Regulating *the* UNDERGROUND INJECTION *of* CO_2

Florida's battles over injecting wastewater deep underground offer a lesson for any future U.S. regulation of the underground disposal and sequestration of CO_2.

PHOTODISC

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When the U.S. finally gets serious about climate change, it will have to reduce emissions of CO_2 by more than a factor of two during this century in order to do its part in stabilizing atmospheric concentrations (*1*). CO_2 capture and disposal is among the most important supply-side technologies for managing the carbon problem. This technology could enable continued access to fossil energy while virtually eliminating emissions by capturing CO_2 from power plants and "storing," "sequestering" or "disposing" of it in deep geological formations (*2–5*). Surprisingly, all the hardware required to capture CO_2, transport it long distances, and inject it deep underground is currently commercially available. A successful technology, however, is more than just hardware; it comprises a network of institutions, financial systems, and regulations that is able to achieve broad public understanding and acceptance.

Disposal of fluids by injection deep underground is not new. Every year, the U.S. disposes of more fluids by deep-well injection than the mass of all the CO_2 now being released from the country's electric power plants (*6*). Regulations for disposal of CO_2 will not be written on a clean sheet; rather, they will be grafted on top of the substantial body of regulations and institutions that now manage underground disposal.

Since the 1970s, Florida has been injecting very large quantities of wastewater from sewage treatment plants deep underground. The subject of regulatory disputes for more than a decade, Florida's experience, as outlined in this feature, holds important lessons for the development of effective and adaptive regulation for the underground disposal of CO_2.

We're already doing it

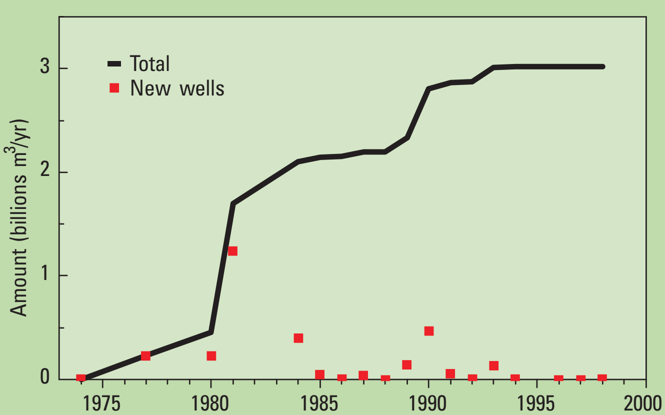
In older oil fields across Saskatchewan, Texas, Wyoming, Colorado, New Mexico, and Mississippi, oil recovery is routinely enhanced by the injection of CO_2 deep underground in a process referred to as enhanced oil recovery (EOR). The regulatory framework for EOR does not require that the CO_2 remain underground. Indeed, a significant fraction of it is typically recovered for reuse elsewhere in the project. Although little or no leakage of CO_2 has been observed from current projects, the regulations governing EOR will likely not be sufficient for geologic disposal because they do not explicitly address the security of disposal over the long durations relevant to climate change.

All underground injection requires drilling an injection well, down which fluid is pumped under high pressure into receiving formations. A typical receiving formation is located in a sedimentary basin and consists of a porous and permeable rock formation overlain by a (relatively) impermeable caprock that confines the injected fluid. Such formations are generally similar, or identical, to the reservoirs that contain oil and gas, and therefore the technologies used for underground injection are derived from the oil and gas industry (*7*).

FIGURE 1

Total volume of injected wastewater over time in Florida

Note the dramatic increase in volume in 1983 after Florida's Underground Injection Control program was approved. New wells data represent (roughly) the amount of the total contributed that year by these wells.



CO_2 captured from power plants or other industrial processes could be disposed of in various underground formations, including abandoned oil and gas fields, deep aquifers that contain water too salty to be useful, and certain types of coal seams. CO_2 disposal requires depths of >1 km, where the pressure is sufficient to raise its density to close to that of water. Nevertheless, the CO_2 will be less dense than the formation waters it displaces, so the entrapped liquefied gas will rise buoyantly to the top of the receiving formation and spread laterally beneath the caprock. Over the lifetime of a coal-fired plant, its CO_2 might spread out over an area >100 km^2. The integrity of the caprock is therefore vital to preventing the buoyant upward movement of CO_2.

