end of Pinellas County on the west coast (Exhibit ES-1).



Source: Florida Department of Environmental Protection, 2001

Exhibit ES-1. Municipal Wastewater Treatment Plants in South Florida

Wastewater Treatment Options

Florida primarily uses four options for the management of treated municipal wastewater (Exhibit ES-2):

- **Deep-well injection:** Wastewater is injected by gravity flow or under pressure into deep geological strata below USDWs. Under EPA and State UIC program regulations Class I wells inject fluids beneath the lowermost formation containing a USDW.
- **Aquifer recharge:** Reclaimed water is discharged to land application systems, such as infiltration basins and unlined ponds.
- **Discharge to ocean outfalls:** Treated wastewater is discharged to the ocean via outfall pipes that may extend from almost 1 mile to more than 3.5 miles from shore.
- **Discharge to surface-water bodies:** Wastewater is discharged into canals, creeks, and estuaries.

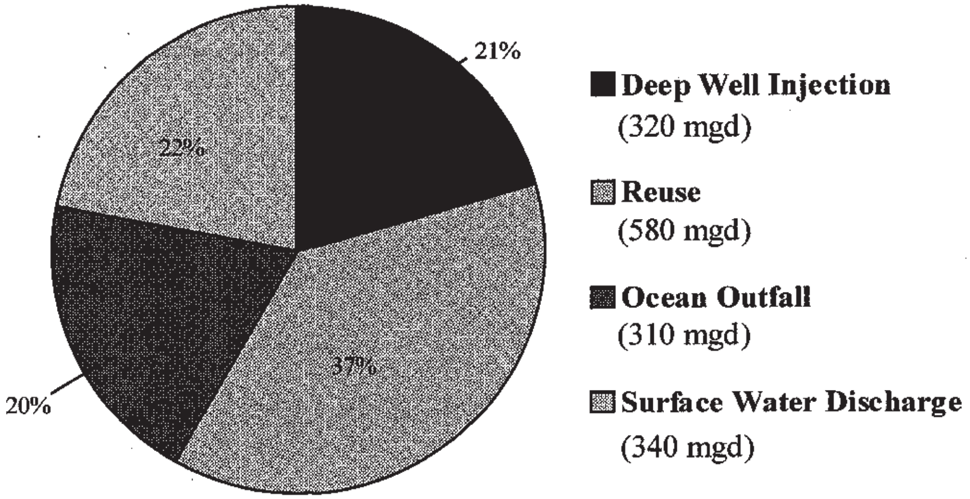


Exhibit ES-2. Use and Disposal of Effluent and Reused Water in Florida[1]

Although the term ***option,*** used to describe the wastewater treatment methods, suggests any of these are available for use by municipalities in South Florida, in fact most municipalities are limited by a variety of critical local conditions, governing regulations and costs in evaluating possible treatment methods. (Exhibit ES-3).

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[1] This chart uses data for the entire state of Florida. No specific data was available for the study area only. The distribution of waste treatment options within the study area is likely to be different than that presented in this chart (i.e. all ocean disposal and deep underground injection is in the Study area and there is much less use of surface water disposal in South Florida).

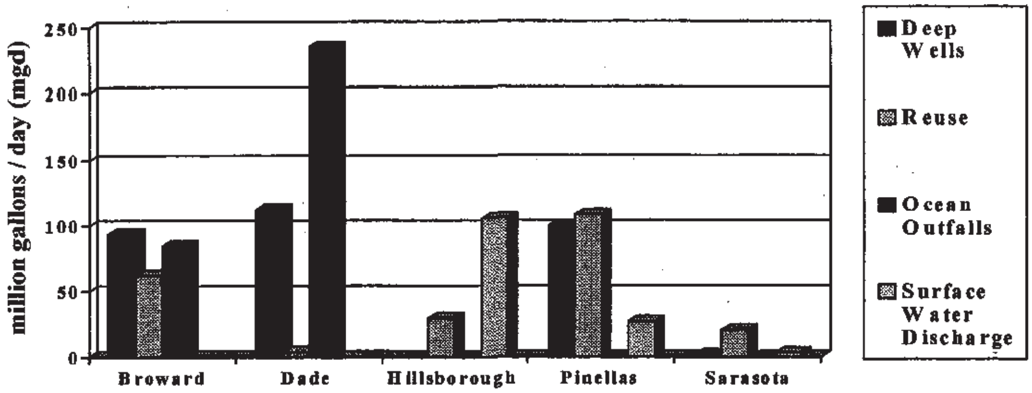


Exhibit ES-3. Wastewater Management for Selected Counties in South Florida

Levels of Wastewater Treatment and Disinfection

Wastewater treatment facilities in South Florida combine various levels of wastewater treatment and disinfection to arrive at effluent concentrations that are appropriate for the local conditions and that comply with State and EPA requirements.

- **Primary Treatment** is a basic treatment process that removes material that will float or settle.
- **Secondary Treatment** is a process in which bacteria consume the biodegradable organic matter and remove suspended solids using chemical and biological processes. The success of treatment may be quantified by its ability to remove Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS).
- **Reclaimed Water** in Florida means water has received at least secondary treatment and is reused. Some uses require high-level disinfection that includes filtration.
- **Advanced Water Treatment** (AWT) refers to treatment beyond secondary but in Florida it has specific regulatory meaning for a combination of treatments that includes secondary treatment, high-level disinfection, nutrient removal, and removal of toxic compounds (usually by filtration). AWT is used if there are requirements to remove specific components, such as nitrogen and phosphorus, which are not removed by secondary treatment alone.
- **Disinfection** is the selective destruction of pathogens. The State regulations define basic, intermediate and high-level disinfection with levels of filtration and bacterial deactivation.

Each of the four wastewater management options (deep-well injection, ocean outfall, aquifer recharge, and surface water discharge) provide different levels of treatment and disinfection, depending upon regulatory and site-specific needs. The levels for Biochemical Oxygen Demand, (BOD), Total Suspended Solids (TSS), Total Nitrogen (TN), and Total Phosphorus, (TP) shown in Exhibit ES-4 are required for some required discharges and do not apply universally to all (see Chapters 62-600 and 62-610 F.A.R.).

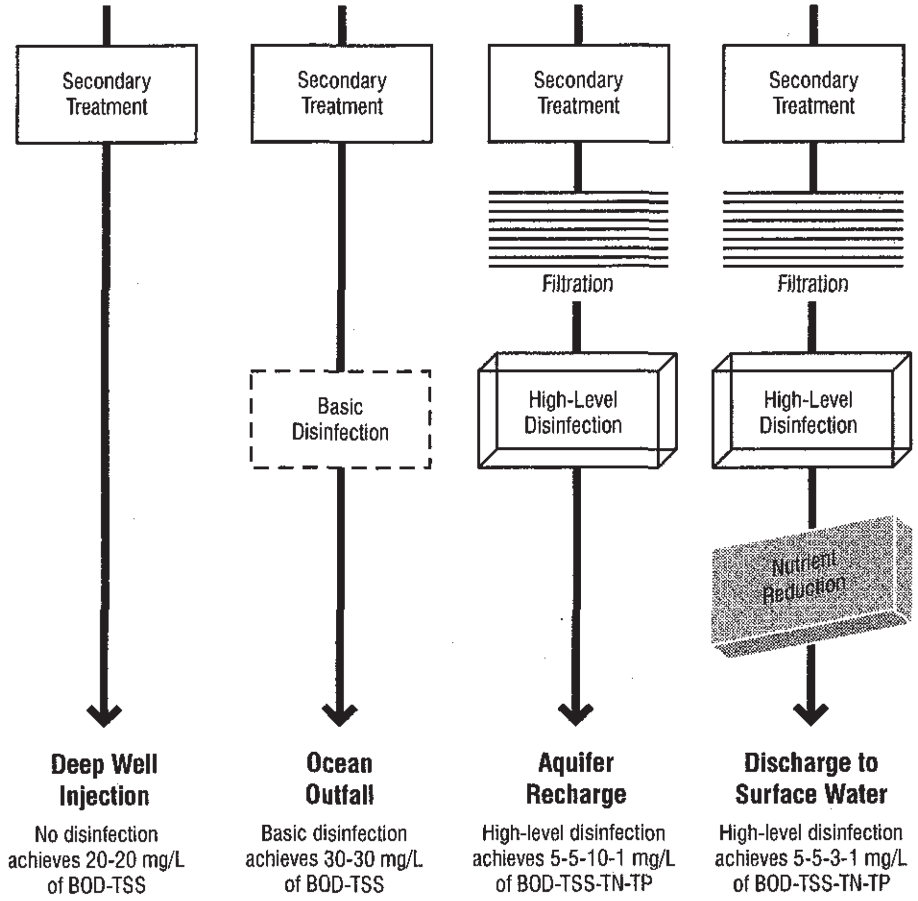


Exhibit ES-4. Levels of Treatment and Disinfection for the Four Disposal Options

RISK ASSESSMENT

Risk assessment is a multistep process. It evaluates the likelihood that adverse human health or ecological effects will occur as a result of exposure to stressors. A ***stressor*** is any physical, chemical, or biological entity that can induce an adverse response. The organism, population, or ecosystem exposed to a stressor is referred to as a ***receptor.*** ***Exposure*** refers to the contact or co-occurrence of a stressor and receptor. If there is no contact or co-occurrence between the stressor and the receptor, then there is no risk.

Risk characterization is the culminating step of the risk assessment process. It conveys the risk assessor's judgment about the existence of human health or ecological risks and their nature (US EPA, 2000). Information from the risk assessment steps is integrated and synthesized into an overall conclusion about risk that is informative and useful for decision-makers and for interested and affected parties.

Approach Used in This Relative Risk Assessment

The risk assessment conducted by EPA involved investigating four very different wastewater disposal options: deep-well injection, aquifer recharge, discharge to ocean outfalls, and discharge to surface-water bodies. Each option has its own specific stressors (hazards), exposure pathways, receptors, and effects.

Data from many sources were used to support the analyses and evaluations. Risk characterization for each wastewater treatment option included identifying and describing the associated risks, the potential magnitude of the risks, and potential effects on human and ecological health. The relative risk assessment then described and compared risks for all four wastewater management options.

This relative risk assessment first used a generalized approach to describe potential risks and identify possible stressors, sources, exposure pathways, and effects on receptors. This step incorporates human health and ecological risk components and provides a conceptual model of potential risk. A conceptual model was developed for each of the four disposal options. Exhibit ES-5 is an example of a conceptual model of potential risks developed for the relative risk assessment. Potential system stressors, exposure pathways, receptors, and the potential effects on receptors are identified in the model.

To assess the risks and to allow comparisons, EPA conducted individual risk assessments for each wastewater disposal option, and the risks associated with each were characterized. The risks and risk factors identified in each disposal option were then evaluated and described. The overall comparisons and conclusions are presented as relative risk assessment matrices. EPA found that the parameters that are relevant to one particular disposal option are not necessarily relevant to the remaining three. Therefore, a strictly quantitative comparison between the four options was not feasible.

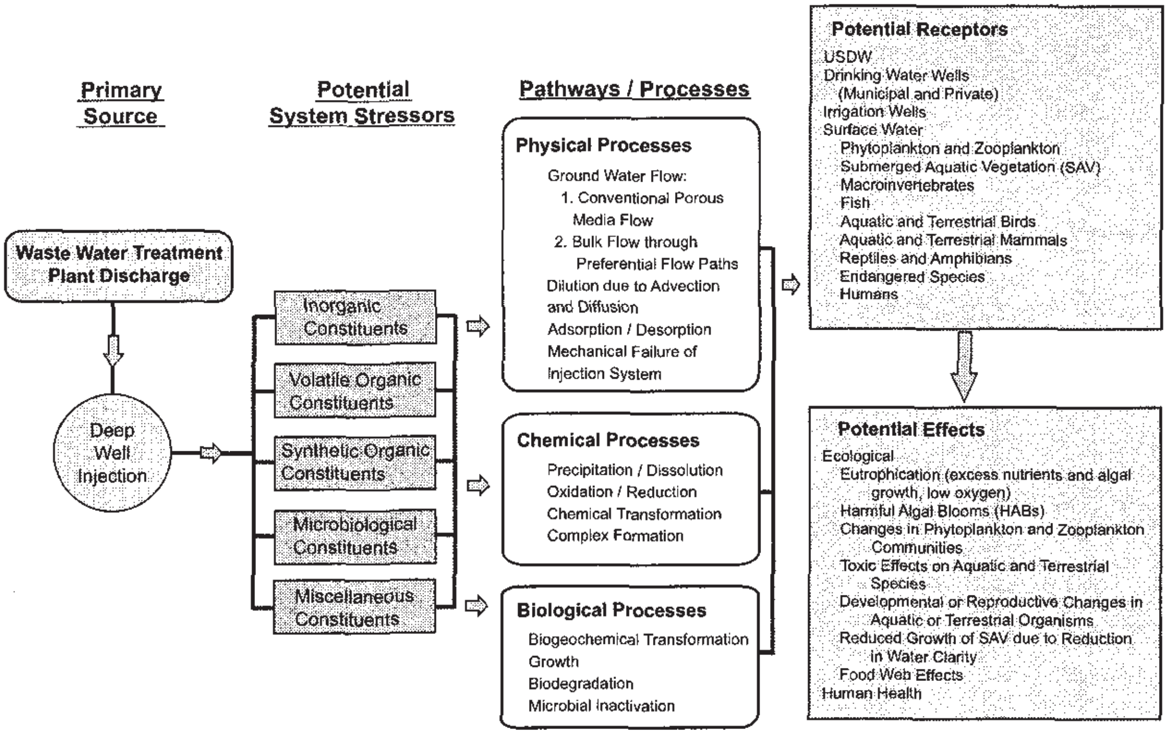
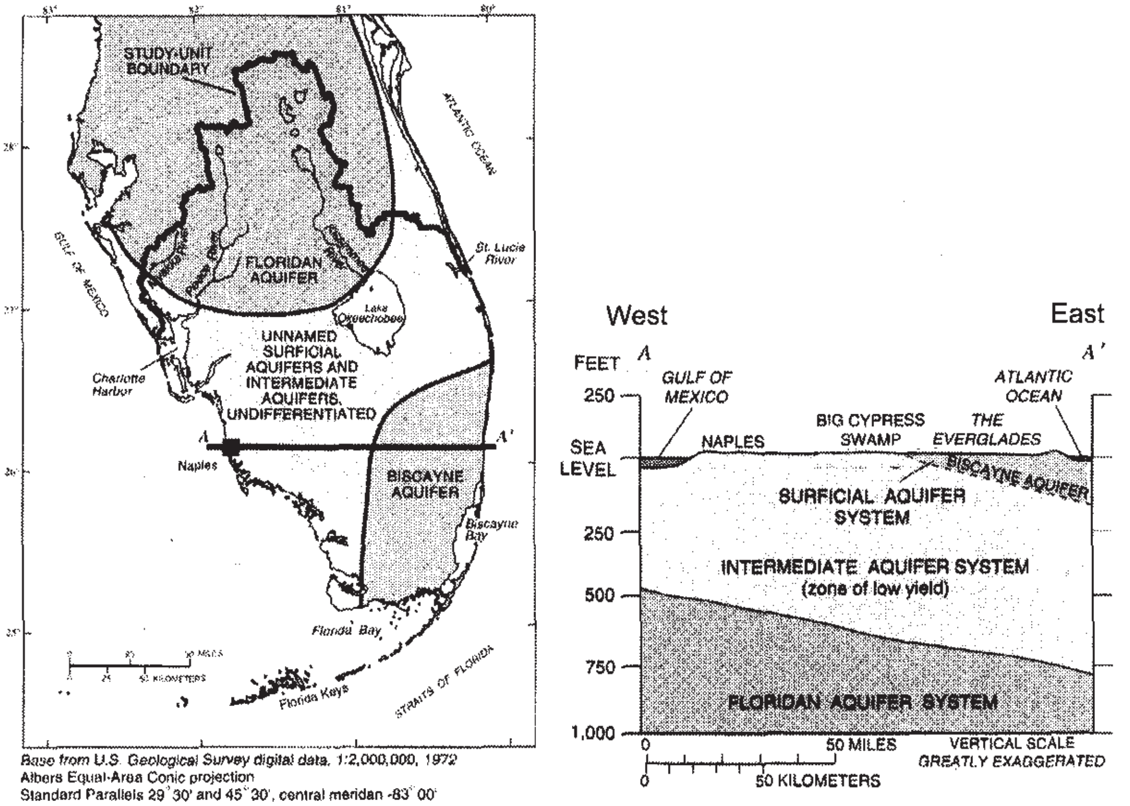


Exhibit ES-5. Conceptual Model of Potential Risks for the Deep-Well Injection Option

DEEP-WELL INJECTION

In South Florida, the most common means of disposal for treated municipal wastewater is by deep-well injection. Deep wells typically inject at depths ranging from 650 to greater than 3,500 feet below land surface, depths that are considerably deeper than the aquifers used for drinking-water supply wells. However, it is acknowledged that in some parts of South Florida, injected water has moved upward into overlying layers and, in some cases, into the base of the area designated as the underground source of drinking water (USDW).

The Upper Floridan Aquifer and the Biscayne Aquifer are the main water sources in the South Florida region (Exhibit ES-6). The Floridan Aquifer is extensive and underlies parts of Alabama, southeastern Georgia, southern South Carolina, and all of Florida. It is divided into the Upper Floridan and Lower Floridan aquifers, which are separated by a middle confining unit.

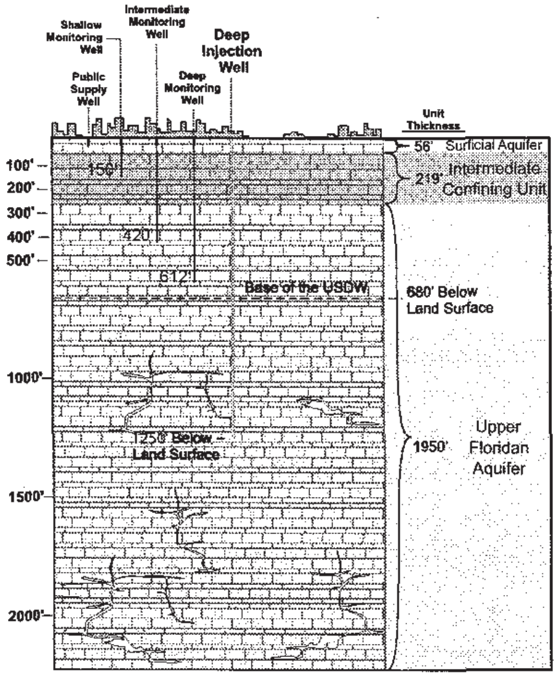


Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30' and 45°30', central meridan -83°00'

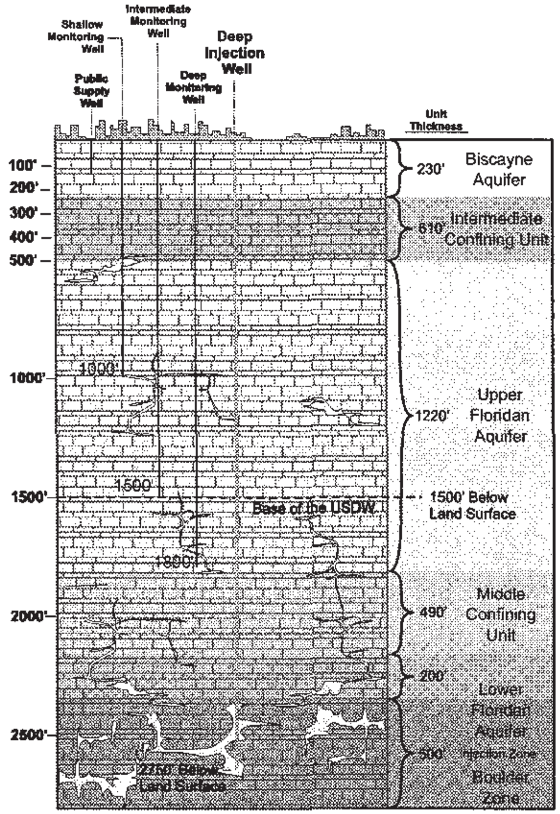
Source: McPherson et al (2000)

Exhibit ES-6. Hydrologic Profile of South Florida Aquifer System

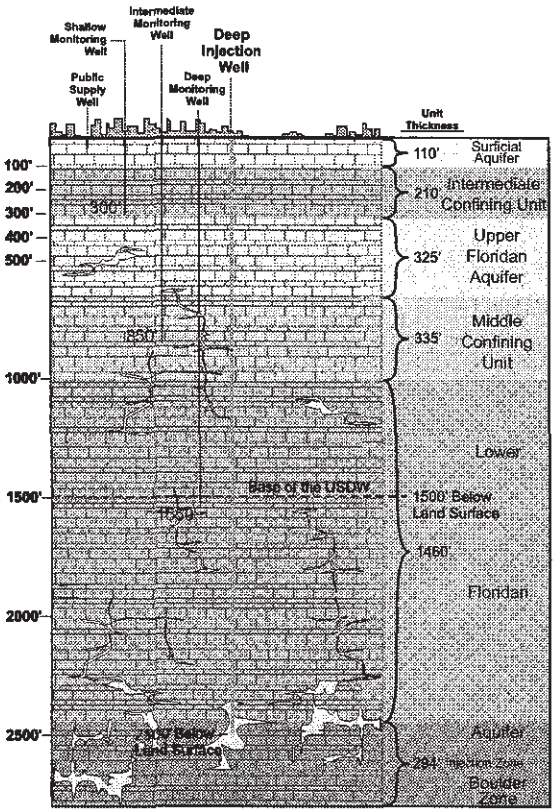
In the southeastern part of South Florida, the Floridan Aquifer is overlain by a relatively shallow surficial aquifer, the Biscayne Aquifer. In general, the surficial aquifer is composed of relatively thin layers of sands with some interbedded shell and limestone (Exhibit ES-6). The surficial aquifer in Pinellas County is only about 56 feet thick; in Brevard County, it is only 110 feet thick (Exhibit ES-7). The underlying intermediate confining unit, which separates the surficial and Upper Floridan aquifers, is also relatively thin (about 219 feet thick in Pinellas County and 210 feet thick in Brevard County). These hydrogeologic characteristics mean that the surficial aquifer yields only small amounts of water. Thus, it is not a major source for public water supply, although it is used extensively for private water supplies. However, in southeastern Florida, the Biscayne Aquifer is the principal source of drinking water. In this area, both the aquifer and the underlying intermediate confining unit are thicker (more than 230 and 610 feet thick, respectively), which results in an increased water-bearing capacity.