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If CO_2 were to migrate out of the receiving formation and rise to the surface, it could cause local ecological damage, primarily by displacing soil gas and affecting plant roots. In rare cases, if the rates of release were large enough and the local conditions were such that concentrations accumulated, animals and humans could face asphyxiation or toxicity risks. Nevertheless, some very limited leakage would not defeat the objective of avoiding climate impact. However, investors purchasing tradable "carbon credits" for the injected CO_2 would require some assurance that the gas was still down there. Most experts agree that migration out of appropriately designed geologic disposal sites will be minimal, but possible risks must be taken into consideration when regulations are designed to govern carbon disposal (*6*). That brings us to Florida.

Wastewater in southern Florida

Underground injection of municipal wastewater in southern Florida arose out of environmental constraints on the use of flowing surface water or ocean outfalls (*8*). Unlike northern Florida, where large rivers or other bodies of water are available for dilution of discharged treated wastewater, southern Florida has only canals, which are relatively stagnant except during seasonal flushing.

Treated wastewater is very high in nutrients such as nitrates and phosphates, which contribute to increased algal blooms and eutrophication. These can have an adverse effect on fish populations by depleting oxygen levels and limiting the penetration of light or by producing toxins that can be harmful to fish and humans. Unless it is subjected to high-level disinfection, water from secondary treatment typically also contains viruses or pathogenic protozoa. All of these problems can be managed through the use of expensive, high-level disinfection and filtration, but most facilities in Florida do not do this (*9*, *10*).

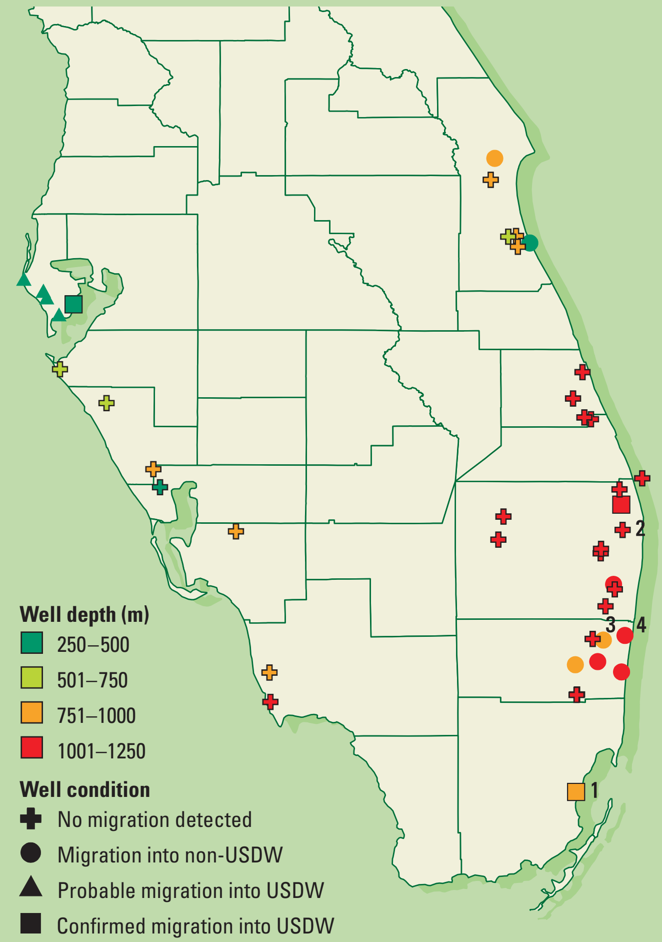
In 1983, southern Florida opted to pursue underground injection as its main method for disposing of secondary treated wastewater (Figure 1). Under the U.S. EPA's Underground Injection Control (UIC) program, 20% of Florida's municipal wastewater, which comes to about 3 gigatons per year (3 cubic kilometers), is injected underground at 62 facilities (Figure 2). Of these injection wells, 93% are >900 m deep (*11*).