Pinellas County, Florida



Dade County, Florida



Brevard County, Florida

Exhibit ES-7. Representative Hydrogeologic Cross Sections

The presence of the separating confining units (intermediate and middle), combined with the considerable depth to the deep-well injection zones, was considered to provide a sufficient level of protection to the water-bearing strata that supply public water. However, the relative safety of this disposal option is now in question because injected water is known to have migrated up to and, in some cases, into the USDWs.

Deep-well injection fluid is given a secondary level of treatment and the State does not require disinfection, although some facilities may dispose of excess (unused) reclaimed wastewater using Class I deep-well injection. Treatment beyond a secondary level is used to varying degrees in the three other disposal options included in the risk assessment (aquifer recharge, discharge to ocean outfalls, and discharge to surface-water bodies) (Exhibit ES-4).

Many parts of the United States use Class I injection wells for disposal of hazardous and nonhazardous fluids. In Florida, deep-well (Class I) injection is an important management option for treated municipal wastewater and accounts for approximately 20% (0.44 billion gallons per day) of the State's wastewater management capacity (FDEP, 1997). Most of this use occurs in South Florida, particularly southeastern Florida and in coastal areas. The wells inject large volumes of wastes into deep rock formations, which are required to be separated from sources of drinking water by layers of impermeable clay and rock.

The use of Class I wells in South Florida has been considered a safe and effective means of disposing of treated wastewater. However, ground-water monitoring data has indicated that, at some facilities, wastewater is not being adequately confined, resulting in unintended movement of the injected fluid into USDWs. At some locations, injected wastewater has migrated from the injection zone into overlying layers and is compromising USDWs. Of 93 facilities with deep injection wells in South Florida, 18 have been identified as having unintended movement of fluid out of the injection zone: 3 have confirmed fluid movement into the USDW, 6 are reported to have probable movement into the USDW, and 9 have movement into non-USDWs, (layers overlying the injected zone but below the USDW).

Regulatory Oversight of Deep-Well Injection

Federal and State regulations govern the siting, construction, operation, and management of Class I injection wells. A key UIC regulatory requirement prohibits the movement of any contaminant from a Class I injection well into a USDW. UIC regulations also specify well siting requirements, including specifications for constructing wells, for defining hydrologic conditions relative to the site, for ensuring the mechanical integrity of injection wells, and for proper operation and maintenance of wells. Class I injection wells must be cased and cemented to prevent the movement of fluids into or between USDWs. Injection pressures may not cause fractures in the confining zone or cause the movement of injection or formation fluids into a USDW. (40CFR146.12 and 13). In addition, the State requires that all Class I municipal waste disposal wells provide, at a minimum, secondary treatment.

In spite of these many regulations and controls, unintended migration of injected wastewater in South Florida has occurred. Therefore, the ability to maintain sufficient confinement between the injection zone and the USDW is in question.

Option-Specific Risk Analysis for Deep-Well Injection

The risk analysis of deep-well injection focused on Brevard, Pinellas, and Dade counties, because these counties are geographically representative (i.e. they are located in the three corners of the assessment area) and fluid movement, to some degree, has occurred in each location. A large volume of treated wastewater is injected into Class I injection wells. Subsequent migration of this wastewater and any dissolved or entrained wastewater constituents that remain after treatment can lead to exposure for receptors such as USDWs and water-supply wells.

Secondary treatment of wastewater with no disinfection does not remove all potential stressors to human health. Nitrate levels can exceed the Federal and State maximum contaminant level (MCL) for drinking water; pathogenic bacteria and viruses are not inactivated and may exceed standards for drinking water; and *Giardia* and *Cryptosporidium* levels may exceed Florida's health-based (reuse) recommended criteria.

Stressors to ecological health that may remain after treatment are generally limited to nitrates and phosphates. These are considered nutrients for ecological systems. When present in excess concentrations, they can destabilize the natural systems and cause eutrophication of aquatic systems. Given this characterization of the level of contaminants remaining in secondary treated effluent, a next step in the risk assessment was to examine the fate and transport of these contaminants in the sub-surface.

How Injected Wastewater Can Reach Drinking-Water Supplies

In general, injected wastewater can move upwards by porous media flow and by bulk flow. These represent two extremes: porous media flow is a slow fluid movement through connected pores in the rock matrix, and bulk flow is a more rapid flow through preferential paths, such as fissures, fractures, caverns, or channels (Exhibit ES-8). Bulk flow can also occur from improperly constructed and poorly maintained injection-well systems that lead to an incomplete seal between the well and its casing.

In most cases in South Florida, both porous flow and bulk flow mechanisms will contribute to upward migration. However, it is not possible to differentiate the contribution of each for a given location. Bulk flow is likely a major contributing process in South Florida, where there are karst geologic features. The most well known geologic feature in the area that can support bulk flow is the Boulder Zone. Located in the middle section of the Lower Floridan Aquifer (Exhibits ES-7 and ES-8), this highly developed and complex fracture zone has extensive cavernous pores, fractures, and widened joints that allow channelized groundwater flow, sometimes at extremely rapid rates.

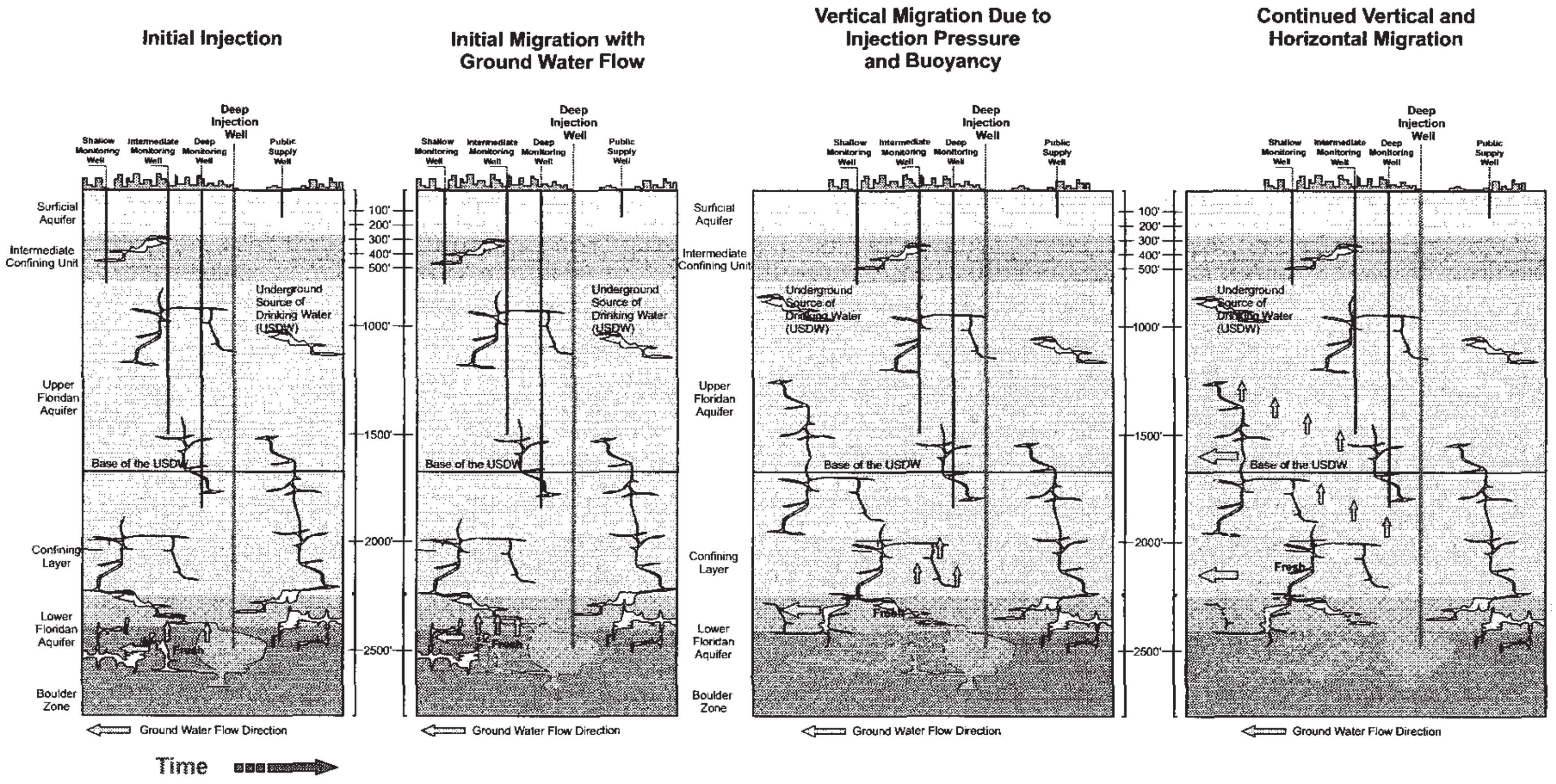


Exhibit ES-8. Migration of Wastewater by Bulk Flow from a Deep-Well Injection Zone. *Bulk flow and porous media flow contribute to migration and are influenced by several factors, including temperature, density, and injection pressure.*

Fluid movement underground is influenced by several factors. Temperature and density differences between native and injected waters affect buoyancy. The fluid density of injected wastewater is roughly equivalent to fresh water. However, wastewater is injected at depths where the native groundwater is saline or hypersaline. Buoyancy tends to force the comparatively lighter, less dense wastewater upward.

Injection pressure also influences fluid movement, but the degree of influence is affected by the geology. In parts of South Florida, where injection zones demonstrate a great capacity to accept injected fluid (for example, the Boulder Zone), the influence of injection pressure may be less significant. Regional differences in the effect of injection pressure were accounted for in the risk analysis by including Dade, Brevard, and Pinellas counties.

The exposure pathway for the stressors found in injected wastewater is upward migration of the injected wastewater into the base of USDWs. In some locations, this upward migration can occur relatively rapidly and with little dilution of stressors. In the area of the Boulder Zone, injected wastewater that has migrated upwards might pose some ecological health risk for the marine environment, were the fluid to migrate more than 2500 feet upward . There is little information currently available to assess such a risk.

Human Health and Ecological Risk Characterization of Deep-Well Injection

Deep-well injection for disposal of treated municipal wastewater has resulted in fluid movement into USDWs. In both Pinellas County and Dade County fluid has moved into the USDW.

The overall human health risk is lower for those USDWs that are deep, and exposure to stressors for currently used drinking-water sources is less likely. The current risk of human exposure is considered lower for Dade and Brevard counties, because the length of time required for contaminants to reach current drinking water supplies is long. However, the time of travel in the Pinellas County area is shorter because of the shallower aquifer depth and lack of confinement. The risk would be therefore higher for Pinellas County and exposure of current water supplies to stressors more likely but for the fact that Pinellas County effluent is subjected to high level disinfection. Failures within the injection system itself clearly increase risk. Improperly constructed or poorly maintained injection-well systems can result in decreased times of travel to receptors and in an associated increase in risks and exposures. However, there is no information to conclude that mechanical failures of Class I municipal waste disposal wells in South Florida have resulted in significant fluid movement into USDWs.

Ecological risk can result from nutrient enrichment of surface waters and the associated ecosystems. However, in South Florida, the risk is considered low because that movement is unlikely. There may be an increased risk in situations where fluid migrates rapidly to surface-water bodies, as in a conduit or a bulk-flow scenario. Nutrient enrichment and other potential impacts to near-shore marine and estuarine environments could occur under such a scenario.

AQUIFER RECHARGE

Any practice that potentially results in the replenishment of a groundwater aquifer can be considered aquifer recharge. Treated municipal wastewater discharged onto the land may percolate through soils and underlying geologic media until it reaches and recharges the surficial aquifer. In Florida, several practices may be considered as aquifer recharge: irrigation, discharge to infiltration basins or absorption fields, and discharge to wetland treatment systems. The State defines reclaimed water as water that has received, at least, secondary treatment and disinfection and is reused after flowing out of a domestic wastewater treatment facility. Reuse is the deliberate application of reclaimed water for a beneficial purpose according to Florida requirements. The final use of the wastewater determines the specific treatment requirements.

Reuse of water for irrigation is significant in Florida. Of a total of 359 reuse irrigation systems, approximately one-half (179) are golf-course irrigation systems, while the other half is divided among irrigation for other public-access areas (98) and residential irrigation (82). Agricultural irrigation systems using reclaimed water number 117.

Reclaimed water is discharged at a rate that prevents surface runoff or ponding and that is within a designated hydraulic loading rate. Loading rates are based on the ability of the plant and soil system to remove pollutants from the reclaimed water, the infiltration capacity, and the hydraulic conductivity of the underlying geology. Slow-rate land application systems must have back-up disposal methods, such as discharge to a storage area or to deep-well injection, for wet-weather conditions and when water-quality treatment standards are not met.

Rapid-rate land application systems discharge reclaimed water to rapid infiltration basins or absorption fields. Infiltration basins operate in series and may include subsurface drains that receive and distribute the water. Absorption fields are subsurface absorption systems covered by soil and vegetation and may include leaching trenches, pipes, or other conduits that receive and disperse water. Rapid-rate systems are potentially high-volume systems. Because of the increased percolation, the loading rates are higher than for slow-rate land application, and rapid-rate systems do not require wet-weather alternatives. For these reasons, EPA focused on rapid-rate infiltration basins (RIBs) for the risk assessment.

Regulatory Oversight of Aquifer Recharge

Aquifer recharge as a wastewater management option is not specifically regulated, but the State regulates the reuse of reclaimed water and land application. State regulations specify system design and operating requirements. Backup treatment and holding capacity is required, in case of system interruption. Slow-rate land application must have back-up wet-weather disposal options. Wastewaters must meet water-quality criteria and must be tested for pathogenic protozoans. Setback distances from surface waters and from potable water sources are required, and Florida's wastewater-to-wetlands rule controls the quantity and quality of treated wastewater discharged to wetlands.

Option-Specific Risk Analysis for Aquifer Recharge

Rapid-rate systems have the potential of discharging large volumes of treated wastewater directly to the surficial aquifer. The public water supply in South Florida is generally drawn from wells about 250 feet deep and located in the surficial aquifer. In Pinellas County, the surficial aquifer is shallow, with a depth of about 56 feet. In Brevard County, the surficial aquifer extends to a depth of 110 feet. In Dade County, the surficial Biscayne Aquifer extends to a depth of 230 feet. Depending upon local groundwater conditions, rapid transport of reclaimed water to these shallow aquifers and current drinking water sources may occur. Similarly, surface-water bodies that are under direct influence of groundwater can be exposed to stressors in the discharged wastewater.

Reclaimed water that is bound for rapid-rate land application must have undergone secondary treatment and basic disinfection, and rapid-rate systems must meet, at the base of the discharge zone, groundwater criteria. Projects with permit applications after January 1, 1996 must provide high level disinfection. As a result, the concentrations of stressors are considerably reduced. Potentially remaining stressors in reclaimed water include metals and other inorganic elements (for example, nitrate, ammonium, phosphate), volatile and synthetic organic compounds, and microorganisms resistant to high-level disinfection. Cyst-forming pathogenic protozoans, such as *Cryptosporidium* and *Giardia,* are resistant to chlorination and basic disinfection and require specialized filtration for removal. Concentrations of these pathogenic protozoans typically meet Florida's health-based (reuse) recommendations in rapid-rate land application waters, but some exceptions have been reported. The disinfection byproducts, trihalomethanes, can pose a human health risk, but the concentrations in reclaimed water rarely exceed the health-based standards.

Just as with deep-well injection waters, stressors to ecological health that may remain in reclaimed water after treatment are nitrates and phosphates. Because they are nutrients, they can destabilize the natural systems and, when present in excess concentrations, can cause eutrophication of aquatic systems. Thus, the next step of the risk assessment, the analysis of the fate and transport mechanisms and a determination of the time of travel, was very important.

The time of travel for discharged effluent to move in groundwater to a receptor is site-specific and dependent on required setback distances, location and distance to receptor water-supply wells, direction of groundwater flow, the actual distance to potential receptor wells, and the aquifer's groundwater flow characteristics.

Natural attenuation processes were also analyzed to determine their affect on final constituent concentrations. Sorption, biological degradation, and chemical transformation of constituents can reduce their overall concentration during transport in groundwater. Rapid-rate infiltration and the associated shorter times of travel tend to limit natural attenuation.

Human Health and Ecological Risk Characterization of Aquifer Recharge

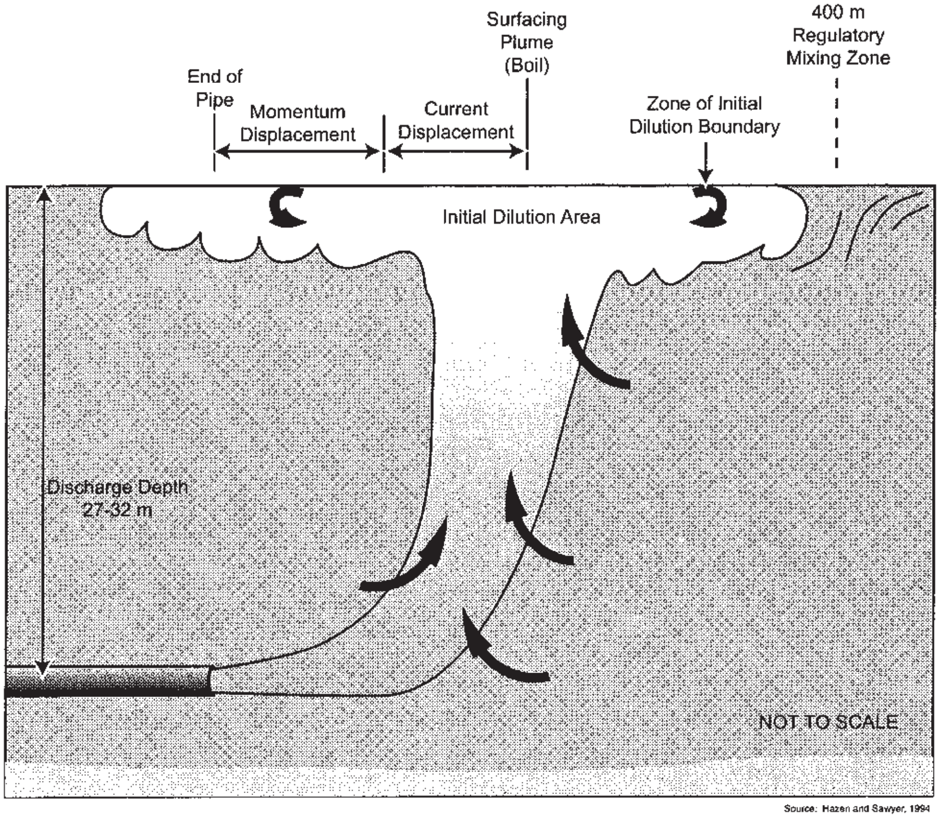
Because of the level of treatment, reclaimed water contains relatively few stressors, which generally are at reduced concentrations. Many constituents remaining in the treated wastewater are at levels that meet the respective drinking-water standards (MCLs). The average concentrations of the cyst-forming *Giardia* protozoan meet risk-based criteria. However, monitoring data from reuse facilities indicate the presence of *Giardia* in 58% of the samples, with detections frequently exceeding the stated recommendation of 1.4 cysts per 100 milliliters.

Although time of travel may be relatively short for some locations and indicate a higher potential risk, a high effluent transport rate does not result in a greater overall risk. Dade County, where the Biscayne Aquifer has a high hydraulic conductivity, has the shortest estimated travel times for treated effluent in groundwater to reach drinking-water supply wells: 0.11 year for a 200-foot setback, 0.28 year for a 500-foot setback, and 1.47 years for a 2,640-foot setback. In spite of these relatively short times of travel, there is little overall risk, because the final concentrations of stressors are below the respective drinking water standards (MCLs).

DISCHARGE TO OCEAN OUTFALLS

Six publicly owned wastewater treatment facilities located in coastal southeastern Florida currently use ocean outfalls to dispose of treated municipal wastewater. The total volume discharged is about 310 mgd. Before discharge, the wastewater undergoes secondary treatment, followed by basic disinfection. The treated wastewater is discharged through outfall pipes into the ocean at depths ranging from 27.3 to 32.5 meters and at distances between 0.94 and 3.56 miles from shore.

The outfalls discharge into the Florida Current, which flows northward to join the Gulf Stream. Circulation created by the Florida Current and associated eddy and rotary flows is important and the western boundary of the current is a major nutrient source for ocean productivity. Effluent discharged from the outfall forms a characteristic plume that tends to rise in seawater because it is less saline. However, the effluent is rapidly diluted and mixed with ocean water (Exhibit ES-9). The speed and direction of the currents are the primary factors that govern plume dispersal.



Source: Hazen and Sawyer, 1994

Exhibit ES-9. Effluent Plume Characteristics for Ocean Outfalls

The risk assessment for this option mainly focused on the potential effects on the marine environment. Discharge to the ocean has no effect on sources of drinking water. The receptors considered in this option are those that may have a direct exposure to seawater containing effluent constituents.

Regulatory Oversight of Discharge to Ocean Outfalls

The Clean Water Act and Florida law require that municipal wastewater receive at least secondary treatment before discharge to the ocean. When chlorine is used as a disinfectant, it must be used at the minimum concentration necessary to achieve water-quality standards. Higher concentrations of chlorine may lead to the production of trihalomethanes, which are a human health risk.

State-designated Class III Waters are used for recreation and for the propagation and maintenance of a healthy, well-balanced population of fish and wildlife. Effluent discharged into the ocean must meet the Class III standards for total suspended solids and for a 5-day biological oxygen demand.

There are additional requirements for the effluent when it meets the receiving waters. There are State and Federal water-quality criteria for effluent water at the end of the outfall pipe, within the mixing zone, and at the edge of the mixing zone. At the edge of the mixing zone, Federal, State, and local regulations require that the water meet surface-water quality standards.

Option-Specific Risk Analysis for Discharge to Ocean Outfalls

The focus of the risk analysis was the potential effects that discharges to the ocean may have on ecological receptors. In Florida, ocean waters are not currently used as a source for drinking water. Therefore, the ocean discharge option is not a human health risk through the drinking-water supply. Human exposure to seawater that contains effluent constituents may occur for recreational users (fishermen, boaters, and swimmers), industrial fishermen, and outfall operators and workers. Exposure may be through dermal contact, incidental ingestion of ocean water, ingestion of contaminated fish or shellfish (near or removed from the point of discharge), or exposure to toxins produced by harmful algal blooms. Ecological receptors include fish and other organisms that occur around the ocean outfall discharge point as well as those that are removed from the outfall but may be affected by the discharge.

Effluent constituents discharged to the ocean are those that typically remain after secondary treatment and basic disinfection: nutrients, inorganic and volatile organic compounds, synthetic organic constituents, metals, and microbial and miscellaneous constituents. The use of disinfection in addition to the secondary treatment reduces the concentrations of the bacterial and viral stressors; however, the disinfection byproduct, trihalomethanes, may occur. Trihalomethanes, a type of organic compound, can pose a human health risk. Although information is lacking, they may also be a health risk to marine life, such as marine mammals. Cyst-forming pathogenic protozoans, such as *Cryptosporidium* and *Giardia,* are resistant to chlorination and require specialized filtration for removal, and therefore, may be present as a stressor.

Potential receptors in the marine environment are numerous and range from submerged aquatic vegetation, plankton (phytoplankton, zooplankton), and larger aquatic organisms, including invertebrates, fish, reptiles, birds, and marine mammals.

Inorganic constituents, such as nitrogen and phosphorus, and metals, such as iron, are nutrients. However, if they are overabundant, they become stressors. In marine and coastal environments, eutrophication can occur when excess nutrients are present. This can produce harmful algal blooms (red tides), change the natural phytoplankton communities, destroy coral reefs, degrade sea grass and algal beds, and destabilize the overall marine community structure.

Dilution and transport, which are controlled for the most part by ocean currents, are important factors included in the risk analysis. Rapid dilution of effluent can reduce or eliminate potential adverse effects on receptors. In addition, chemical and biological processes that have the potential to affect the level of stressors were included in the risk analysis.

Human Health and Ecological Risk Characterization of Discharge to Ocean Outfalls

The risks associated with discharging effluent using ocean outfalls are low for both human and ecological receptors. There is no drinking-water receptors associated with ocean disposal and therefore, exposure through this pathway is unlikely.

Effluent plumes are rapidly dispersed and diluted by the Florida Current, and flows towards coastal areas are infrequent because of the current's prevailing direction and speed. The concentrations of potential stressors in the effluent plume are low, because of the secondary treatment and disinfection, permit effluent concentration limits, and the subsequent dilution of the effluent after discharge. The distances of the outfalls from shore also decrease risk, with those more distant having the lowest risk. Outfalls that have multiport diffuser systems seem to further reduce risk by dispersing the effluent over a wider area further reducing concentrations of potential stressors.

The treatment level used in ocean disposal does not remove certain pathogenic protozoans that could potentially affect human and ecological health. Pathogenic protozoans may pose a risk to marine mammals that come in contact with the effluent constituents. However, there is a lack of ecological health information on the effects of pathogenic protozoans, as well as other stressors, including metals, endocrine disruptors, and surfactants. Although the concentrations of these compounds may meet required water-quality standards, their effect on biological receptors at low concentrations is not understood. For example, endocrine disruptors operate at extremely low concentrations.

Although chlorinated effluent meets water-quality standards generally within 400 meters of the outfall, the long-term ecological effects of discharging effluent into the ocean are not understood. Currently, there are no long-term monitoring data available for these discharges to describe the ecological impacts or to determine what interaction there is, if any, between outfall constituent effects and terrestrial or coastal sources (such as pesticide runoff or river and groundwater inputs).

DISCHARGE TO SURFACE WATERS

Surface water disposal involves discharging treated wastewater directly into canals, creeks, and estuaries that may be brackish, coastal/saline, or fresh water. The wastewater must receive at least secondary treatment and basic disinfection before discharge. Advanced wastewater treatment is required in some locations.

The use of this option in South Florida varies greatly. Treatment facilities in Hillsborough County rely on this option for about 75% of their total design capacity, whereas facilities in Collier County discharge to surface waters about 1% of their design capacity.

Surface waters that receive discharges vary in physical, chemical, and biological characteristics. As a result, the uses and applications of this disposal option are very site-specific. The estuarine and lagoon systems that receive discharges are typically large expanses of mostly shallow water. Tampa Bay is the largest open estuary in Florida, encompassing over 400 square miles, with an average depth of 12 feet (Pribble et al., 1999). Sarasota Bay is about 56 miles long and about 300 feet to 4.5 miles wide. It has an average depth between 8 and 10 feet (Roat and Alderson, 1990). The Indian River Lagoon is comprised of several water bodies and stretches for about 156 miles, from south of Daytona Beach to near Palm Beach (Adams et al., 1996). Effluent entering these three major surface water systems must undergo advanced wastewater treatment.

These shallow surface-water bodies include many different and extensive features, such as wetlands, lakes, streams, and canals. In South Florida, many of these surface-water bodies have direct hydrologic connections to the underlying surficial aquifers.

Regulatory Oversight of Discharge to Surface Waters

Florida regulations require that wastewater receive at least secondary treatment and basic disinfection before discharge. Discharge to Class I waters (potable water supply) requires principal treatment, (defined within State requirements as secondary treatment, basic disinfection, filtration and high level disinfection) and discharges to the Tampa Bay, Sarasota Bay, and Indian River Lagoon systems require advanced wastewater treatment. Additional permitting requirements may include that effluent meet certain effluent limits, such as technology-based effluent limits or water-quality-based effluent limits.

State-mandated discharge standards apply for overall pollutants, nitrogen, total suspended solids, and fecal coliforms. Currently, there are no Federal or State limits for protozoan pathogens in wastewater but Florida applies its reclaimed water standard (no more than 5.8 cysts or oocysts per 100 liters for *Cryptosporidium* and no more than 1.4 cysts per 100 liters for *Giardia*) to wastewater discharged to surface waters.

Water-quality standards also apply to discharges to surface waters. The standards are dependent on the end-use class of the receiving surface water. The following classes are relevant to the risk assessment: Class I surface waters may be used as a potable water supply; Class II waters may be used for shellfish propagation or harvesting; Class III water may be used for recreation or can support the propagation and maintenance of a healthy, well-balanced population of fish and wildlife.

Option-Specific Risk Analysis for Discharge to Surface Waters

Because of the variability between and within the receiving surface waters and the regulatory standards governing them, the human health and ecological risks associated with this option are site-specific. To overcome this challenge, surface-water quality was the major parameter used in the risk analysis. The water quality of discharges was compared to the relevant surface-water quality standards. The risk analysis also examined the types of adverse effects that might be anticipated when standards are exceeded.

The potential stressors associated with this option can vary substantially, depending upon the level of treatment applied to the wastewater, but may include nutrients (nitrogen and phosphorus), metals, organic compounds, pathogenic microorganisms, and hormonally active agents. Metals remaining in discharged effluent may be taken up and bioaccumulate in the food chain to potentially toxic levels. Excess nutrients, particularly nitrogen and phosphorus, are stressors and can have a significant effect on aquatic ecosystems. Excess nutrients can change biological productivity and community structure and cause harmful algal blooms.

Before discharge to surface water, wastewater must undergo secondary treatment and basic disinfection. Stressors in wastewater subjected to secondary treatment and disinfection are similar to those remaining in water bound for ocean disposal, that is, inorganic and volatile organic compounds; synthetic organic constituents; microbial and miscellaneous constituents; and trihalomethanes, a disinfection by-product. However, wastewater discharged to Tampa Bay or to Indian River Lagoon must be treated using advanced wastewater treatment. This typically includes secondary treatment, basic disinfection, nutrient removal (nitrification, denitrification, and phosphorus removal), removal of metals and organic compounds, and filtration to remove cyst-forming protozoans.

In many cases, it is not possible to identify the source of stressors in surface waters. In South Florida, surface-water quality shows significant degradation that may be from urban and agricultural activities (McPherson et al., 2000; McPherson and Halley, 1996). Canal water in urban and agricultural areas commonly contains high concentrations of nutrients, coliform bacteria, metals, and organic compounds when compared to water taken from remote areas. The relative contribution of stressors from these sources compared to the contribution from effluent discharge is poorly understood.

Contamination of Florida's coastal environments with enteric viruses, bacteria, or protozoans is a widespread and chronic problem. Potential causes include the prevalence and high density of septic systems, the predominantly porous and sandy soils, the karst topography, and the hydrologic connections between groundwater and coastal embayments and estuaries (Lipp et al., 2001; Paul et al., 1995). The disinfection of treated effluent before discharge eliminates most pathogens. However, pathogenic protozoans are resistant to disinfection and can persist in effluent.

Under optimal natural conditions, estuaries and lagoons are some of the most productive and diverse habitats. Potential receptors are many and range from microscopic phytoplankton and submerged aquatic vegetation to reptiles, birds, marine mammals, and humans. Threatened and endangered species, such as the West Indian manatee and green and loggerhead sea turtles, can be found in these estuary and lagoon areas. Of the almost 800 fish species known to occur in east-central Florida, more than half use the estuaries and lagoons during part of their life cycle (Gilmore et al, 1981; Gilmore 1995). These shallow waters are important breeding and spawning areas for many fish.

USDWs or water-supply wells may be affected where surface waters that receive effluent have a direct hydrological connection to the groundwater resource. In South Florida, there is a strong interconnection of groundwater and surface water, but the processes and hydrologic fluxes are not well understood. Canals, which frequently receive discharge, are often hydrologically connected to groundwater. Whether the canal is being recharged or is discharging to groundwater depends on the specific hydrologic conditions, but canals that discharge to groundwater provide a pathway for potential contamination of the underground drinking water supply.

In addition to USDWs, human health exposure can include dermal contact with an affected water body, incidental ingestion of affected water, ingestion of contaminated fish or shellfish (near or removed from the point of discharge), or exposure to toxins from harmful algal blooms. Ecological resources can include fish and other organisms present in the surface water body at the point of discharge as well as those that are removed from but may be affected by the discharge. Also, nutrient loading can adversely impact waters, especially sensitive or impaired waters, and this in turn can destabilize the aquatic system.

Human Health Risk and Ecological Risk Characterization of Discharge to Surface Waters

Effluent discharged to surface waters poses limited risks to human health. The volumes discharged in South Florida are not great, there is a generally higher level of effluent treatment, and the discharges are typically intermittent. Although not required at all treatment plants, AWT is used to remove additional nutrients, organic compounds, and total suspended solids. Facilities using this treatment level frequently are within the standard requirements and may be below detection levels for some effluent constituents (for example, pathogenic microorganisms, inorganic compounds, organic compounds, volatile organic compounds). Pathogenic protozoan levels are generally low and usually within recommended standards. However, some facilities did not meet the recommended levels, even when using filtration. In these cases, there is a potential human health risk, albeit a low risk.

Similarly, the overall risk to ecological receptors is low. This is because most facilities use AWT. For example, based on information collected before and after Tampa Bay implemented AWT, the relative risk of AWT-treated wastewater is lower than the risks posed by wastewater treated to a lesser degree.

Although the risk analysis identified limited human health and ecological risks associated with the discharge of treated effluent to surface-water bodies, the receiving surface waters in many cases are already significantly impacted by contamination from urban and agricultural sources. Additional inputs of nutrients, even from effluent containing low nutrient concentrations, are likely to pose some ecological risk. The cumulative effect of the various inputs into these surface waters is not currently understood. Considerable scientific study and public involvement would be needed to identify and address the problems associated with the relative contributions of different sources of stressors to these estuarine and lagoon waters.

OVERALL RISK ASSESSMENT

The degree of treatment of wastewater before its disposal is an important factor that controls the concentrations of stressors present at the receptor. Risk can be significantly reduced by attenuation factors, such as travel time, distance, filtration by geologic media, dispersion by groundwater or ocean currents, biological degradation, and adsorption.

Pathogenic microorganisms pose a significant human health risk for deep-well injection and discharge to ocean outfalls and, to a lesser extent, aquifer recharge and discharge to surface waters. Filtration can significantly reduce the level for pathogenic protozoans in treated water. However, natural water bodies may contain pathogenic protozoans at levels that exceed the recommended levels.

In addition, nutrient levels can still exceed ambient water-quality levels. Excess nutrients can lead to a variety of ecological problems and can affect entire ecosystems.

Most risk analyses have data and knowledge gaps, and it is important to acknowledge and understand their extent and type. This risk assessment identified data and knowledge gaps for all the options (Exhibit ES-10).

Deep Well Injection	Aquifer Recharge (using RIBs)	Discharge to the Ocean	Discharge to Surface Waters
Site-specific mechanisms of transport (for example, porous media flow vs. conduit flow); locations and connectivity of natural conduits such as solution channels. The fate and transport of pathogenic microorganisms; rates of die-off and natural attenuation. The extent of, if any, reduction in inorganic stressor concentration resulting from local geochemical conditions (for example, rate of biologically mediated transformation of ammonia). Groundwater monitoring data to describe transport to (or within) the Biscayne and surficial aquifers.	Site-specific hydrologic data (for example, horizontal hydraulic conductivities); site-specific estimates of horizontal time-of-travel. Groundwater monitoring data to describe transport within the Biscayne and surficial aquifers. Geospatial data to describe proximity to water-supply wells (especially private wells). Fate and transport of pathogenic micro-organisms still present after disinfection; rates and die-off.	The potential for adverse ecological effects near outfalls. The potential for bioaccumulation (such as metals, persistent organic compounds) through food chains. Water-quality and ecological monitoring downcurrent of outfalls (beyond mixing zones). The potential for changes in ocean currents, sea level, or climate that might affect changes in circulation and transportation patterns or exposure.	The potential for adverse ecological effects near points of discharge. The potential for bioaccumulation (such as metals, persistent organic compounds) through food chains. Water-quality and ecological monitoring data for specific potentially impacted water bodies. The nature and extent of recharge to surficial USDWs.

Exhibit ES-10. Data and Knowledge Gaps

Findings on Risk to Human Health

Overall, the risks to human health are generally low for the four disposal options (Exhibit ES-11). The risks are somewhat higher in all options when there is less treatment or when exposure pathways are short. High-level disinfection, combined with filtration for pathogenic protozoans (using an effective process), significantly reduces risk for all the disposal options. There is an increased risk to human health when the disposal location coincides with recreational uses, such as the ocean (outfall location), canals, streams, bays, and lagoons, and when discharges cause harmful algal blooms. Deep-well injection and aquifer recharge disposal options have the potential to directly impact drinking-water supplies, thereby creating a potential risk to human health.

Deep-Well Injection	Aquifer Recharge (using RIBs)	Discharge to the Ocean	Discharge to Surface Waters
Low where proper siting, construction, and operation result in physical isolation of stressors, with no fluid movement. Low where there have been impacts to deep USDWs; however, exposure of current water supplies is unlikely. Increased risk where short times of travel prevail and where exposure of current water supplies is more likely. In all cases, the risk would be further reduced when injected wastewater is treated to reclaimed water standards.	Low because of high-level disinfection, filtration, and treatment to reclaimed-water standards. Increased risk where filtration is not adequate to meet health-based recommendations for Giardia or Cryptosporidium. Increased risk where chlorination results in high levels of disinfection byproducts (that is, failure to dechlorinate).	Low because of rapid dilution and an absence of drinking-water receptors. The low occurrence (less than 4%) of current flow towards the coast means that human exposure along coastal beaches is reduced. Increased risk where recreational use is near the discharge. Increased risk where discharges contribute to stimulation of harmful algal blooms.	Low because of high-level disinfection and additional treatment (e.g. AWT standards). Increased risk where filtration is not provided or is inadequate to meet health-based recommendations for Giardia or Cryptosporidium. Increased risk where surface-water discharges are near recreational use of water bodies. Increased risk where discharges contribute to stimulation of harmful algal blooms.

Exhibit ES-11. Estimate of Risk to Human Health Associated With Each Wastewater Disposal Option

Findings on Risk to Ecological Health

The risk to the ecological health of surface waters is very low for the deep-well injection and aquifer recharge options (Exhibit ES-12). Similarly, the risk to surface waters receiving treated discharge directly is low because of the advanced level of treatment the wastewater receives. However, irrespective of the contribution of contaminants by treated municipal wastewater, many surface waters in South Florida are considered to be in an impaired status. When a discharge is in close proximity to an impaired water body, there is a higher ecological health risk.

Deep-Well Injection	Aquifer Recharge (using RIBs)	Discharge to the Ocean	Discharge to Surface Waters
The risks from chemical constituents are low but not zero because of possible hydrologic connectivity. Risks related to pathogenic microorganisms are low to moderate for Dade and Brevard counties because of lack of disinfection and filtration. Microbial risk is low in Pinellas County because of use of disinfection and filtration.	Low because of possibility of hydrologic connectivity between wetlands and surficial aquifer. Cumulative and long-term effects are not known.	Low because of the concentrations of nutrients in the discharged effluent. No ecological monitoring is currently conducted. Cumulative and long-term effects are not known.	Low because of the concentrations of nutrients in the discharged effluent.

Exhibit ES-12. Estimate of Risk to Ecological Health Associated With Each Wastewater Disposal Option

Risks are also considered low for ocean outfalls in the areas outside the mixing zones and for marine ecosystems that may be impacted by deep-well injection.

Discharges from ocean outfalls and discharges to surface waters will have increased risk if the discharges cause harmful algal blooms or result in bioconcentration in food webs. Construction of new ocean outfalls may increase risk to coral reefs.

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1.0 INTRODUCTION

This report provides a relative risk assessment of four management options for treated municipal wastewater in South Florida. The four wastewater management options evaluated by the study are the following:

- Disposal via deep-well injection
- Aquifer recharge
- Ocean outfall disposal
- Disposal via surface-water discharge.

The study described in this report compiles new and existing sources of information and provides an evaluation of potential human health and ecological risks associated with the four wastewater management options studied.

1.1 Congressional Mandate

This study was conducted in response to a Congressional mandate included in the fiscal year 2000 appropriation language:

> *Within available funds, the conferees direct EPA to conduct a relative risk assessment of deep-well injection, ocean disposal, surface discharge, and aquifer recharge of treated effluent in South Florida, in close cooperation with the Florida Department of Environmental Protection and South Florida municipal water utilities.*

1.2 Purpose

There is an immediate need for information that will assist EPA, Florida regulatory agencies, and concerned stakeholders to determine an appropriate course for proposed revisions to rules concerning Class I underground injection wells in South Florida. These wells inject treated wastewater below the lower most underground source of drinking water and the surficial aquifers that provide much of Florida's drinking water. Groundwater monitoring information indicates that the injected wastewater has migrated from the injection zone into overlying layers of the subsurface. Stakeholders have expressed concern that such migration may compromise drinking-water sources.

This risk assessment will provide information that regulators, utilities, and communities in South Florida can use to make informed judgments and decisions regarding wastewater management.

Wastewater management involves complex and interrelated issues, many of which are beyond the scope of this risk assessment. Examples of such complex issues include modified wastewater management approaches, changes in the required level of treatment, encouraging flexibility in use of management options and backup methods, economic comparisons relating risks to management costs, and consideration of water conservation and water quantity. However, a risk assessment that takes all of these issues into account would far exceed the scope and available resources for this study. Accordingly, this risk assessment has been designed to address the Congressional mandate directly. It does not attempt to assess the full range of risk-related considerations that figure into wastewater management decision-making.

Because the purpose of the study is to characterize potential risks to human health and the environment, this study does not incorporate an analysis of cost-effectiveness. As a result, operational lifespan, implementation and maintenance costs, and other economic issues will not be assessed. However, the potential for system failure for each of the four wastewater management options will be addressed, with particular emphasis on the potential for failure of deep injection wells.

The geographic area covered in this study includes areas south of a line drawn from the northern end of Brevard County west to the northern end of Pinellas County (figure 1–1). In an effort to focus data collection within areas exhibiting the most urgent wastewater management needs, the heavily populated counties of Dade, Palm Beach, Broward, Pinellas, Brevard, Sarasota, and Hillsborough were selected.

EPA acknowledges that this study area may or may not be entirely consistent with what has been traditionally considered as South Florida. However, EPA collected data and conducted this risk assessment within a study area that provides for the fullest and most informative evaluation of the human health and ecological risks associated with the four studied management options.