The wastewater is injected into the Boulder Zone, part of the Lower Floridan aquifer system that underlies 13 counties in southern Florida. This cavelike formation was created by partial dissolution of fractured dolomite. This zone is extremely permeable and cavernous, but despite its name, it does not contain boulders. The top of the Boulder Zone ranges in depth from 600 to ~1050 m below sea level and is typically overlain by 150–300 m of low-permeability limestone and dolomite, which impede the upward migration of injected waste (*12*). The formation's extremely high permeability limits pressure buildup in wells, which allows the injection of tremendous amounts of wastewater using a relatively small number of wells. The zone also contains saltwater rather than potential drinking water, making it an attractive target for disposal of municipal and industrial waste. No other state disposes of municipal wastewater via underground injection, although many inject other hazardous and nonhazardous wastes underground (*6*; Table 1).

FIGURE 2

Locations and depths of Florida wells used for secondary wastewater disposal

The top four sites for disposal are in Miami–Dade County (13 wells for a total of 1.80 billion m^3/yr, location 1), East Central Regional (6 wells for a total of 0.46 billion m^3/yr, location 2), Ft. Lauderdale (4 wells for a total of 0.40 billion m^3/yr, location 3), and Broward County North (4 wells for a total of 0.33 billion m^3/yr, location 4). Authors' calculations using data from the Florida Department of Environmental Protection.



The UIC program

Federal UIC regulations were first promulgated in 1980 under the 1974 Safe Drinking Water Act, with the explicit purpose of protecting underground sources of drinking water (USDW) from contamination. The UIC permit program regulates wells under five classes, as outlined in Table 1.

Florida's municipal waste injection wells are currently regulated as Class I wells (see box on page 503A). These are wells that inject hazardous, nonhazardous, municipal, or radioactive waste beneath the lowermost formation containing a USDW, which is defined as an aquifer or portion of an aquifer that is capable of supplying a public water system and contains <10,000 mg/L total dissolved solids (salinity). This criterion is conservative because water at the 10,000 mg/L threshold is much too saline to be acceptable as normal drinking water.

Fluids may escape the receiving formation either through wells or by migration through the caprock and other overlying geologic formations. The regulations include very strict and detailed specifications for well drilling and construction, whereas the requirements for analysis of the geologic setting are less rigidly prescribed. In most cases, a review of publicly available geologic data is all that is required, although additional information may be requested by an individual regulator.

The Florida Department of Environmental Protection (FDEP) was given primary responsibility (primacy) for regulatory enforcement of the UIC program by EPA in 1983. The state's UIC program is tailored to the hydrogeology of Florida and is supposed to be consistent with the requirements of the federal program. Florida's UIC rules are similar to EPA's and consist of construction, operating, monitoring, and reporting requirements, with two necessary permits: a construction permit and an operation permit, both of which are valid for five years, after which they must be renewed (*13*).

Florida's regulations lay out detailed requirements that, in many cases, are stricter than those of the federal government. Unique to Florida is the requirement for use of separate monitoring wells. Whereas a monitoring program may be mandatory in other states, all facilities in Florida must have at least one monitor well to detect fluid migration. The monitoring must include periodic sampling of groundwater quality in the first aquifer overlying the injection zone and in the lowermost USDW (*13*).

Both the federal and state UIC regulations are primarily procedural rather than performance-based. That is, they specify detailed procedures that must be followed regarding activities such as well construction and monitoring, rather than prescribing the outcome to be achieved. Two important exceptions exist. First, Class I regulations prohibit any migration of the injected fluid into a USDW. This may be viewed as an overarching requirement that the performance be perfect and that the probability of migration into a USDW be zero. Should contamination occur, the regulations mandate various corrective actions, which may include additional construction, operation, monitoring, or reporting requirements, or, at the discretion of the regulator, immediate closure of the injection well.