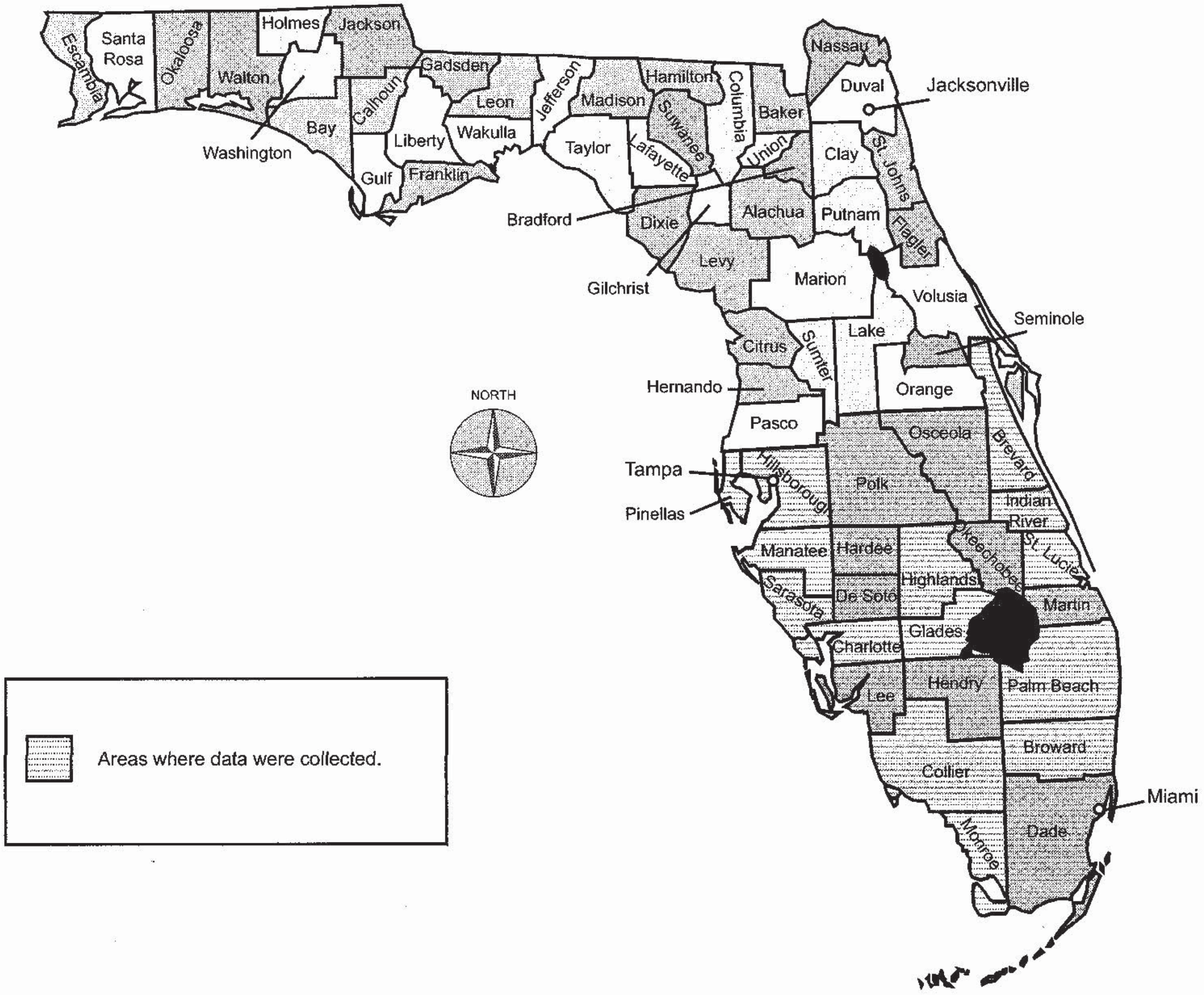

Figure 1-1. The South Florida Study Area

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2.0 BACKGROUND

This report analyzes risk in areas that are the most densely populated or that exhibit hydrogeologic conditions that will affect the risks associated with different wastewater management options. Wastewater management needs in South Florida are most critical in southeast Florida and in the more densely populated cities along both the Atlantic and Gulf coasts of Florida. The interior of South Florida and the Everglades have the lowest density of wastewater treatment plants. The distribution of public municipal wastewater treatment plants in South Florida is shown in Figure 2-1 (FDEP, 2002). Municipal wastewater treatment plants reviewed for this study are listed in Table 2-1, according to the county in which they are located.

The tables in Appendix 1 provide data on the water quality of treated wastewater. Other data used in this study are also presented in Appendix 1, including data on the following topics:

- Chemical constituents (Appendix Table 1-1)
- The Southeast Florida Outfall Experiment or SEFLOE (Appendix Table 1-2)
- Microorganisms in wastewater (Appendix Table 1–3)
- Groundwater monitoring of fecal coliforms (Appendix Tables 1-4 and 1-5)
- Injection well locations, capacities, and treatment (Appendix Table 1-6).

2.1 Wastewater Management Options Used in South Florida

Wastewater treatment facilities often incorporate multiple management options to ensure continuous operation. The capacity of South Florida counties to manage treated wastewater using different management options is illustrated in Figure 2-2. Discharge volume capacities, not actual flow volumes, are represented in this figure. Information for this figure was obtained from the Florida Department of Environmental Protection (DEP) wastewater facilities database (FDEP, 2002) and the Florida DEP (personal communication, Kathryn Muldoon, February, 2002). Note that the DEP database does not always distinguish between Class I deep injection wells and Class V shallow injection wells.

Broward, Palm Beach, and Dade counties discharge the majority of their treated wastewater through ocean outfalls and deep injection wells. In Hillsborough, Sarasota, Pinellas, and Collier counties, aquifer recharge can be done using reclaimed water, surface water discharge, or deep injection well disposal, depending on irrigation needs and weather conditions. Facilities in Brevard County discharge reclaimed water to the Indian River Lagoon only when there is no demand for irrigation water. Dade, Broward, and Palm Beach counties primarily use Class I deep injection wells and ocean outfalls to dispose of wastewater treated to secondary standards, but they also reuse a small amount of reclaimed water.

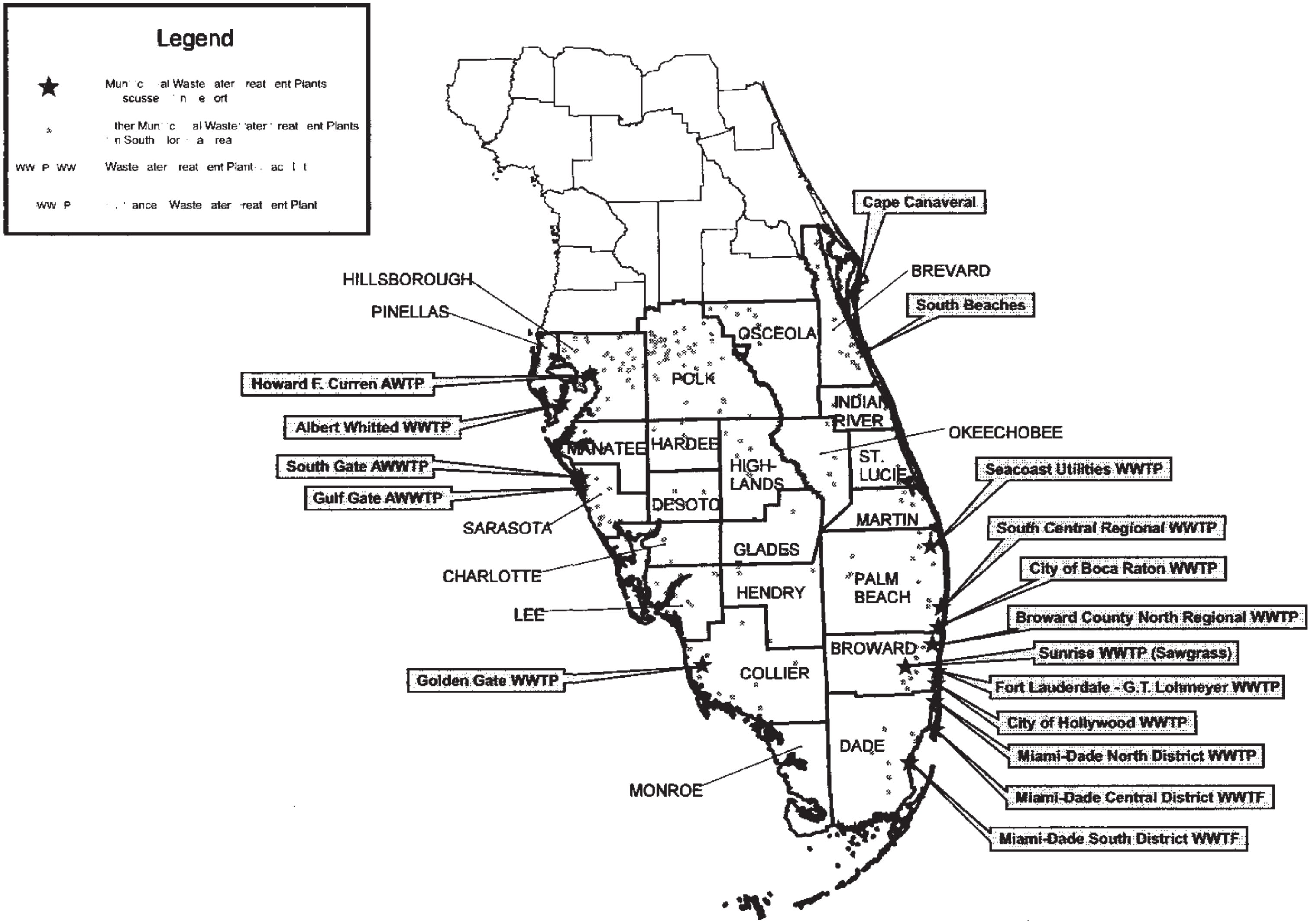

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Figure 2-1. Municipal Wastewater Treatment Plants in South Florida

Table 2-1. Wastewater Treatment Plants Discussed in This Report

Wastewater Treatment Plant	County	Type of Disposal	Treatment	Design or Current Capacity in mgd)[a, b]
Cape Canaveral	Brevard	Surface water, reuse	Secondary and High-level disinfection	1.80
South Beaches	Brevard	Surface water, reuse, deep-well injection[c]	Secondary and High-level disinfection	12.4
City of Fort Lauderdale[d]	Broward	Deep-well injection	Secondary	43
City of Sunrise (Sawgrass)[d]	Broward	Deep-well injection	Secondary	13
City of Hollywood[d, e]	Broward	Some Reuse, Ocean outfall	Secondary and High-level disinfection	42
Broward County North Regional[d, e]	Broward	Some Reuse, Ocean outfall, deep-well injection	Secondary and High-level disinfection	80
Golden Gate (Naples)[d]	Collier	Reuse	Secondary and High-level disinfection	0.95
Miami-Dade South District[d]	Dade	Deep-well injection	Secondary	112.5
Miami-Dade Central District[e]	Dade	Ocean outfall, deep-well injection	Secondary	121
Miami-Dade North District[d, e]	Dade	Ocean outfall, deep-well injection Some reuse	Secondary and High-level disinfection	112.5
Howard F. Curren (Tampa)	Hillsborough	Surface water, reclaimed	Advanced	96
Seacoast[d]	Palm Beach	Reuse and Deep-well injection	Secondary and High-level disinfection	12
Boca Raton[d, e]	Palm Beach	Some reuse, Ocean outfall	Secondary and High-level disinfection	20
South Central Regional/Delray Beach[d, e]	Palm Beach	Ocean outfall	Secondary and High-level disinfection	24
Albert Whitted	Pinellas	Deep-well injection, Some reuse[c]	Secondary and High-level disinfection	12.4
Gulf Gate[d]	Sarasota	Surface water	Advanced	1.80
South Gate[d]	Sarasota	Surface water, reuse	Advanced	1.36

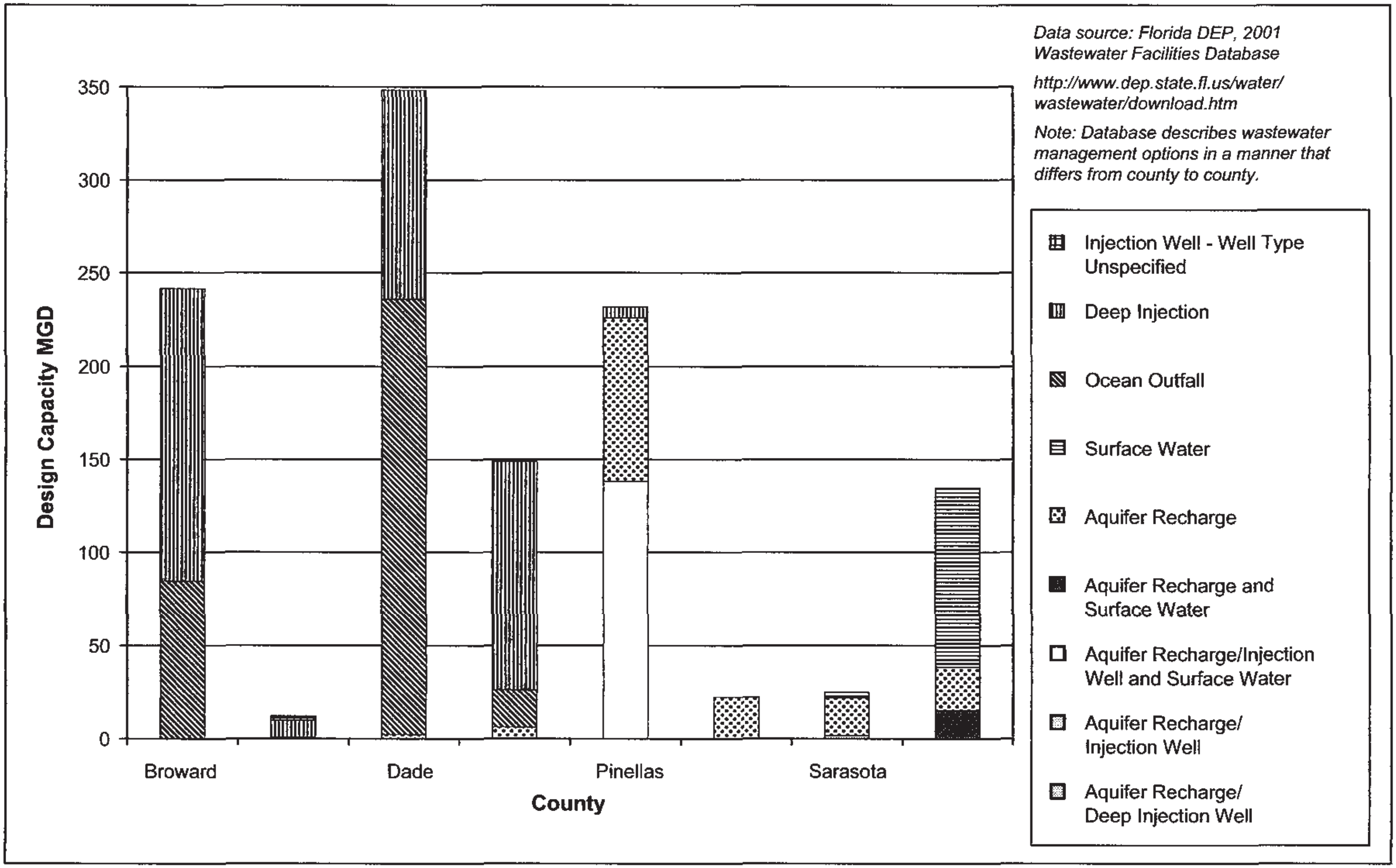
[a] mgd = million gallons per day

[b] FDEP, 2001

[c] US EPA, 1997

[d] Englehardt et al., 2001

[e] Hazen and Sawyer, 1994



Data source: Florida DEP, 2001 Wastewater Facilities Database

http://www.dep.state.fl.us/water/wastewater/download.htm

Note: Database describes wastewater management options in a manner that differs from county to county.

Figure 2-2. Wastewater Management Options and Design Capacities for Counties in South Florida

Approximately 1.2 million people are served by the Dade Central and Dade North District wastewater treatment plants, which discharge a total of approximately 230 million gallons per day (mgd) to the open ocean (Marella, 1999). Both outfalls have multi-port diffusers. In Broward County, approximately 80 mgd are treated and discharged to the Atlantic Ocean (Marella, 1999). (Note: This is 1995 data and may not reflect the impact of Class I injection wells that became operative in 1996; at this time, discharge to the ocean may have been diverted to the Class I wells.)

Wastewater treatment facilities located in Brevard, Collier, and Pinellas counties are permitted to discharge to surface waters. However, these facilities often use other management options, such as spray irrigation, in conjunction with discharges to surface water. When there is no need for spray irrigation, treated wastewater may be discharged into a surface-water body or injection well. For example, the South Beaches wastewater treatment facility in Brevard County discharges into the Indian River Lagoon when there is no demand for irrigation water.

In Sarasota, two wastewater treatment plants, Gulfgate and Southgate, discharge into freshwater canals (Phillippe Creek and Methany Creek). These eventually drain to Roberts Bay (Camp, Dresser, McKee, 1992; Roat and Alderson, 1990). The Sarasota facilities have no alternative for discharging wastewater and thus treat to advanced wastewater standards at all times.

In Pinellas County, the City of Clearwater and the City of Bellaire have permits to discharge to surface waters. Bellaire discharges to Clearwater Bay, and the City of Clearwater Northeast Wastewater Treatment Plant discharges to Tampa Bay. These facilities also have the option of reusing treated or reclaimed wastewater.

Each of the four studied methods of managing treated wastewater is described briefly below and in more detail in Chapters 4 through 7.

2.1.1 Class I Deep-Well Injection

Class I underground injection wells are used to dispose of secondary treated municipal wastewater to deep geologic strata. Injection zones are selected so that they are situated beneath the lowermost geologic formation that contains an underground source of drinking water (FDEP, 1999). An underground source of drinking water (USDW) is defined as an aquifer, or portion of an aquifer, with a sufficient quantity of ground water to supply a public water system and containing a total dissolved solids concentration of less than 10,000 milligrams per liter (mg/L) (FDEP, 1999; 40 CFR 144.3).

Class I wells are located throughout the South Florida study area, including Dade, Brevard, and Pinellas counties. Wastewater is injected at depths ranging from 650 to 3,500 feet below the land surface (US EPA, 1998). Management of treated municipal wastewater by Class I deep-injection wells constitutes approximately 20 percent (0.44 billion gallons per day) of the total wastewater disposal capacity in Florida, based on design capacity (FDEP, 1997).

Movement of injected fluids into USDWs by Class I is prohibited by Federal and State requirements. A major purpose of the Federal and State regulations is to protect the quality of USDWs by regulating the construction and operation of injection wells to ensure that the injected fluid remains in the injection zone. 40 CFR 146 establishes criteria and standards that apply to the construction, operation, and monitoring of Class I wells. Many specific regulations governing the construction and operation of injection wells serve to prevent fluid movement into USDWs.

Chapter 4 discusses deep-well injection in greater detail and examines potential human and ecological risks associated with this wastewater management option.

2.1.2 Aquifer Recharge

Aquifer recharge involves the infiltration of water into the ground and includes such practices as infiltration basins, percolation ponds, wetland treatment systems, and irrigation of turf, landscaped areas, and crops. Ultimately, these result in recharging groundwater aquifers and may benefit wetlands habitat as well. For these reasons, aquifer recharge using reclaimed wastewater is widely considered to be a beneficial reuse of treated wastewater.

Under the State of Florida's regulatory framework (the Florida Administrative Code [FAC]), Chapter 62-600 contains definitions of secondary treatment, disinfection levels, and requirements for effluent disposal systems; and Chapter 62-610 contains detailed requirements for a wide range of reuse options; and that Chapter 62-611 regulates discharges to wetlands.

Chapter 5 discusses aquifer recharge in greater detail and examines potential human and ecological risks associated with this wastewater management option. Wastewater treatment and disinfection is discussed in detail in Section 2.3.

2.1.3 Ocean Outfalls

There are six existing publicly owned treatment facilities that use ocean outfalls for management of treated wastewater in South Florida (Hazen and Sawyer, 1994). A seventh ocean outfall with limited discharge capacity is located in the Florida Keys, according to Hoch et al. (1995). The six major ocean outfalls in southeast Florida discharge effluent from the Dade Central District, Dade North District, City of Hollywood, Broward County, Delray Beach, and Boca Raton treatment facilities. The outfalls discharge secondary-treated chlorinated wastewater effluent at ocean depths ranging from 27.3 meters to 32.5 meters. Discharge points are located between 1,515 and 5,730 meters offshore.

The southeast Florida outfalls discharge along the western boundary of the Florida Current, a tributary of the Gulf Stream. The Florida Current is a fast-flowing current, with maximum current speeds occurring in the Florida Strait between southeast Florida and the Bahamas, in the vicinity of the southeast Florida outfalls. Maximum current speeds measured at the outfall sites during the Southeast Florida Outfall Experiment (SEFLOE) were upwards of 60 to 70 centimeters per second. The speed and strength of the Florida Current causes effluent plumes to be rapidly dispersed (Huang et al., 1998; Proni et al., 1994; Proni et al., 1996; Proni and Williams, 1997).

Chapter 6 discusses ocean outfall disposal in greater detail and examines potential human and ecological risks associated with this wastewater management option.

2.1.4 Surface-Water Discharges

Surface-water disposal consists of discharge of treated municipal wastewater into estuaries, lagoons, canals, rivers, or streams. Surface-water discharge of treated municipal wastewater is limited and discouraged in South Florida because of potential ecological and health concerns. There are no known permitted discharges into fresh water lakes or ponds in South Florida (personal communication, K. Muldoon, Florida DEP). Discharge into canals is the predominant form of surface-water discharge (Marella, 1999; Kapadia and Swain, 1996; Englehardt et al., 2001; personal communication, K. Muldoon, Florida DEP). Discharges into estuaries may also be permitted. Tampa Bay, Roberts Bay, and the Indian River Lagoon each receive surface-water discharges through discharges into canals or estuaries that empty into these coastal embayments (City of Tampa Bay Study Group, 2001).

Wastewater intended for discharge to certain coastal embayments generally must be treated to advanced wastewater treatment standards. Advanced wastewater treatment refers to secondary treatment, plus further removal of nitrogen and phosphorus to attain the 5mg/L $CBOD_5$, 5 mg/L TSS, 3 mg/L total nitrogen (as N) and 1 mg/L total phosphorus (as P) or treatment to water-quality-based effluent standards. Discharge to Tampa Bay and Indian River Lagoon areas must be treated to these standards. While it represents a reasonable assumption for the level of treatment required for surface water discharges, it is not a formal statewide requirement.

Most surface-water discharges are also subject to water-quality-based effluent limits (WQBELs) established using the processes outlined in Chapter 62-650, F.A.C. WQBELs generally include nutrient limits for nitrogen and phosphorus established to protect water quality in the receiving waters. This may include very stringent nutrient limits. While filtration may be needed to achieve the TSS limit, it is not specifically designed to remove pathogenic protozoa, nor is it required to do so. In addition, any new or expanded surface water discharge is subject to Florida's Antidegradation Policy.

Chapter 7 discusses surface water discharges in greater detail and examines potential human and ecological risks associated with this wastewater management option.

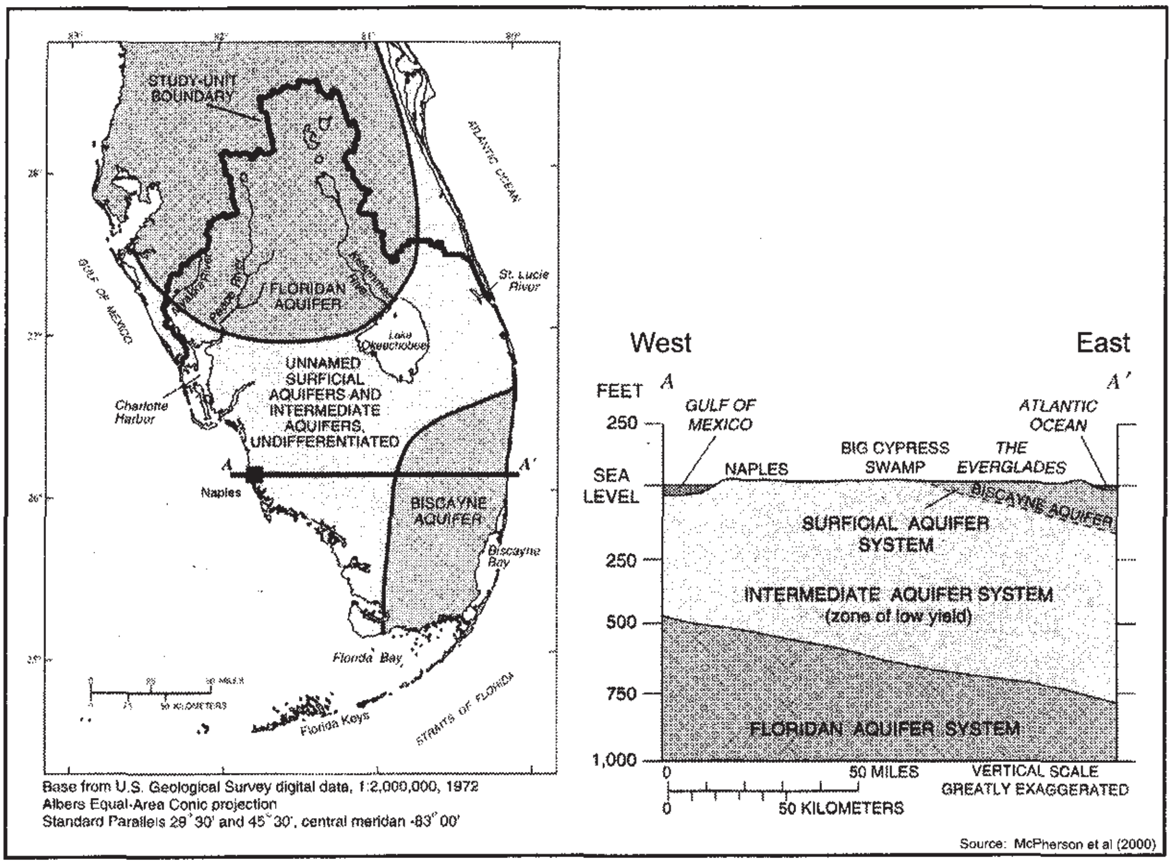
2.2 Drinking Water in South Florida

Concerns about potential effects on drinking-water quality lie at the heart of stakeholder anxieties regarding management of treated wastewater. In order to evaluate potential human health risks associated with these management options, it is important to understand the sources of drinking water used by South Florida communities.

The USGS National Water Quality Assessment Program (NAWQA) has estimated that ground water accounts for approximately 94 percent (872 million gallons per day, or mgd) of the water used by 5.8 million people in South Florida as of 1990, generally from wells less than 250 feet deep in the surficial aquifer. The remaining 6 percent of drinking water is supplied by surface water sources (McPherson et al., 2000). (Note that the NAWQA report encompasses an area of South Florida that is approximately similar to the area of this risk study, with the exclusion of a portion of Sarasota County and the inclusion of several other counties not addressed in this study.)

Most Community Water Systems within the geographic area covered by this study are supplied by ground water. As of October 18, 2001, a total of 133 Community Water Systems in five counties (Brevard, Broward, Dade, Palm Beach, and Pinellas Counties) provide ground water from their own wells or purchase ground water from nearby utilities. Current figures indicate that only 12 Community Water Systems provide surface water to their customers (US EPA, 2001).

Water suppliers that use ground water generally use either the Floridan Aquifer or the Biscayne Aquifer as a water source. The Biscayne Aquifer underlies 4,000 square miles in Broward, Dade, and Palm Beach Counties. The Miami-Dade Water and Sewer Department withdraws approximately 330 mgd from the Biscayne Aquifer for distribution to the City of Miami and surrounding communities. The City of Fort Lauderdale draws water from the Biscayne Aquifer as well. The City of St. Petersburg, in Pinellas County, purchases ground water (from the Floridan Aquifer).



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-Area Conic projection
Standard Parallels 29°30' and 45°30', central meridan -83°00'

Source: McPherson et al (2000)

Figure 2-3. Hydrologic Profile of South Florida Aquifer System

2.2.1 Floridan Aquifer System

The Floridan Aquifer System underlies approximately 100,000 square miles in southern Alabama, southeastern Georgia, southern South Carolina, and all of Florida. Several large cities in the southeastern United States use the Floridan Aquifer as a drinking water source, including St. Petersburg in Florida. In addition, the aquifer is a source of water for many smaller communities and rural areas. During 1985, approximately three billion gallons per day of fresh water were withdrawn from the Floridan Aquifer (USGS, 2000).

In most places, the Floridan Aquifer can be divided into two aquifers (the Upper and Lower Floridan aquifers) with a confining layer of material in between. The hydraulic properties and geology of the Upper Floridan aquifer are better known than the properties of the Lower Floridan because the Lower Floridan occurs at greater depths than the Upper Floridan, and therefore fewer borehole data are available. Most of the fresh water that is withdrawn from the Floridan Aquifer is pumped from the Upper Floridan.

Since 1988, approximately 320 million gallons per day of wastes are injected into disposal wells that empty into the Lower Floridan; about 97 percent of this volume is municipal wastewater.

2.2.2 Biscayne Aquifer System

The Biscayne Aquifer system, the main source of water for Dade, Broward, and southeastern Palm Beach Counties, underlies approximately 4,000 square miles (USGS, 2000). In 1985, approximately 786 million gallons per day of fresh water were withdrawn from the aquifer for all purposes; withdrawals as of 1990 were somewhat greater. About 70 percent of the water is estimated to be withdrawn for public supply. Major population centers that depend on the Biscayne aquifer for water supply include Boca Raton, Pompano Beach, Fort Lauderdale, Hollywood, Hialeah, Miami, Miami Beach, and Homestead. Water from the Biscayne Aquifer also supplies the Florida Keys with water transported from the mainland by pipeline.

Because the Biscayne Aquifer lies at shallow depths and is highly permeable, it is highly susceptible to contamination. According to the USGS, this aquifer is the sole source of drinking water for 3 million people.

The Biscayne Aquifer lies on top of the Floridan Aquifer, and is separated from that deeper aquifer by approximately 1,000 feet of low-permeability clay deposits. The Biscayne Aquifer ranges in thickness from a few feet in the west to about 240 feet near the Florida coast.

2.2.3 Surficial Aquifer

In areas of South Florida outside the Biscayne Aquifer, the unnamed surficial aquifer is used locally for community and public water supply.

2.2.4 Drinking-Water Quality in South Florida Communities

The City of St. Petersburg purchases ground water pumped by the City of Tampa from the Floridan Aquifer. Routine monitoring reported in the city's 2000 Water Quality Report indicates that the water system produces drinking water that meets all Federal and State drinking water standards. According to data in the report, the concentrations of all constituents in the water were below Federal and State Maximum Contaminant Levels (MCLs). The maximum concentration of arsenic (MCL 50 ug/l) was 3.3 ug/l and the maximum concentration of nitrate (MCL for nitrate is 10 mg/l) was 0.05 mg/l during the latest round of water quality testing.

Dade County withdraws approximately 330 million gallons per day of fresh water for distribution to Miami and surrounding communities. The Miami-Dade 2000 Water Quality Report indicates that concentrations of all constituents detected in the water were below Federal and State MCLs. The concentration of nitrate as measured at nine water treatment plants ranged from ND (not detected) to 7 mg/l; the concentration of arsenic at the nine plants ranged from ND to 2 ug/l.

The Biscayne Aquifer is used by millions as a source of drinking water and is suitable for most other purposes. In some areas in Broward county and portions of Dade County, however, the water is colored as a result of decomposing organic material in the aquifer. While this coloration is an aesthetic issue, it does not present a risk to human health.

Canals managed by the South Florida Water Management District have been used in South Florida to control flooding and drainage. These canals are hydraulically connected to the Biscayne Aquifer and present a potential contamination route. Major sources of contamination to the Biscayne Aquifer include salt water intrusion and infiltration of contaminants from the canal system. Other potential sources of contamination include the infiltration of substances spilled on the ground, fertilizer carried in surface runoff, septic tanks, and improperly constructed disposal wells.

2.3 *General Description of Wastewater Treatment*

2.3.1 Wastewater Treatment Methods Used in Florida

In the State of Florida, there are four primary means of managing treated municipal wastewater:

- Release of treated wastewater effluent to ocean outfalls
- Release of treated wastewater effluent to surface waters
- Aquifer recharge of reclaimed wastewater
- Underground injection of treated wastewater into subsurface geologic formations using Class I injection wells.

A precise knowledge of the regulation, treatment, and disinfection of municipal wastewater is important for evaluating and understanding human health and ecological risks associated with the four different wastewater management alternatives. Treatment and regulatory oversight are two critically important risk management tools that greatly affect the final risk determination.

Regulations governing water-quality treatment and the quality of water in receiving water bodies are important because they require that wastewater be treated to a certain standard that depends on its management method; therefore, treated wastewater is likely to have a composition that falls within a predictable range. Risk assessment is made simpler when the quality of treated wastewater can be expected to be fairly predictable. Furthermore, regulations concerning water quality are based upon rational evidence that human health or ecological entities would be better protected if such standards were met. Risk assessment is made easier when such standards exist. In addition, comparison of risks of different management options may depend to a large extent upon the kind and amount of treatment required. Regulations for treatment of wastewater and standards for receiving waters are discussed generally in Chapter 3 and in Chapters 4 through 7 for each wastewater management option.

In order to understand how wastewater treatment reduces risks, it is helpful to understand the composition of untreated wastewater and to compare it with that of treated wastewater. Typical untreated (raw) municipal wastewater contains a variety of constituents, the concentration of which depends on the type and size of commercial and industrial flows added and on the amount and quality of ground water infiltrating into the sewage system. For instance, food-handling wastewater (for example, from food stores and restaurants) can have higher concentrations of organic matter than typical domestic wastewater, while industrial flows may exhibit higher levels of metals. Untreated wastewater typically contains notably high concentrations of pollutants, including organic and inorganic compounds, microorganisms and metals (WPCF, 1983; Metcalf and Eddy, 1991; Richardson and Nichols, 1985; Krishnan and Smith, 1987; and Williams, 1982). Table 2-2 lists typical concentrations and ranges of several raw wastewater constituents as well as the percent removal of these constituents that can be achieved using primary and secondary wastewater treatment methods.

Table 2-2. Typical Levels of Constituents in Wastewater and Percent Removal Using Treatment (Primary and Secondary)

Constituent	Raw Wastewater (mg/L)		Percent Removal		Secondary Effluent (mg/L)	
	Typical	Range	Primary	Secondary	Typical	Range
BOD_5	220	110–400	0–45	65–95	20	10–45
COD	500	250–1000	0–40	60–85	75	35–75
TSS	220	100–350	0–65	60–90	30	15–60
VSS	165	80–275	—	—	—	—
NH_4-N	25	12–50	0–20	8–15	10	<1–20
NO_3 + NO_2-N	0	0	—	—	6	<1–20
Org-N	15	8–35	0–20	15–50	4	2–6
TKN	40	20–85	0–20	20–60	14	10–20
Total N	40	20–85	5–10	10–20	20	10–30
Inorg P	5	4–15	—	—	4	2–8
Org P	3	2–5	—	—	2	0–4
Total P	8	6–20	0–30	10–20	6	4–8
Arsenic	0.007	0.002–0.02	34	28	0.002	—
Cadmium	0.008	<0.005–0.02	38	33–54	0.01	<0.005–6.4
Chromium	0.2	<0.05–3.6	44	58–74	0.09	<0.05–6.8
Copper	0.1	<0.02–0.4	49	28–76	0.05	<0.02–5.9
Iron	0.9	0.10–1.9	43	47–72	0.36	0.10–4.3
Lead	0.1	<0.02–0.2	52	44–69	0.05	<0.02–6.0
Manganese	0.14	0–0.3	20	13–33	0.05	—
Mercury	0.001	<0.0001–0.0045	11	13–83	0.001	<0.0001–0.125
Nickel	0.2	—	—	33	0.02	<0.02–5.4
Silver	0.022	0.004–0.044	55	79	0.002	—
Zinc	1.0	—	36	47–50	0.15	<0.02–20

Note: Partially adapted from WPCF, 1983; Metcalf and Eddy, 1991; Richardson and Nichols, 1985; Krishnan and Smith, 1987; and Williams, 1982.
[Please insert note explaining meaning of cells occupied by em dash (—): for example, "— = no data was collected for this consitutent."

Raw wastewater must be treated at a wastewater treatment facility prior to discharge, regardless of the disposal method. Wastewater treatment facilities provide what is known as primary, secondary, and/or tertiary or advanced treatment. The dividing boundaries between these levels of treatment can become blurred, especially in recent years with the development of new processes that can accomplish several treatment objectives at once. As Table 2-2 indicates, percent removal of raw wastewater constituents depends largely on the level of treatment, though it is important to note that even primary treatment alone will produce a much cleaner effluent. Treatment facilities are designed to meet national, state and local treatment standards, and the processes are chosen on the basis of those standards and local wastewater composition. Most importantly, the level of treatment is dictated by the disposal or reuse option chosen.

Wastewater treatment and disinfection methods and levels are summarized below. A summary of treatment methods used in South Florida is presented in Table 2-4. Disinfection methods are summarized in Table 2-5. Treatment and disinfection for different wastewater management options are discussed fully in Chapters 4 through 7.

2.3.2 Definitions of Wastewater Treatment Methods and Levels of Disinfection

Primary wastewater treatment generally consists of physical separation of solids from the wastewater and includes screening and grinding operations, as well as sedimentation.

Secondary wastewater treatment provides for the removal of suspended solids and biodegradable organic matter using chemical and biological processes before discharge to receiving waters. Secondary treatment, which often includes basic disinfection (described below), is required for ocean discharge but disinfection is not required for underground injection via Class I injection wells. Pursuant to the Clean Water Act, EPA first issued its definition of secondary treatment in 1973. Current Federal standards for secondary treatment are included in 40 CFR Part 133 and presented in Table 2-3. The State's requirements for secondary treatment are contained in Chapter 62-600, F.A.C.

Table 2-3. National Standards for Secondary Treatment

Parameter	Minimum % Removal	Maximum 7-Day Avg.	Maximum 30-Day Avg.
BOD_5, mg/L	85	45	30
TSS, mg/L	85	45	30
pH, units	Within range of 6.0 to 9.0 at all times		

Most secondary treatment of domestic wastewater is accomplished using activated sludge processes. These processes utilize microorganisms already present in the wastewater. The wastewater is aerated and mixed vigorously, which increases contact between the microorganisms and both organics and oxygen. The microorganisms oxidize the dissolved and suspended organics into carbon dioxide and water. Inorganic and organic nitrogen, sulfur, and phosphorus are oxidized to nitrates, sulfates, and phosphates. Some suspended organic and mineral solids are not broken down; these are settled out in clarifiers or a clarification step. The liquid flows out of the top of the clarifier, and after undergoing whatever final treatment is required, it is on its way out of the wastewater treatment facility.

Principal treatment and disinfection (more advanced secondary) requires secondary treatment and high-level disinfection. The reclaimed water must meet a standard of 5.0 mg/L of total suspended solids before application of the disinfectant and total nitrogen is limited to 10 mg/L. Filtration is also required for total suspended solids control, increasing the ability of the disinfection process to remove protozoan pathogens.

Reclaimed water treatment requires secondary treatment, filtration, and high-level disinfection. The quality of water discharged via reclaimed water treatment systems is intended to be high so that it may be reused. Reclaimed water treatment is required if wastewater is being reclaimed for reuse. A standard of 5.0 mg/l TSS (a single sample maximum applied after the filter and before the application of the disinfectant) is required for reuse projects permitted under Part III of Chapter 62-610, F.A.C. Part III imposes a number of additional operational and reliability requirements.

Advanced (or tertiary) wastewater treatment is a term of art that simply means wastewater treatment beyond secondary treatment such as processes that are used if there are requirements to remove specific components, such as nitrogen and phosphorus, which are not removed by the secondary treatment.

Basic disinfection must result in not more than 200 fecal coliforms per 100 ml of reclaimed water of effluent sample. Where chlorine is used, facilities must provide for rapid and uniform mixing and a total chlorine residual of at least 0.5 milligram per liter shall be maintained after at least 15 minutes contact time at the peak hourly flow. Higher residuals or longer contact times may be needed. (See Rule 62-600.440(4) F.A.C.)

High-level disinfection includes additional removal of total suspended solids (TSS) beyond secondary treatment, to achieve a TSS concentration of 5.0 mg/L or less before the application of disinfectant, in order to maximize disinfection effectiveness. It results in reclaimed water in which fecal coliform values (per 100 ml of sample) are below detectable limits (at least 75% of all observations: with no single sample above 25/100 mL. Where chlorine is used, facilities must provide for rapid and uniform mixing and a total chlorine residual of at least 1.0 milligram per liter must be maintained at all times. Larger residuals or longer contact times may be required and as well as minimum contact times if chlorine is used as the disinfectant. This requirement does not preclude an additional application of disinfectant prior to filtration for the purpose of improving filter performance. (See Rule 62-600.440(5) F.A.C.)

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3.0 METHODOLOGY FOR RELATIVE RISK ASSESSMENT

Risk assessment is a process that evaluates the likelihood that adverse ecological or human health effects will occur as a result of exposure to stressors (US EPA, 1998a). It is a process for organizing and analyzing data, information, assumptions, and uncertainties. Risk assessment involves identification of hazards or stressors, analysis of the linkage between exposure to stressors and effects on receptors, and risk characterization (US EPA, 1998a). Risk assessments are used to help risk managers determine priorities for actions that are designed to manage or reduce risk. Risk management is a decision-making process which involves such considerations as risk assessment, technological feasibility, statutory requirements, public concerns, and other factors.

In this study, the terms *risk analysis, risk characterization* and *relative risk assessment* refer to the processes of analyzing risks, describing risks, and the final comparison of relative risk assessment, respectively.

For this study, risk analysis and relative risk assessment of four different wastewater management options involved three steps:

1. Creation of a generic risk analysis framework (GRAF) for each wastewater management option
2. Conducting a risk analysis of each management option using the GRAF and characterizing the risk associated with each option
3. Comparing the risks associated with all four wastewater management options, based on the results of risk analysis of each management option, to arrive at a relative risk assessment.

3.1 Generic Risk Analysis Framework and Problem Formulation

In order to provide a consistent and comprehensive procedure for analyzing risk, a generic risk analysis framework (GRAF) was developed. The GRAF is a procedure for describing all potential risks and identifying all possible hazards, sources, exposure pathways, and effects on receptors, based on a generalized approach to the issue. This framework, also known as problem formulation, outlines potential issues to be analyzed for risk, using site-specific information. In this study, the GRAF was used to develop a conceptual model of potential risk for each management option. The GRAF incorporates human health and ecological risk components.

The use of a GRAF to analyze risks of individual wastewater management options is based upon the *Guide for Developing Conceptual Models for Ecological Risk Assessments* (Suter, 1996), a risk assessment framework outlined in EPA's *Residual Risk Report to Congress* (US EPA, 1999a), and EPA's ecological risk assessment framework, presented in *Guidelines for Ecological Risk Assessment* (US EPA, 1998a).