Second, in the case of hazardous wastes, operators are required to demonstrate that the waste will not migrate out of the receiving formation or beyond a given radius from the injection wells for 10,000 years. Numerical models of fluid transport are generally used to demonstrate this—the only significant case in which the UIC regulations mandate that operators assess the ability of a disposal site to meet a performance standard before operation begins. Florida's municipal wastes are not classified as hazardous, so this rule did not apply.

Migration has happened

Contamination of USDWs by migrating wastewater was detected in the late 1980s when increased ammonia concentrations and decreased total dissolved solids were found at monitoring wells in Pinellas and Brevard counties in Florida. If the procedural regulations had worked as intended, no contamination would have occurred.

Regulations required remedial action at all the responsible wells as soon as any contamination was detected. Even after a series of tests failed to resolve the problem, FDEP declined to order a shutdown. A plausible rationale for this decision was that the contamination posed comparatively little risk to public health. Although not explicitly mentioned, the absence of other low-cost disposal alternatives was presumably also a consideration.

The UIC regulations were drafted with the intention of controlling the migration of comparatively hazardous industrial wastes rather than that of the relatively benign municipal wastewater at issue in Florida; therefore, it may reasonably be argued that the absolute prohibition of migration into USDWs is too strict. Whatever the merits of such arguments about risk and cost-effectiveness, the reality on the ground was at odds with the regulations.

In 1991, the Legal Environmental Assistance Foundation (LEAF), a local environmental group,

TABLE 1

The Underground Injection Control program

The U.S. EPA administers the UIC program under rules laid out in Parts 144–147 and 149 of Chapter 40 of the U.S. Code of Federal Regulations. EPA defines five classes of wells, depending on the type of fluid being injected, the nature of the party performing the injection, and where the injection occurs. Some states, including Florida, have received authority from EPA to administer the UIC program at the state level with only general EPA oversight. The five classes of wells currently included in the UIC program are listed below. Data on well numbers are for 1999, the most recent date for which comprehensive data are available (*5*).

Well class	Number of wells
Class I. Deep injection of hazardous, municipal, radioactive, and other industrial wastes.	Close to 500 active wells, including 266 nonhazardous wells in 19 states, 84 municipal wells in Florida, and 123 wells injecting hazardous materials.
Class II. Injection of fluids produced during oil and gas production or in association with natural gas storage, for enhanced oil or gas recovery, and for storage of liquid hydrocarbons at standard temperature and pressure.	Approximately 154,000 wells in 32 states.
Class III. Injection for mineral extraction, including in situ solution mining of uranium, metals, salt, etc.	About 30,000 wells; 80% of the uranium and 50% of the salt used in the U.S. comes from solution mining.
Class IV. Injection of hazardous or radioactive wastes above or into a formation containing underground sources of drinking water (USDW) within 0.25 miles, or injection into or above a USDW. Wells of this type are banned except for remediation and are prohibited under the UIC program and the Resource Conservation and Recovery Act.	Several hundred wells at ~40 locations in remedial cleanups.
Class V. All other wells not included in Classes I–IV, including shallow disposal ponds, large-capacity cesspools, drainage wells, recharge wells, subsidence-control wells, experimental, geothermal-energy, and solution mining of conventional mines.	Officially, 200,000 wells; there may actually be >500,000. They occur in all states, and no comprehensive inventory exists.

filed a petition with EPA for the withdrawal of Florida's primacy over the UIC program on the grounds that the program did not meet several of the federal UIC requirements (*14*). EPA eventually denied the petition in 1995. Dissatisfied with this result, LEAF then filed a petition with the U.S. Court of Appeals to review EPA's decision, arguing that Florida's UIC regulations were contrary to the Safe Drinking Water Act because they were not protecting groundwater. In 1998, LEAF, EPA, the U.S. Department of Justice, and FDEP reached a settlement involving modest revisions to the state's UIC program (*15*). However, LEAF continues to argue that the solution is not satisfactory (*10*).

Fluid migration into USDWs has been confirmed at three facilities in Pinellas, Dade, and Palm Beach counties and is probable at six additional facilities in Pinellas and Brevard counties. All these facilities are still in operation. In addition, fluid movement into non-USDWs (aquifers that exceed the salinity standard for a USDW) has occurred at nine other facilities, primarily in Broward county. The indicators of fluid migration include "freshening" of the saline groundwater caused by migration of the relatively "fresh" wastewater and contamination by ammonia and fecal coliforms (*9*).