The first step in developing a GRAF is formulating the problem and developing a conceptual model of potential risk. In formulating the problem, the purpose for conducting the risk assessment is articulated, data are collected and assessed, and potential stressors, receptors, and exposure pathways are selected for further analysis. This information is then organized within a conceptual model, which is a "written description and visual representation of predicted relationships between ecological [or other] entities and the stressors to which they may be exposed" (US EPA, 1998a). For each wastewater management option, a conceptual model helps to define the information necessary to complete the risk analysis. The analyses necessary to characterize risk are then conducted as part of the next step, the option-specific risk analysis and characterization (see below).

Potential stressors include constituents of concern, such as compounds and elements, present in treated wastewater and their degradation byproducts or other derivatives. Potential secondary stressors include other effects of stressors that may pose additional risks themselves. Secondary stressors and the risks they pose can be particularly difficult to anticipate and describe.

Receptors are the human and ecological entities that are exposed to stressors and that may suffer potential adverse effects. Exposure to a stressor must be demonstrated before the linkage between a stressor and an adverse effect can be evaluated. Exposure pathways are the ways in which stressors and receptors are brought into contact with each other. Assessment endpoints provide yardsticks for measuring the effects of stressors. Important assessment endpoints selected for this study included drinking-water quality standards, surface- and marine-water quality standards, and other human health and environmental indicators. Where no assessment endpoints existed, potential adverse effects were evaluated using a weight-of-evidence approach.

3.2 Option-Specific Risk Analysis and Risk Characterization

The second step in risk assessment is conducting an analysis and evaluation of the conceptual model of risk for each wastewater management option. In this step, specific information concerning stressors, receptors, and exposure pathways is used to analyze relationships and anticipate potential adverse effects (or risks). In this study, such information included site-specific data on hydrogeology, water quality, wastewater treatment plant effluent, and wastewater management options used in South Florida. In order to evaluate exposure pathways, information concerning properties of stressors (for example, concentration, solubility, half-life, tendency to bioaccumulate) and the environment they pass through (groundwater, surface water, ocean, subsurface geology, and soils) were compiled and analyzed. Information about large-scale physicochemical processes that determine exposure pathways is also essential for determining whether receptors will actually be exposed to stressors. Such information was used to evaluate and refine the conceptual model for each wastewater management option.

Evaluation of the conceptual model involves an exposure analysis and risk characterization. Exposure analysis is critical to risk analysis and risk assessment; without exposure to a stressor, there is no risk (US EPA, 1998a). In this study, as the conceptual models were evaluated and refined, pathways that did not result in exposure of a receptor to stressors or exposure pathways that were insignificant or improbable were eliminated. Areas of uncertainty and data gaps were identified. Whenever appropriate, conservative assumptions were made that may result in overstating, rather than understating, exposure and risk. A conservative approach will be more protective of human and ecological health.

Risk characterization involves describing the potential adverse ecological and human health effects (risks) that may result from exposure to stressors (US EPA, 2000). Risks may be estimated, compared, or qualitatively described. In this study, risk characterization was performed at assessment endpoints for each conceptual model of a wastewater management option. Upon completion of the risk characterization, issues that pose actual risks were identified, while issues that pose little or no risk were eliminated or assigned lower priority in the final conceptual model of risk. Other risk factors were also taken into account, such as receptor sensitivity, response to change, and potential for recovery if the stress is removed or decreased (Brickey, 1995; GMIED, 1997).

3.3 Relative Risk Assessment

Risks and risk factors may be compared using a variety of methods; comparisons may be quantitative, semiquantitative, or qualitative. Frequently, such an assessment requires that professional judgment be applied to evaluate the relative magnitude of effects (US EPA, 1998a; Suter, 1999a, 1999b).

In this study, relative risk assessment relied upon results of the option-specific risk analysis and risk characterization to compare the risks and risk factors of the four wastewater management options. This relative risk assessment used a qualitative approach to prioritizing risk factors and describing the relative risks and risk factors. There are many risk factors that could have been used in the relative risk assessment. Risk factors were chosen on the basis of how they contributed to making useful comparisons between the potential risks to human and ecological health. Chapter 8 compares risk findings for each wastewater management option and discusses their priorities.

The following sections provide detailed descriptions of the risk methodology used.

3.4 Detailed Description of Problem Formulation

This study of relative risk develops conceptual models of risk that are based on the physical, chemical, and biological processes that govern the fate and transport of discharged wastewater constituents. Developing an understanding of such large-scale fate and transport processes is critical for providing the risk manager with the necessary information to make informed decisions on managing and decreasing risks. Without an understanding of the physical, chemical, biological, and human factors that influence risk, a risk manager may expend time and resources on managing risk symptoms without addressing and eliminating the causes of risk.

3.4.1 Selection of Potential Exposure Pathways

Once treated wastewater is released into the environment, the processes that determine fate and transport of wastewater constituents (stressors) define the large-scale nature of exposure pathways that must be evaluated. These large-scale processes act upon stressors in ways that are strongly governed by the specific chemical and physical properties of the stressors themselves. How these large-scale processes operate in the environments that receive discharges of treated wastewater also varies. Descriptions of the receiving environments (for example, groundwater, surface water, subsurface geology, and soils) are given in Chapters 4 through 7, which examine each of the wastewater management options in detail.

Advection, dispersion, and dilution are large-scale physical processes that play an important role in determining the transport of wastewater constituents. Advection involves mixing and transport by bulk movement of water and is often the single most important mechanism responsible for migration of wastewater constituents. Dispersion refers to slow spreading of constituents in response to gradients in concentration (molecular diffusion) and other phenomena. Dilution is a reduction in concentration of a stressor or other wastewater constituent, which may result from advection or dispersion.

In groundwater, the large-scale movement of wastewater constituents in the subsurface is strongly influenced by the characteristics of the geological media through which discharged effluent and groundwater flows. Porous media flow occurs where primary porosity exists, and it can result in widely varying rates of groundwater flow, depending on the size of pores, amount of pore space, and interconnection of pore spaces. Secondary porosity refers to larger fractures or solution channels in sediments or rock, where groundwater and effluent can move along solution channels, fractures, and other preferential flow paths. In such preferential flow, advective transport rates may be greater than porous media flow rates. In this case, dispersion frequently results from mixing at intersections of fractures and as a result of variations in fracture openings.

The eventual fate of wastewater constituents in the environment determines the final concentrations of stressors to which receptors may be exposed. *Attenuation* describes a variety of processes involving interactions between wastewater constituents and the environment that cause concentrations of constituents to decrease as time passes. Examples of processes that may result in attenuation include filtration, precipitation, settling, biological uptake, chemical transformation, dissolution and adsorption of constituents. Porous media may allow filtration of small bacteria and viruses, which can result in attenuation of these microorganisms, although very small microorganisms may be transported over long distances in porous media. Such attenuation may not occur if open fractures and solution channels are present, which may allow more rapid transport of both chemical compounds and microorganisms (US EPA, 1989).

Other important physical and chemical properties that influence the behavior of wastewater constituents include the stressor's solubility in water; tendency to adsorb to soil, sediments or geologic media; and half-life. Wastewater constituents with higher solubilities may remain longer in effluent and groundwater and may also be present at higher concentrations in the initial effluent. The tendency to adsorb or bind to soil, sediments, or geologic media is determined by complex interactions between wastewater constituents and the physical and chemical environment. Adsorption of a constituent can result in retardation, or slowing, of the transport of stressors. For organic components, organic carbon partition coefficients (k_{oc}) provide measures of this tendency. Chapters 4 and 5 use such characteristics, in conjunction with distribution coefficients (k_d) and other measures, to determine rates of retardation for wastewater constituents.

The residence time of a compound or element in the environment is equivalent to the lifetime of the compound or element before attenuation or other processes cause it to dilute or disappear. The half-life ($t_{1/2}$) of a compound or element is the time required for it to decrease to half of its initial concentration. Half-life values take into account biodegradation and hydrolysis. Biodegradation is a geological process whereby microorganisms bring about chemical changes that can reduce the concentration of a specific wastewater constituent. Hydrolysis is a chemical reaction that adds water to the chemical structure of a compound, disrupting existing bonds or adding new bonds. Hydrolysis can increase solubility of a compound in water and enhance biodegradation, but it may also make a constituent more biologically available (Suthersan, 2001).

3.4.2 Definition of Potential Receptors

For this risk assessment, several potential receptors were selected. Drinking-water receptors are groundwater or surface-water resources that are potential receptors of underground or surface-water contaminants derived from treated wastewater. Potential drinking water receptors include underground sources of drinking water (USDWs), shallow public-water supply wells, private drinking-water wells, and some surface-water bodies used for drinking water sources (the latter are very uncommon in South Florida). Potential ecological receptors in surface water and ocean environments include organisms and ecosystems. Potential human receptors are people who may be exposed to treated wastewater constituents through recreational or occupational activities that bring them into contact with the disposed water.

3.4.3 Selection of Assessment Endpoints

The assessment endpoints chosen for this study are related to the type of receptor chosen. The first category of assessment endpoints pertains to USDWs and public and private drinking-water supply wells. For these drinking-water receptors, drinking-water standards were used as assessment endpoints. Federal drinking-water standards, also known as maximum contaminant levels, or MCLs, were designed to protect human health by establishing minimum standards for drinking water. MCLs are assumed to be protective of human health, although they may not be relevant to ecological standards. The Florida Department of Environmental Health (DEP) also regulates water quality of Class I surface waters intended for drinking water sources. In addition to treatment and disinfection requirements for the different wastewater management options, DEP regulations ensure protection of groundwater quality by establishing minimum criteria for groundwater according to Florida Administrative Code (FAC) 62-520.400.

Construction, operation, and monitoring of wastewater treatment facilities to certain standards are also considered in this category of drinking water-related assessment endpoints. All management methods are also subject to regulations concerning operation, maintenance, and monitoring.

The second category of assessment endpoints is used for ecological risk assessment in fresh surface-water bodies and the ocean. Surface-water quality standards for fresh water and marine water are intended to protect human recreation and ecological values. DEP regulations protect surface-water quality through an extensive set of regulations contained in FAC 62-302. These include state surface-water quality standards for fresh water and nearly marine or marine waters (Class III standards).

The third category of assessment endpoints addresses unregulated substances that may be present in drinking-water supplies, treated municipal wastewater effluent, and other water bodies. For unregulated substances, a weight-of-evidence approach was used, based on examination of the scientific literature concerning the effects of these substances. Examples of unregulated substances include emerging contaminants, such as hormonally active substances (endocrine-disrupting compounds), surfactants, and a wide range of other organic and inorganic compounds. Emerging contaminants are of concern because there is some evidence, based on a limited number of studies, that they may cause adverse effects in humans or other organisms. However, extensive and definitive testing under controlled conditions has generally not been conducted. Where possible, a range of concentrations that may have adverse effects is defined, and the concentration in USDWs or other water bodies is compared with this range-of-effects levels.

Assessment endpoints and the regulatory standards for surface water, groundwater, drinking water, and other operational standards are described more fully in Chapters 4 through 7 for each wastewater management option.

3.4.4 Selection of Potential Stressors

General characteristics of the potential human health or ecological stressors selected for this study are described in this section. Understanding the behavior and characteristics of stressors and their response to wastewater treatment is critically important in the analysis of risk. The stressors considered for this risk assessment were selected based on their occurrence in treated wastewater, scientific information concerning their toxic properties or other potential adverse effects, whether they are representative of a larger group of similar compounds, and their long-term fate in the environment.

In order to conduct a focused risk assessment, suitable representatives of each major category of stressors were chosen. Criteria for selection of representative stressors that might affect human health included severity of effects, level and efficacy of wastewater treatment, representative behavior, and whether the representative stressor provides a conservative (that is, protective) approach to evaluating risk. Contaminants of concern to public health also included substances for which human health effects are not yet fully understood, but for which there may be adverse human health effects, based on laboratory tests, observed effects, or other evidence.

General categories of human health stressors selected for this study include the following:

- Pathogenic microorganisms (for example, viruses, bacteria, protozoans)
- Inorganic compounds and elements (for example, metals and inorganic nutrients)
- Synthetic organic compounds (for example, pesticides and surfactants)
- Volatile organic compounds (VOCs)
- Hormonally active agents (for example, endocrine modulators and disruptors).

Representative ecological stressors that may cause adverse effects on organisms or ecosystems were selected based on a review of the scientific literature. Ecological stressors were chosen if they are known or suspected stressors to aquatic ecosystems, cause toxic effects in aquatic species, and are commonly found in wastewater effluent. Because many similar physical, chemical, and biological processes occur in both freshwater and marine systems, the contaminants of concern are similar in both environments. Categories of ecological stressors selected for this study include the following:

- Inorganic compounds and elements (for example, inorganic nutrients and metals)
- Synthetic organic compounds (for example, pesticides, surfactants)
- Volatile organic compounds (VOCs)
- Hormonally active agents (for example, endocrine modulators and disruptors)
- Pathogenic microorganisms.

The general categories of human health and ecological stressors and the representative stressors selected to represent different stressor categories are listed in Table 3-1.

Table 3-1. Representative Human Health and Ecological Stressors Selected for this Study

Stressor Category	Representative Human Health Stressors	Representative Ecological Stressors
Pathogenic microorganisms	Rotavirus, total coliform, fecal coliform, enterococci, *Cryptosporidium parvum, Escherichia coli, Giardia lamblia*	*Cryptosporidium parvum*
Inorganic compounds (metals, metalloids)	Arsenic, copper	Arsenic, copper, lead, silver, cyanide
Inorganic nutrients	Nitrate, ammonia	Nitrate, total nitrogen, ammonia, total phosphorus, orthophosphate
Volatile organic compounds (VOCs)	Tetrachloroethene (PCE)	Tetrachloroethene (PCE)
Synthetic organic compounds (SOCs)	Chloroform (trihalomethanes) and chlordane (pesticides)	Methylene blue anionic surfactant (MBAS)
Hormonally active agents (endocrine-disrupting compounds)	Di(2-ethylhexl)phthalate (DEPH)	Estrogen equivalence

The characteristics of the selected stressors are described below.

3.4.4.1 Pathogenic Microorganisms

Microbial pathogens in water pose a high-priority public health concern (Raucher, 1996). In the United States, the number of microbiological diseases originating in contaminated drinking water is estimated to be as high as 40 to 50 million cases per year. While the total number of outbreaks of diseases caused by contaminated drinking water has decreased by 20% since the mid-nineties, the proportion of outbreaks associated with groundwater sources has increased by almost 30% (PSR, 2000). The emergence of new pathogens (for example, *Escherichia coli* O157:H7 and *Cryptosporidium parvum*), antibiotic-resistant strains of microorganisms, and a larger sensitive population have resulted in increased public health concerns (Rose et al., 2001). Microbiological diseases caused by ingestion of contaminated shellfish are included in this category of waterborne infections because contaminated water is often the major carrier (Wittman and Flick, 1995). Enteric microbial pathogens (that is, microbes that live in the intestinal tracts of humans and animals and that cause disease) present in wastewater are listed in Table 3-2.

Table 3-2. Microbial Pathogens Potentially Present in Untreated Domestic Wastewater

Bacteria

- *Campylobacter jejuni*
- *Escherichia coli*
- *Legionella pneumophila*
- *Salmonella typhi*
- *Shigella*
- *Vibrio cholerae*

Helminths

- *Ancylostoma duodenale* (hookworm)
- *Ascaris lumbricoides* (roundworm)
- *Echinococcus granulosis* (tapeworm)
- *Enterobius vermicularis* (pinworm)
- *Necator americanus* (roundworm)
- *Schistosoma*
- *Strongyloides stercoralis* (threadworm)
- *Taenia* (tapeworm)
- *Trichuris trichiura* (whipworm)

Protozoa

- *Cryptosporidium parvum*
- *Giardia lamblia*
- *Balantidium coli*
- *Entamoeba histolytica*

Viruses

- *Adenovirus* (51 types)
- *Astrovirus* (5 types)
- *Calicivirus* (2 types)
- *Coronavirus*
- Enteroviruses (72 types)
- Hepatitis A
- Norwalk agent
- *Parvovirus* (3 types)
- *Reovirus* (3 types)
- Rotavirus (4 types)

Source: York et al., 2002.

Depending upon the level of treatment and disinfection, concentrations of microbial pathogens in treated wastewater discharged to the environment can vary widely. An aggressive treatment combines disinfection with filtration to kill or physically remove microbial pathogens present in drinking water. For example, most bacteria and viruses in wastewater are generally effectively inactivated by disinfection with chlorine and filtration (York et al., 2002). However, disinfection byproducts, such as trihalomethanes, that are formed when chlorine reacts with organic compounds can pose human health concerns as well.

Survival of pathogenic microorganisms in soil and water generally is limited to days, weeks, or months, depending on the microorganism and whether it can form cysts or spores that persist in the environment. Survival is affected by factors such as temperature, availability of water and oxygen, and whether an animal host is needed for survival or growth of the microorganism. There is a small but growing body of information concerning survival of pathogenic microorganisms in the shallow subsurface and other microbial processes in geologic formations such as microbial denitrification in the shallow subsurface in northeast Florida (USGS, 2000). If viruses are not inactivated by treatment and are released, their small size and longevity may allow them to be distributed widely through the environment. Viruses may survive in surface water and groundwater, although most viruses typically cannot reproduce outside the human host (PSR, 2000). Viral contamination of wells, especially private wells with no treatment, poses concerns.

Potential human exposure pathways to pathogenic microorganisms include the following:

- Ingestion of water contaminated by exposure to wastewater
- Ingestion of contaminated food (such as shellfish, fish, produce, or foods processed in contaminated water)
- Dermal contact with contaminated water or soil through swimming, showers, spray irrigation, or occupational exposure
- Inhalation of contaminated water or soil (aerosols, shower spray, spray irrigation, dust, occupational exposure).

Secondary spread may also be possible, which includes person-to-person contact, use of public swimming facilities, and transmission from food handlers and care facilities (Chick et al., 2001).

Microbial growth in groundwater is not well characterized in general because of the difficulty of obtaining microbiologically representative samples without introducing surface contaminants. There are many gaps in knowledge concerning potential human health effects from ingestion of pathogenic microorganisms in water:

- Whether indicator organisms for microbial pathogens, such as coliform, are representative of pathogenic microorganisms
- Whether environmental sources other than wastewater exist for pathogenic microorganisms
- Exposure factors
- Modes of transmission
- Modes of environmental transport of microorganisms
- Survival potential of microorganisms in groundwater.

Three representative pathogenic microorganisms were selected to evaluate human exposure to treated wastewater: rotavirus, *Cryptosporidium parvum,* and pathogenic strains of *Escherichia coli* (*E. coli*). These are described below.

Rotaviruses

Rotaviruses are highly infective viruses that can be transmitted in water, causing a highly contagious disease that induces vomiting and diarrhea. In the United States, rotavirus has been estimated to cause 3 million cases of childhood diarrhea, resulting in 500,000 doctor visits, 100,000 hospitalizations, and up to 100 deaths annually (EHP, 1998a; SAIC, 2000). Because of the easily transmitted and highly contagious nature of the illness, rotaviruses were selected as a representative of pathogenic enteric viruses.

Other enteric viruses that are associated with poor-quality or untreated wastewater have been detected in near-shore waters and canals, including coxsackie viruses, Hepatitis A viruses, and Norwalk-like virus (Rose et al., 2000). These viruses, if ingested, can cause diarrhea, aseptic meningitis, and myocarditis. Their small size (in the nanometer range) and structure enhances viral survival and transport in water; these viruses can survive in groundwater for more than 2 months (Rose et al., 2000). Plankton and marine sediments may serve as reservoirs for pathogenic microorganisms, which can emerge to become infective when conditions are favorable (Henrickson et al., 2001).

Cryptosporidium parvum

Cryptosporidium parvum, an enteric protozoan, is considered to be a major risk to U.S. water supplies because it is highly infectious, forms cysts and oocysts that are resistant to chlorine disinfection, and is difficult to filter because of its small size. *Cryptosporidium* poses significant challenges to public health and water authorities (Gostin et al., 2000). If it is present in drinking water, it poses a high risk of waterborne disease (particularly for immunocompromised individuals). There have been 12 documented waterborne outbreaks of *Cryptosporidium* in North America since 1985; in two of these (Milwaukee and Las Vegas), mortality rates among exposed immunocompromised individuals ranged from 52% to 68% (Rose, 1997). Similar enteric protozoans include *Giardia lamblia*, *Entamoeba histolytica*, and *Balantidium coli* (York et al., 2002).

Protozoan cysts and oocysts are very persistent in the environment, particularly where water exists. Dormant oocysts may remain viable for months in sewage or groundwater until they find a new host. *Cryptosporidium* infects both humans and animals and can be transmitted through ingestion of contaminated water or food. Secondary infection can also occur. *Cryptosporidium* forms a reproductive oocyst that, once ingested, continues its life cycle in the gastrointestinal tract, causing the disease Cryptosporidiosis. The parasite can also be spread through the fecal-oral route by infected food handlers or in day-care settings. As few as 10 to 25 oocysts can cause infection; however, the disease is usually self-limiting with 2 to 10 days of symptoms in healthy persons. In sensitive populations and individuals, the disease can be life threatening.

Chlorine, the traditional water disinfectant for killing water-borne pathogenic bacteria and viruses, is not as effective against *Cryptosporidium* as other waterborne organisms, for example, *Giardia* (Joyce, 1996). Standard screening methods have proven ineffective as well. Filtration is the accepted method of removing *Cryptosporidium.*

Because of the severity of the disease, its widespread occurrence in nature, and because water and wastewater treatment does not always address *Cryptosporidium*, it was chosen for use as a representative pathogenic protozoan for evaluating human health risks from pathogenic protozoans in discharged treated wastewater.