In 2003, EPA publicly acknowledged that migration was taking place and published a risk assessment that concluded that the contamination posed little risk to public health.

In response to continued legal action by interveners, EPA proposed to amend the federal UIC requirements either by modifying the rules for Class I wells or by reclassifying some of the Florida wells as Class V (Table 1). Both proposed options essentially create a performance-based standard, allowing for the migration of wastewater—treated to a more stringent standard—as long as it does not endanger USDWs by exceeding national primary drinking-water treatment standards. These new rules would allow continued injection at facilities in violation of the current regulations but require implementation of advanced wastewater treatment by 2015 (*16*).

With the proposed amendments, EPA has essentially replaced the strict "no migration" constraint with a less-rigid, risk-based standard. The result is a standard whose goal is to reduce risks to some presumed socially acceptable level rather than to eliminate them altogether. Moreover, it specifies performance criteria for outcomes rather than simply setting procedures to be followed. This approach may be seen in two ways: as simple temporizing, or as a reasoned response based on the presumption that the problems arise from the inability of the UIC regulations to effectively manage a high-volume, low-toxicity waste stream rather than from the actual risks posed by wastewater disposal.

The existing regulations focus primarily on managing contamination from the injection well, whereas all current migration issues arose from lack of confinement in the receiving formation (presumably due to migration though the caprock) and not problems with well design or construction. The proposed amendments will presumably add to the rigor of the hydrogeologic characterization, although it is unclear exactly how a risk-based standard will be applied, given the difficulty of predicting subsurface fluid migration.

LEAF, the Sierra Club, and other environmental groups have voiced their opinions on these proposed rules. A common sentiment is that the proposals do little to minimize the risk to human health and that the government will alter the regulations in any way necessary to allow underground injection because it is the cheaper, out-of-sight alternative to most other disposal options. Some groups have said that regulators will take serious action only when a disaster occurs and widespread public attention is brought to the underground injection process. On the other hand, operators of UIC facilities, especially those with USDW contamination, may feel that the proposed rules will only make running their facilities more difficult and costly, given that current regulations appear to have adequately managed risk to human health and the environment. EPA promised to take into account all comments and promulgate

Rules for Class I wells

Construction. The application for a construction permit must include general facility information, a description of the type of waste to be injected, a topographic map of the area showing the structures of the facility and natural features, and a plugging and abandonment plan. Reporting requirements include results from various well logs and tests carried out during drilling and construction; most requirements are to ensure drilling accuracy and determine the physical characteristics of the injection zone (*17*).

Operation. After construction, but before operation has commenced, the operator must apply for an operating permit. More specific information is required with this application, including a map showing all wells; specific well data, such as type, depth, and injection and pressure test results; maps and cross-sections of geologic structures, aquifers, and USDWs within the area of review; proposed operating data, including average and maximum daily rate, volume of fluid to be injected, average and maximum injection pressure, and chemical, physical, radiological, biological, and source information on the waste to be injected. The applicant must also demonstrate the mechanical integrity of each injection well. This is defined as the absence of any significant leaks in the casing, tubing, or packer of a well and the absence of significant fluid movement into a USDW through vertical channels adjacent to the well bore. After a permit has been issued, well-specific operating requirements dictate a maximum injection pressure to prevent fracturing in the injection or confining zones (*17*).

Monitoring. Required monitoring includes analysis of injected fluids; continuous monitoring of injection pressure, flow rate, and volume; demonstration of mechanical integrity once every five years; and a sufficient number and placement of monitoring wells to assess any migration of fluids into a USDW. Operators of Class I injection wells are required to submit quarterly reports on the characteristics of the injected fluids; monthly values for injection pressure, flow rate and volume, and annular pressure; and the results of monitoring and testing described above (*16*). If monitoring indicates movement of a contaminant into a USDW, then preventive actions must be taken, including additional construction, operation, monitoring, or reporting requirements; corrective action; or permit termination and well closure (*18*).

final rule, which was signed by the EPA Administrator on November 16, 2005.