Fecal Coliforms (*Escherichia coli*)

Fecal coliforms are bacteria that are normally found in human and animal wastes. *Escherichia coli,* or *E. coli*, is a type of fecal coliform bacteria. The presence of *E. coli* in water is a frequently used indicator of recent sewage or animal waste contamination, although it is not a reliable indicator of human sewage. It is important to note that sewage-indicator bacteria such as fecal coliforms have short survival times in the environment and may not be good indicators of the presence of protozoans and viruses in some environments (Henrickson et al., 2001). For example, one injection well monitoring study performed in Florida found that indicator bacteria and coliphages were not detected, while *Cryptosporidium* oocysts were detected at very low concentrations (Rose et al., 2001).

Most strains of *E. coli* are harmless and live in the intestines of healthy humans and animals without causing illness. However, *E. coli* O157:H7 is one strain of *E. coli* that produces a powerful toxin that can cause severe gastrointestinal illness. Infection by *E. coli* O157:H7 may cause hemolytic uremic syndrome, in which red blood cells are destroyed and kidney failure occurs. About 2% to 7% of infections lead to this complication. In the United States, most cases of hemolytic uremic syndrome are caused by *E. coli* O157:H7 (US EPA, 2001a). Exposure may occur through ingestion, recreational contact, or consumption of contaminated water or food (Schmidt, 1999). Sensitive human receptors include children, the ill, the immunocompromised, and the elderly. Because of the severity of illness that may occur upon exposure to *E. coli* O157:H7, fecal coliforms were selected as a representative human health stressor.

Pathogen fate, transport, and survival in the environment are discussed more in Chapter 4. Data on concentrations of pathogenic and indicator microorganisms in treated wastewater and from groundwater monitoring are provided in Appendix 1 (Appendix Tables 1-3, 1-4, and 1-5).

3.4.4.2 Inorganic Stressors

Wastewater contains a large number and variety of inorganic constituents, including metals, salts, nutrients, and other substances. Many, if not all, of these inorganic constituents are natural in origin (that is, they are ultimately derived from natural materials and are not "manmade" in the sense of being synthesized by humans), but their concentrations in wastewater may be elevated because of human activities. Many inorganic substances, if present at high enough concentrations, can pose some risk to human health. For this reason, many drinking-water standards (maximum contaminant levels, or MCLs) address the maximum amount of a given inorganic substance allowed in drinking water. Removal of these constituents will depend upon the level and type of wastewater treatment that is used.

Metals

Like nutrients, metals are naturally occurring and play a necessary biological role in the environment. However, in excessive amounts, metals can be toxic to wildlife, fish, and aquatic organisms. Metals have complex and dynamic physical and chemical reactions in the environment and can occur in different chemical forms or species. Metal speciation is important in understanding biological uptake by fish and wildlife. Factors that affect chemical speciation of metals include pH, alkalinity, the presence of organic matter and colloidal particles, and the oxidation-reduction potential of the environment (Stumm and Morgan, 1981). Organisms also differ in their capacity to store, remove, and detoxify metal contaminants (Wallace and Braasch, 1997).

Copper is an example of an essential micronutrient metal that is required by plants, animals, and most microorganisms in trace amounts. However, at higher concentrations, copper is toxic to algae, inhibiting growth and photosynthesis; copper sulfate and other copper-containing compounds have been used to control algal blooms in fresh water bodies and reservoirs since the early 1900s. The bioavailability of copper, or its ability to be taken up by organisms, depends in large part on its speciation. Total copper is not a good measure of bioavailablity. Reduced copper, or Cu^{2+}, is more readily taken up by organisms than the oxidized form and is therefore a better indicator of potential stress.

Arsenic is a metalloid element that is often present in groundwater where underlying rocks and soil contain arsenic salts or arsenic-containing minerals. A variety of industrial and agricultural activities also generate or release arsenic-containing compounds, including production and use of wood preservatives (for example, copper chromium arsenate), mining of arsenic-containing ores, and manufacture and use of arsenic-containing pesticides (for example, lead arsenate). Since arsenic is highly soluble, particularly under reducing conditions (which are often found in groundwater), it may also be highly mobile. Movement of surface water and groundwater provide important potential transport pathways for arsenic and other metals.

Chronic arsenic exposure causes a variety of human health effects, including carcinogenic and noncarcinogenic effects (Chowdhury et al., 2000; Morales et al., 2000). The population cancer risks from arsenic in U.S. water supplies may be comparable to those from environmental tobacco smoke and radon in homes (Smith et al., 1992). Noncarcinogenic effects of low levels of arsenic include adverse effects on the gastrointestinal system, central nervous system, cardiovascular system, liver, kidney, and blood (Abernathy et al., 1999; Tseng et al., 2000; Kaltreider et al., 2001; and Hopenhayn-Rich et al., 2000). At higher oral doses (600 milligrams per kilogram per day or more), poisoning and death will result.

Human exposure to inorganic arsenic results primarily from ingestion of contaminated drinking water or ingestion of contaminated food. Examples of food that can contain elevated arsenic levels include fish, shellfish, crustaceans, and some cereals, such as rice, taken from water or soils with high arsenic concentrations. Consumption of fish and shellfish from waters that contain elevated amounts of arsenic may be an important source of arsenic in humans. In food, the highest levels of arsenic in the U.S. Food and Drug Administration's total diet survey were found in fish, with a mean level of about 15 parts per million (ppm) As_2O_3 in the edible portion of finfish (Jelinek and Corneliussen, 1977).

Approximately 5% of large and small regulated water-supply systems in the United States are estimated to have arsenic concentrations that exceed 20 micrograms per liter ($\mu g/L$) (Morales et al., 2000). The MCL for arsenic was formerly 50 parts per billion (ppb). In January 2001, the EPA lowered the MCL to 10 ppb. This lower standard was reviewed in 2001 and early 2002. After considerable public comment and deliberation, the 10 ppb MCL level was determined to be appropriate, and the Final Arsenic Rule went into effect in February 2002. The World Health Organization also recognizes an arsenic standard for drinking water of 10 ppb.

In the marine environment, arsenic typically occurs in seawater at concentrations ranging from 1 to 8 ppb and in sediments at 2 to 20 ppm. The distribution of arsenic in terrestrial environments is not nearly so homogeneous, as indicated by the higher levels of arsenic in marine organisms than terrestrial organisms; the biological concentration factor may vary by orders of magnitude between aquatic and terrestrial organisms (Fishbein, 1981). Arsenic may bioaccumulate in aquatic organisms. However, there is considerable variability in aquatic food-web bioaccumulation (Penrose et al., 1977; Vallette-Silver et al., 1999; Woolson, 1977). Organisms containing high levels of arsenic tend to be those that ingest sediment particles while feeding; that is, benthic filter-feeders or detritus-feeders exhibit higher concentrations of arsenic than pelagic fish.

As with copper, factors that govern biological effects of arsenic include its bioavailability, the quantity ingested or respired, the degree of assimilation, and the extent of retention in tissues.

Gaps in knowledge concerning arsenic and human health and ecological effects concern detailed transport mechanisms, mobility in the environment, carcinogenesis, whether there are cumulative or synergistic effects in combination with other contaminants, differences in bioaccumulation by different species, and the proper dose-response relationship to use in ecological risk assessment.

Inorganic Nutrients

Wastewater is a source of nutrients such as nitrogen, phosphorus, and other substances that act as nutrients. Secondary treatment removes only a portion of the nitrogen and phosphorus that may be present (see Chapter 2).

Nitrogen is the most important nutrient to consider in an ecological risk assessment for a marine environment because nitrogen limits primary production in marine environments. While many studies focus on total nitrogen (all forms of nitrogen), nitrate is the form that is most readily available for uptake by algae and plants. Excess nitrate in drinking water can potentially affect the health of infants, young children, and pregnant women and can cause methemoglobinemia (Knobeloch et al., 2000; Gupta et al., 2000). Human exposure to excess nitrate can occur through drinking or accidentally ingesting water that has elevated concentrations of nitrate. Little is known about the potential health effects of long-term exposure to excess nitrate in drinking water. Some studies of chronic nitrate ingestion have suggested connections to reproductive and developmental health effects, certain cancers, childhood diabetes, and thyroid disease.

The Safe Drinking Water Act established an MCL for nitrate of 10 milligrams per liter (mg/L), or 10 parts per million (ppm). This federal standard is used to ensure the safety of public water supplies, but does not apply to private wells. An estimated 2 million private household water supplies in the United States today may fail to meet this federal standard for nitrate (Knobeloch et al., 2000).

Excessive nitrate in the marine environment can stimulate phytoplankton and macroalgal growth. This can create adverse effects such as eutrophication (reduction of available oxygen), loss of eelgrass, dead zones because of low dissolved oxygen concentration from decomposing organic matter, and increases in harmful algal blooms (Nixon, 1998; Joyce, 2000). It is important to note that the 10 ppm drinking water standard for nitrate is generally much higher than the concentration of nitrate typically present in seawater or coastal waters, which ranges from several tenths of a part per million to several parts per million.

Excess nutrients may create secondary stressors, such as harmful or nuisance algal blooms. The algal toxins that may be produced by harmful algal blooms (HABs) can cause adverse effects on humans, aquatic mammals, fish, shellfish, and other organisms. Human ingestion of seafood contaminated by HABs can result in respiratory illness, gastroenteritis, and skin irritation. Paralytic shellfish poisoning is one example of an illness caused by toxin-producing dinoflagellates that form red tides. However, most scientists agree that, although excess nutrients may be a factor in some blooms, other environmental factors such as changes in temperature or circulation may cause many algal blooms (Tibbetts, 2000).

Phosphorus is a nutrient of concern in freshwater ecosystems because it is frequently the limiting nutrient for algal and plant growth, in contrast to nitrogen which tends to be the limiting nutrient in marine waters. Excess phosphate in freshwater can cause excessive algal growth, eutrophication, and low dissolved oxygen, just as excess nitrate in coastal waters can result in similar effects. Excess phosphate already exists in many of South Florida's fresh water aquatic ecosystems, and a phosphate-based water quality standard is being considered for Lake Okeechobee, which is heavily affected by fertilizer runoff from adjacent agricultural lands.

Different forms of phosphorus exist in the aquatic environment; the most important are orthophosphate, total phosphorus, and particulate phosphorus. Orthophosphate (also known as soluble reactive phosphorus) is the major inorganic form of dissolved phosphorus most readily available for biological assimilation. Total phosphorus, as the name implies, refers to all the phosphorus in a volume of water including dissolved and particulate forms. Orthophosphate was chosen as a representative nutrient stressor in fresh water ecosystems.

3.4.4.3 Organic Compounds

Pesticides

Pesticides in wastewater primarily originate from stormwater runoff from lawns and gardens and other areas where pesticides are used. Human exposure to pesticides can occur through ingestion of contaminated drinking water, food, or dermal contact with contaminated water (Moody and Chu, 1995). Potential human receptors include adults, children, subsistence fishermen, farmers, and sensitive portions of the population, such as the elderly and ill. A number of pesticides, including chlordane, were evaluated for deep-well injection, while chlordane alone was used as a representative pesticide in other wastewater management options.

Chlordane is a chlorinated insecticide that was widely used in agricultural, industrial, and domestic applications; about one-third of the chlordane used in the United States was applied to control pests in homes, gardens, lawns, and turf (ATSDR, 1995). The EPA in 1983 banned all use of chlordane, except for control of termites. In 1988, because of concerns about carcinogenicity, toxicity, and harmful effects on wildlife, the EPA banned its use except for fire-ant control in power transformers. Chlordane is no longer distributed in the United States.

Despite having been banned years ago, chlordane is extremely persistent in the environment and may remain in soil for 20 years (ATSDR, 1995a). It is associated with many human health effects: chlordane may be carcinogenic, toxic, and impair human immune and neurological systems (IARC, 1997; Hardell et al., 1998; Kilburn and Thornton, 1995). Gaps in knowledge concerning human health risks posed by chlordane include the effects of long-term, low-dose exposure, whether it is carcinogenic, and whether it affects fertility, development, or neural systems.

Chlordane binds strongly to particles, does not dissolve easily in water, and may concentrate in the surface microlayer of surface water or in aquatic sediments. Because it is highly lipophilic, chlordane bioaccumulates in aquatic organisms. For compounds such as chlordane, groundwater transport is minimal (Thomann, 1995). The solids on which the chemical is adsorbed are stationary for the most part in groundwater. In surface water, the solids are transported during advection, and there may be significant interactions with aquatic sediments (Thomann, 1995).

Volatile Organic Compounds

Tetrachloroethene (PCE) is a VOC that may be formed in small quantities during chlorination of water or wastewater. Due to its volatility, tetrachloroethene does not remain long in surface or marine waters and will evaporate to the atmosphere; therefore, it has little potential for accumulating in aquatic organisms (US EPA-OW, 2002). However, in groundwater, tetrachloroethene is very mobile and persistent, which enables it to travel significant distances. Research studies have concluded that PCE-contaminated drinking water can be linked to elevated incidence rates of leukemia, bladder, lung and colorectal cancers in humans and experimental animals.

Human exposure pathways for VOCs could include drinking water, ingestion of water during recreational or occupational activities, and exposure to vapor in water. Potential human receptors include private well owners, who may be operating wells that are neither monitored nor treated to national drinking water standards.

The Florida Class III Marine water quality standards for tetrachloroethene are ≤8.85 µg/L on an annual average. The estimated half-lives of trichloroethylene (3.2 µg/L) from an experimental marine mesocosm during the spring (8 to16°C), summer (20 to 22°C), and winter (3 to 7°C) were 28, 13, and 15 days respectively (Wakeham, et al., 1983, in Montgomery, 2000). Toxicity tests indicate toxic levels range from 22 mg/L (LC_{50} (24 hours) for *Daphnia magna* (LeBlanc, 1980, in Montgomery, 2000) to 3,760 milligrams per kilogram (mg/kg) acute oral LD_{50} in rats (TECS, 1985, in Montgomery, 2000).

Surfactants

Gaps in knowledge concerning the human health effects of surfactant compounds in drinking water include the effects of chronic low-dose exposures, suitable critical endpoints for risk estimates to represent sensitive populations, and the exact biological mechanisms by which these compounds affect human health.

Surfactants were chosen as a potential ecological stressor to evaluate because of their widespread use, occurrence in wastewater, their effects upon organic matter, and the relative lack of information concerning their ecological effects, in comparison to compounds currently regulated under the Safe Drinking Water Act. Surfactants are found in laundry detergents and in wastewater and are known to persist in wastewater, sewage sludge, and the environment (Dental et al., 1993). Surfactants have also been suggested as a potential precursor to an endocrine-disrupting agent or estrogenic substance. Estrogenic substances, such as alkylphenol-polyethoxylates (APE), and other alkylphenols, such as nonylphenol, in sewage effluent may also originate from biodegradation of surfactants and detergents during wastewater treatment (Purdom et al., 1994 and Jobling and Sumpter, 1993, both in US EPA, 1997). The representative surfactant chosen for this study is methylene blue anionic surfactant (MBAS), which is an anionic surfactant found in commercially available detergents (Dental et al., 1993).

Hormonally Active Agents

Estrogenic hormones and potential endocrine disrupters include pharmaceuticals (for example, estrogens and their degradation products), surfactants, some pesticides, dioxins, and plasticizers. Scientific opinion is mixed concerning whether such compounds disrupt normal endocrine function, reproductive and developmental processes, or immunological processes (Birnbaum, 1994; Colborn, 1995; vom Saal, 1995). Not all scientists agree that exposure to hormonally-active agents represents cause for alarm. Authors of one paper reported that "there is little direct evidence to indicate that exposures to ambient levels of estrogenic xenobiotics are affecting reproductive health" (Daston et al., 1997). In addition, they state that "estrogenicity is an important mechanism of reproductive and developmental toxicity; however, there is little evidence at this point that low level exposures constitute a human or ecologic risk." The picture regarding hormonally active agents is therefore complex.

Hormonally active agents found in wastewater and in surface water elsewhere include estradiols (an active component of oral contraceptives), as well as alkylphenols (biodegradation products of nonionic surfactants). Industrial and pharmaceutical compounds with hormonally active effects include butylbenzylphthalate (BBP), di-n-butylphthalate (DBP), tributylphosphate, butylated hydroxyanisole (BHA), dimethylphthalate, and 4-nonylphenol, dioxin (2,3,7,8-TCDD), bisphenol A, PCBs, PBBs, pentachlorophenol, penta- to nonylphenols, phthalates, and styrenes (Daughton and Ternes, 1999; Jobling et al., 1995).

Scientific studies suggest that these chemicals may cause adverse effects in aquatic organisms and that wastewater is one source of such chemicals (Rodgers-Gray et al., 2000; Nichols et al., 1998). Studies in Florida have documented potential endocrine exposure effects on the Florida panther (Facemire et al., 1995) and American alligator (Semenza, 1997). However, the sources of endocrine disruptors were not documented in these studies.

These substances have been identified in concentrations in the nanograms-per-liter (or parts-per-trillion) range in secondary-treated municipal wastewater effluent and receiving waters (Huang and Sedlak, 2000; and Harries et al., 1998). Because these substances are often highly soluble in water, they may be difficult to remove using conventional technology; estrogenicity has been identified primarily in the water-soluble fraction of wastewater (Raloff, 2000). Municipal wastewater treatment may remove these compounds if they are associated with other organic particles or substances that are removed by treatment.

Environmental monitoring indicates that such chemicals can be present in drinking water as well (Potera, 2000). Potential human exposure pathways include ingestion of water containing such substances, dermal contact with water, and inhalation of volatile compounds from water vapor. Potential human receptors include people consuming or drinking water containing such substances and those exposed to such water as a result of recreational or occupational activities, including subsistence fishermen and farmers.

Significant gaps in knowledge exist concerning the human health and ecological effects of these compounds because they have only recently been recognized as potential contaminants of concern. Comprehensive and long-term epidemiological studies are needed to critically evaluate the effects of exposures to these compounds. Other gaps in knowledge include the concentrations of hormonally active substances in treated municipal wastewater effluent, whether they present an ecological concern, effects of exposures to mixtures, and cumulative effects of all sources of such compounds. Better monitoring methods need to be developed in order to conduct such studies.

The EPA requires testing of commercial chemicals to determine their endocrine disruption potential. Screening techniques to test chemicals for endocrine disruption are being developed. Because of the relative newness of the science, no regulatory guidelines have yet been established for concentrations of hormonally active agents in wastewater.

The hormonally active substance selected to evaluate potential human health risk was di(2-ethylhexyl)phthalate, or DEPH. DEPH is a plasticizer, used to make polymers (such as PVC) flexible. The threshold limit value for constant 8-hour exposure in air (OSHA, ACGIH) is 5 ppm. DEPH poses some human health concerns, but because it is mostly insoluble in water and is biodegradable in small quantities, it is not considered a critical ecological risk stressor. Large quantities can cause liver damage and reproductive problems in lab animals, but the effects are reversible if the stressor is removed.

One advanced wastewater treatment plant in South Florida also provided data on estrogen equivalence in treated wastewater. Estrogen equivalence is a measure of the response of breast cancer cells to exposure to strongly estrogenic substances, such as hormone replacement and birth control pills (Frederic Bloettscher, Consulting Professional Engineer. September 13, 2001. E-mail communication to Jo Ann Muramoto, Horsley & Witten, Inc.).

3.5 Analysis Plan

This relative risk assessment focused on characterizing and evaluating the major fate and transport processes that determine where the vast majority of discharged effluent and effluent constituents will end up. The focus is on the major exposure pathways that could lead to potential exposure of receptors to effluent constituents that act as stressors.

One of the goals of the risk assessment team was to determine whether final dilutions of wastewater stressors could be predicted or modeled for the ends of major exposure pathways (that is, at the USDW, surface water, or ocean receptors). There are many other potential sources of these stressors in the South Florida environment; wherever possible, evidence linking the stressor to the wastewater management option was sought. Analysis of fate and transport pathways is particularly important for singling out the concentration of stressors that can be ascribed to discharged treated wastewater. Without an analysis of fate and transport, it would be difficult to rule out other sources of the same stressor in surface-water receptors or the ocean or even in drinking-water receptors, such as the USDW or surficial aquifer.

In order to evaluate human health risks, concentrations of representative stressors in treated wastewater at the treatment plant and in drinking water or other receptors were compared with the assessment endpoints: drinking-water standards such as the federal drinking-water standards (MCLs) or Florida's water quality standards for Class I waters intended to protect drinking-water sources. If there was no human exposure pathway involving a particular water resource, then the standards for that pathway were not used (for example, as there is no human exposure pathway involving ingestion of seawater, then the drinking-water standards were not used). To evaluate ecological risks, monitoring data for treated wastewater were likewise compared with water quality standards intended to protect ecological values. Examples include Florida's regulations pertaining to Class III coastal and marine waters.

For unregulated compounds, a weight-of-evidence approach based on general scientific literature was used to determine whether disposal of treated wastewater containing such compounds could pose a risk to human health or aquatic ecosystems.

3.6 Final Conceptual Model of Probable Risk

When the conceptual model of potential risk was evaluated using site-specific information, stressors, receptors, or exposure pathways that were insignificant or improbable were eliminated. Criteria for elimination of exposure pathways, stressors, or receptors included the following:

- The transport or exposure pathways that would expose a receptor to a stressor never or hardly ever exist or occur
- The time it would take for a stressor to be transported from the discharge point to the receptor is longer than the residence time of the stressor in the environment
- Wastewater treatment or other attenuation processes routinely decrease the concentration of a particular stressor well below required standards or assessment endpoints
- Attenuation processes that would in all probability result in a significant decrease in concentration of a stressor are known to exist in the receiving environment
- A receptor does not exist in the receiving environment
- There is little or no evidence that adverse effects occur from exposure of receptors to stressors, despite the fact that exposure must occur, using site-specific information.