Florida's regulatory lessons

Under current law, deep geologic injection of CO_2 would be most likely regulated under the UIC program. The Florida experience suggests that this would not be sufficient.

The UIC Class I rules were written primarily to deal with small quantities of toxic industrial waste. In Florida, this regulatory framework was ill suited to managing huge quantities of relatively nontoxic waste. Geologic disposal of CO_2, like that of Floridian wastewater, involves disposal of huge quantities of a relatively benign substance. This analogy is important but not perfect. The most critical risk posed by injection of either highly toxic industrial wastes or Floridian wastewater is contamination of drinking water. However, the most important risks posed by injected CO_2 are ecosystem impacts and acute health risks arising from surface exposure to the gas.

In the low-volume, high-toxicity case for which the regulations were designed, the greatest concern is failure of the well itself, such as a cracked casing, which might lead to contamination of USDWs. The experience in Florida shows that injection-well failure may not be the dominant migration pathway when very large volumes are injected. Better tools are needed for predicting and managing fluid migration through the subsurface. Similar arguments are likely to apply to the management of CO_2 disposal.

The existing regulations impose rigid limits on what can and cannot happen. They do not facilitate an adaptive approach to regulation and risk management as field experience develops. As a result, Florida and EPA have been forced to temporize, loosening a regulatory regime in order to reconcile it with reality. This is not the way a major new injection activity should be managed.

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A clear lesson from the experience in Florida is that specifying an absolute prohibition on fluid migration is not realistic. While the risks posed by leakage of relatively benign CO_2 must not be ignored, the environmental risks with a well-designed disposal system are likely to be small compared with the environmental benefits in the form of reduced costs for controlling the emission of the global-warming gas. Whether they result from a revision of Class I rules or from an entirely new set of rules, regulations governing CO_2 injection must be performance-based. They should specify that geologic disposal facilities be operated so that risks are reduced below some socially acceptable threshold. However, the regulations must also acknowledge that absolute prevention of fluid migration cannot be ensured.

New regulations governing CO_2 will require more careful characterization of the reservoir before injection begins, clear guidance on how the disposal of fluid must be monitored, and explicit procedures for how unanticipated migration should be handled, including when injection should be halted and various remediation activities begun.

Unfortunately, performance is difficult to predict, and once injection is under way, it is hard to evaluate deep underground. Fortunately, various sophisticated tools, such as 3-D seismic monitoring, now exist; more are under development, and field studies are now in progress. This is an area of research that needs continued urgent attention. Moreover, regulatory agencies will need to integrate such tools into the regulatory process to develop a sound performance-based approach.

The federal research program on geologic sequestration is managed by the U.S. Department of Energy (DOE), for which the EPA will be the federal regulator. Close collaboration between EPA and DOE is therefore vital to ensure that research programs deliver the scientific understanding needed to develop adequate adaptive, science-based, regulations for CO_2 disposal. Recently, EPA took the first steps to track and evaluate research on geologic sequestration. This effort should be expanded and pursued with vigor. EPA must be able to ensure that federal research efforts on geologic storage will adequately address the topics required to enable protection of human and ecological health.

It seems unlikely that large-scale injection of CO_2 can proceed without at least some leakage. Limited leakage is probably acceptable, but an allowable amount of leakage must be established and procedures created for dealing with leaks when they occur. Regulations must limit the amount of leakage for three reasons: to avoid ecological and human health damage, to determine the ongoing economic value of carbon credits that have been assigned to injected CO_2 so that they can be reliably traded in domestic and international markets, and to ensure that the problem of serious increases in atmospheric CO_2 concentration is not simply being put off. Meeting each of these three objectives will require different criteria, none of which are adequately considered under current UIC regulations.

Any new regulations governing the underground injection of CO_2 must be adaptive to new information and technology as they become available. However, while assimilating new ideas, regulators must not lose sight of the primary goal: to limit climate change by keeping injected CO_2 underground and out of the atmosphere.

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