The risk to human health or the environment from stressors in treated effluent was described to be nonexistent to very low, when either of the following occurs—

- A stressor, receptor, or exposure pathway is eliminated
- It is demonstrated that adverse effects do not occur.

The risk was judged to be low or moderate when any of the following occurs—

- There is a small chance of exposure
- Assessment endpoints (standards) are usually but not always met
- Adverse effects are possible.

The risk was judged to be moderate to high when any of the following occurred—

- There is a moderate-to-high chance of exposure
- Assessment endpoints were almost always exceeded for some stressor
- Adverse effects can occur.

The risk was judged to be very high when there is a high chance of exposure and monitoring indicates that adverse effects have already occurred.

The final conceptual model for each option describes in narrative form the risk findings and conclusions for each wastewater management option.

3.7 Relative Risk Assessment

The risk findings for each wastewater management option were compared and evaluated. Ecological and human health risk factors were compared across all four wastewater management options. A final set of criteria for risk prioritization was developed. The product of the relative risk comparison of wastewater management options is a prioritized list of risk factors for each wastewater management option.

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4.0 DEEP-WELL INJECTION

In this chapter, human health and ecological risks associated with the deep-well injection wastewater management option are described and evaluated. Sources of data and information are used to develop a conceptual model of potential risks. A wastewater fate and transport analysis examines the factors that may be most important in determining risk and levels of risk. This evaluation results in a refined final conceptual model that describes the risks that are most probable.

4.1 Definition of the Deep-Well Injection Option

Deep wells are used in South Florida to dispose of secondary-treated municipal wastewater. These wells are permitted as Class I municipal wells, which by definition dispose of wastewater beneath the lowermost formations containing, within a minimum of one-quarter mile of the well bore, an underground source of drinking water (USDW) (FDEP, 1999a). Deep municipal wells in South Florida inject at depths ranging from approximately 1,000 feet to greater than 2,500 feet below surface of the land.

4.2 Deep-Well Capacity and Use in South Florida

Class I injection wells are used in various regions of the United States for disposal of hazardous and nonhazardous fluids. In South Florida, they provide an important means of managing treated municipal wastewater. The Florida Department of Environmental Protection (DEP) estimates that deep-well injection accounts for approximately 20% (0.44 billion gallons per day) of the total wastewater management capacity in the State of Florida (FDEP, June 1997).

Although deep-well injection is practiced throughout much of South Florida, these wells are concentrated in southeastern portions of the State and in the coastal areas (Figure 4-1; Figure 2-2; Appendix Table 1-6). Dade, Pinellas, and Brevard counties serve as three areas of focus for this risk analysis and are at three corners of the triangular study area. These counties present unique geologic environments and differences in injection system operation that may have a substantial bearing on risk.

4.3 Environment into Which Treated Wastewater is Discharged

To evaluate risk, it is critical to understand regional variations in geology and hydrogeology that influence subsurface fate and transport of injected wastewater. Hydrogeologic units vary in thickness and in their characteristics (for example, porosity and conductivity) across various regions of South Florida. A description of the hydrologic system and hydrogeologic units in South Florida is provided below.

Hydraulic conductivity ("K") is a measure of a formation's capability to transmit water under pressure. Aquifer units or layers that exhibit low hydraulic conductivity typically slow the rate at which groundwater flows.

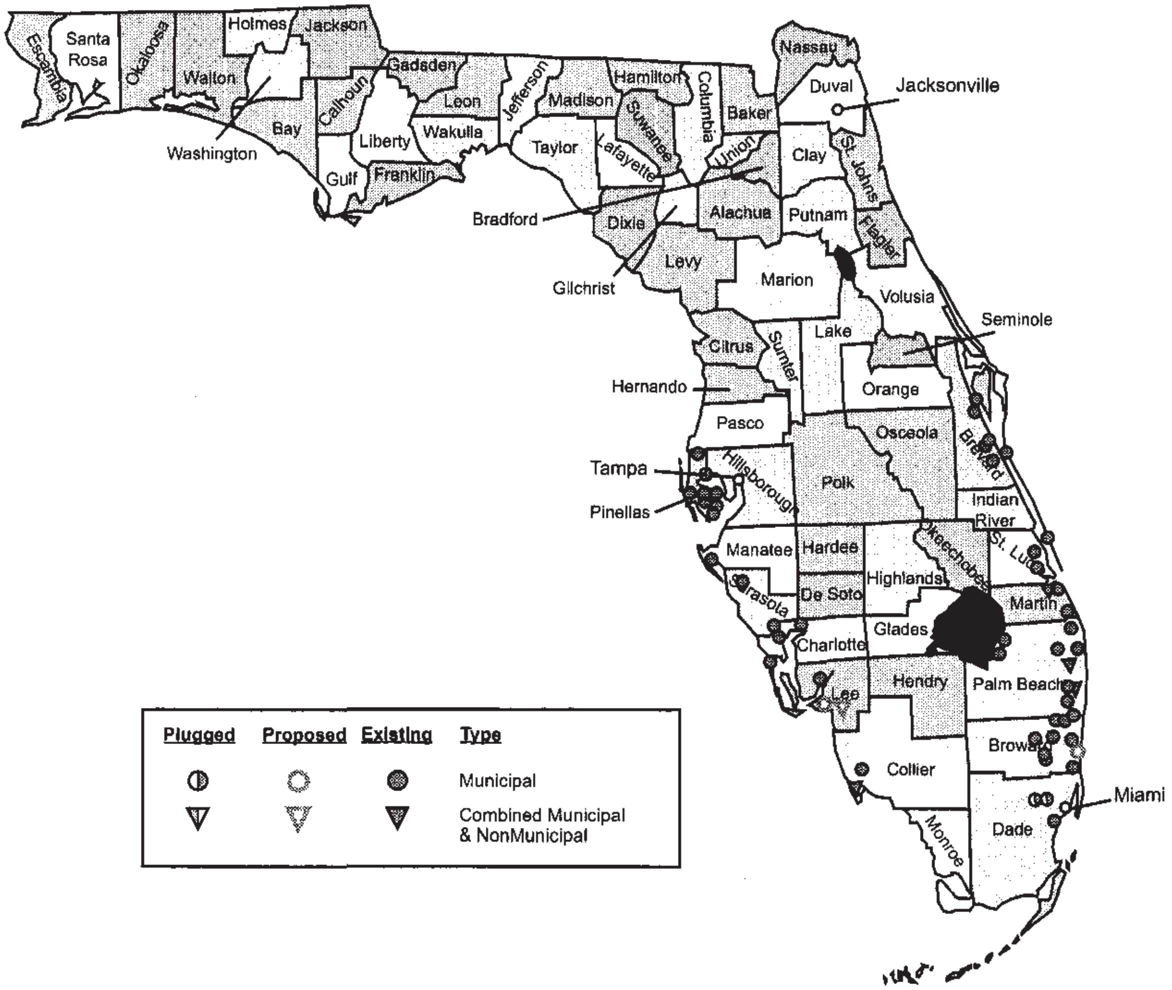


Figure 4-1. Locations of Class I Injection Wells in South Florida

The hydrogeologic system throughout much of South Florida consists of thick sequences of carbonate rocks overlain by clastic deposits (Tibbals, 1990; Broska and Barnette, 1999; Tihansky and Knochenmus, 2001). Three hydrogeologic features are common to Dade, Pinellas and Brevard counties: the presence of a relatively shallow surficial aquifer (called the Biscayne Aquifer in Dade County), the presence of a unit with lower relative hydraulic conductivity (the intermediate confining unit), and the presence of the Floridan Aquifer System. Figure 4-2 presents representative hydrogeologic cross sections that illustrate these and other features in the three counties.

The surficial aquifer (and the Biscayne Aquifer in Dade County) represents the uppermost hydrogeologic unit. These shallow aquifers lie above sequences exhibiting lower relative hydraulic conductivity (the intermediate confining unit) which, in turn, overlie the Floridan Aquifer System. The Floridan Aquifer System is divided into three distinct units, referred to as the Upper Floridan Aquifer, the middle confining unit, and the Lower Floridan Aquifer. Each of these aquifers is described in more detail below.

Deep-well injection is conducted within the Lower Floridan Aquifer in Dade and Brevard counties and within the Upper Floridan Aquifer in Pinellas County (Hutchinson, 1991; Hickey, 1982; Florida Department of Regulation, 1989; FDEP, 1999a).

4.3.1 Aquifers in South Florida

The Biscayne and surficial aquifers are the uppermost aquifers in South Florida. The surficial aquifer is composed of relatively thin layers of sands with some interbedded shells and limestone. Thickness of the surficial aquifer ranges from 20 to 800 feet, with the greatest thickness occurring in southeastern Florida (Adams, 1992; Barr, 1996; Lukasiewiez and Adams, 1996; Reese and Cunningham, 2000). The surficial aquifer yields relatively small volumes of water and is thus of limited use for public water supply; however, it is an important source of private water supplies (Miller, 1997).

The Biscayne Aquifer is the only formally named surficial aquifer unit in South Florida. The Biscayne Aquifer is the principal source of drinking water in Dade County. This aquifer extends along the eastern coast from southern Dade County into coastal Palm Beach County. The Biscayne Aquifer varies in thickness from a few feet to 240 feet and is composed of highly permeable limestone or calcareous sandstone (Meyer, 1989; Reese, 1994; Maliva and Walker, 1998; Reese and Memburg, 1999; Reese and Cunningham, 2000).

The intermediate confining unit lies beneath the surficial aquifers in Dade, Pinellas, and Brevard counties. Thick upper and lower clay layers confine depositional layers within this aquifer and limit, but do not eliminate the aquifer's hydraulic conductivity (Miller, 1997).

The intermediate confining unit consists of sedimentary deposits from the Arcadia Formation of the upper Hawthorn Group and the Tamiami Formation. Figure 4-3 presents a geologic profile of South Florida. Unit thickness varies across a broad range, with the greatest unit thickness generally occurring in southeast Florida. Sedimentary layers are composed mostly of sand, sandy-limestone, and shell beds, with interlayered dolomite and clayey beds.

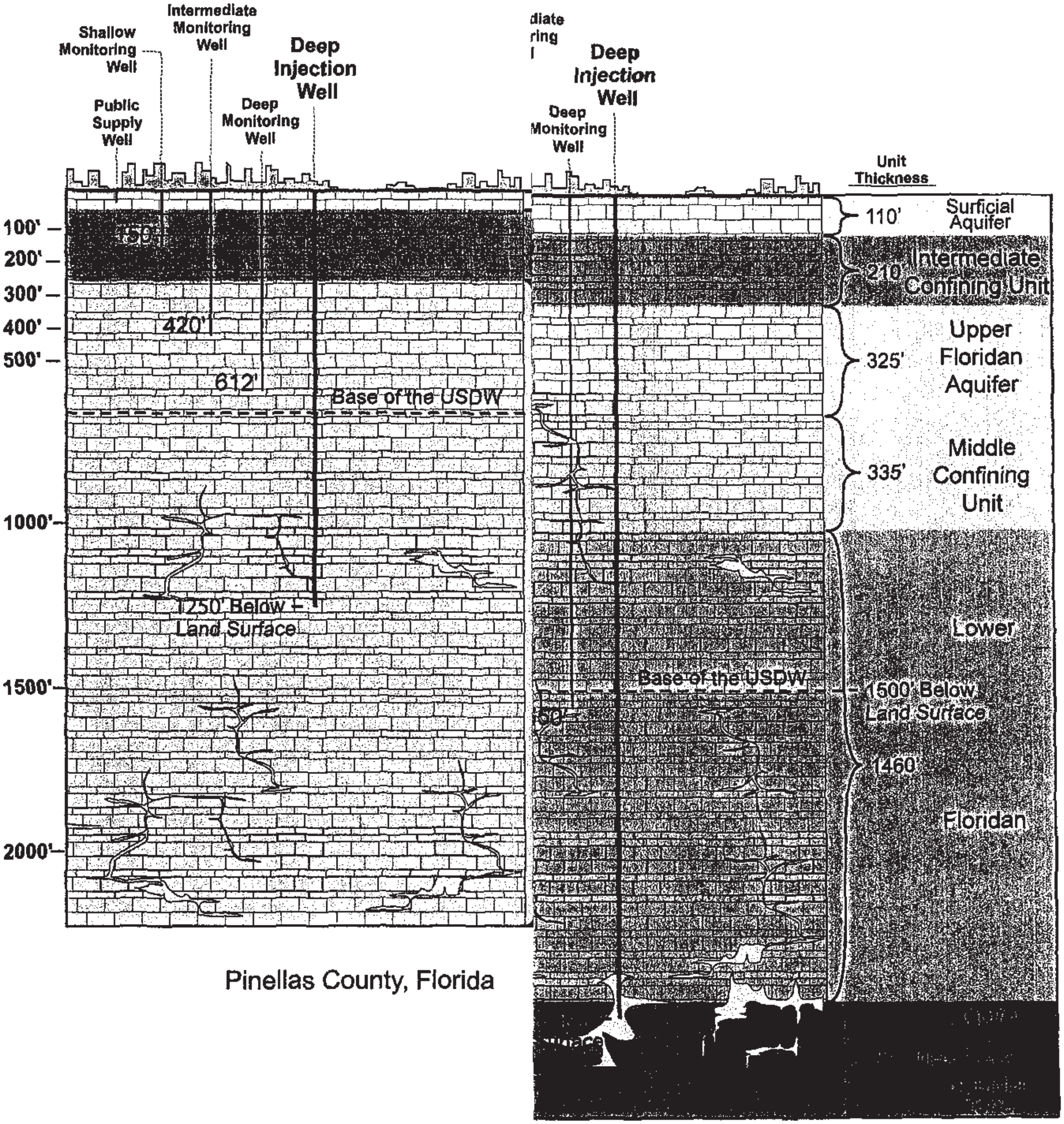
The intermediate confining unit is characterized by low hydraulic conductivity and acts as a confining unit, preventing or slowing migration between the overlying surficial aquifer and the underlying Floridan Aquifer System (Duerr and Enos, 1991; Barr, 1996; Knochenmus and Bowman, 1998). Similarly, the intermediate confining unit present in Dade County separates the Biscayne Aquifer from the Floridan Aquifer System.

The Floridan Aquifer System is subdivided into three distinct hydrogeologic units: the Upper Floridan Aquifer, the middle confining unit, and the Lower Floridan Aquifer. In general, the rocks of the Upper and Lower Floridan Aquifers consist of fractured and karstified limestones and dolomites of varying but generally high permeability. The hydrologic units of the Upper Floridan Aquifer correlate to the geologic units identified as the Suwannee Limestone, the Ocala Limestone, and the upper portion of the Avon Park Formation. The portions of the Upper Floridan Aquifer that yield lower amounts of water are typically associated with the Avon Park Formation (Hickey, 1982; Hutchinson, 1991; Hutchinson and Trommer, 1992; Reese, 1994).

The Upper and Lower Floridan Aquifers are separated by the middle confining unit, which contains lower-permeability rocks and clays (Meyer, 1989; Tibbals, 1990; Duncan et al., 1994; Reese, 1994; Reese and Memburg, 1999). The middle confining unit is comprised of rocks from the lower portion of the Avon Park Formation and upper part of the underlying Oldsmar Formation. These rocks consist of low-permeability clays, fine-grained limestones, and anhydrous dolomite, ranging in thickness across South Florida from 900 to 1,100 feet (Bush and Johnston, 1988; Duncan et al., 1994; Miller, 1997; Reese and Memburg, 1999).

The Lower Floridan Aquifer consists of three distinct layers within one depositional unit. The upper portion of this aquifer consists of dolostones and limestones of the Upper Oldsmar Formation (Duncan et al., 1994). The middle portion is commonly referred to as the Boulder Zone and consists of heavily karstified limestone and dolomite (Duncan et al., 1994; Maliva and Walker, 1998). Below this middle portion, the Lower Floridan Aquifer has properties that are largely consistent with the upper portion of the aquifer.

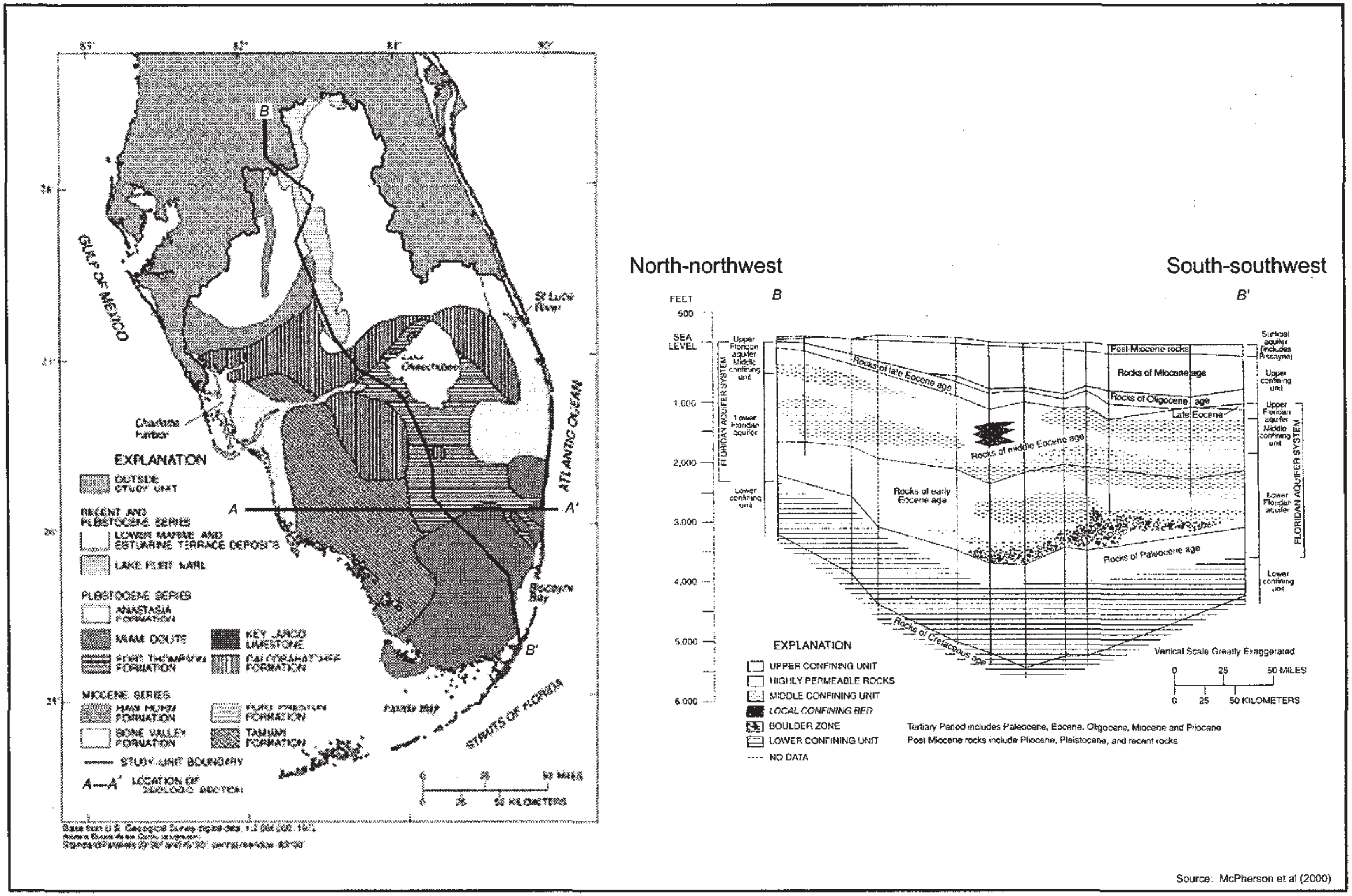
Within the Boulder Zone, solution channels, fractures, and widened joints allow channelized groundwater flow, sometimes at extremely rapid rates. Flow through fractures, solution channels, or other large voids are referred to as bulk flow through preferential flow paths, fracture flow, or channel flow.



Pinellas County, Florida

Brevard County, Florida

Figure 4-2. Representative Hydrogeolo



Source: McPherson et al (2000)

Figure 4-□. Geologic Profile of South Florida

Some reports indicate that groundwater flow in the Upper Oldsmar Formation is consistent with flow through porous media, with little or no channel flow (Meyer, 1989; Duncan et al., 1994; Maliva and Walker, 1998). This type of porous media flow through fine, interconnected pore spaces is typically less rapid than channel flow.

Representative values for hydraulic conductivity, porosity and thickness for each of the aquifer units in Dade, Brevard, and Pinellas counties are presented in the following sections. Mean (weighted) values are based on a statistical analysis of data reported in the scientific literature. Primary and secondary values of porosity and hydraulic conductivity are presented; these are used to examine flow through porous and fractured media, respectively.

4.3.2 Regional Conditions in Dade County

All documented deep-well injection in Dade County occurs within the Boulder Zone of the Lower Floridan Aquifer (Meyer, 1984, Duncan et al., 1994; Maliva and Walker, 1998). Typically, injection wells discharge within the top 250 to 300 feet of the Boulder Zone (FDEP, 1999a). In Dade County, this results in injection into saline groundwater at approximately 2,750 feet below the land surface. The base of the USDW is located approximately 990 feet above the injection zone, within the Upper Floridan Aquifer (Duerr, 1995) (Figure 4-2). Table 4-1 displays the representative values for hydraulic conductivity, porosity, and thickness for the aquifer units in Dade County.