TECHNICAL SUPPORT DOCUMENT

Vulnerability Evaluation Framework for Geologic Sequestration of Carbon Dioxide

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ACRONYMS

Ar	Argon
CCD	Climate Change Division
CCS	Carbon Dioxide Capture and Storage
CH_4	Methane
Cn	Cyanide
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOE	U.S. Department of Energy
DWPD	Drinking Water Protection Division
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
Fe	Iron
GHG	Greenhouse Gas
GS	Geologic Sequestration
H_2	Hydrogen
H_2S	Hydrogen Sulfide
Hg	Mercury
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IZ	Injection Zone
mg/L	Milligrams per Liter
N_2	Nitrogen
NETL	National Energy Technology Laboratory
NO	Nitrogen Oxide
NO_3	Nitrate
NOAA	National Oceanic and Atmospheric Administration
O_2	Oxygen
ppm	Parts Per Million
SDWA	Safe Drinking Water Act
SO_2	Sulfur Dioxide
SO_4	Sulfate
TDS	Total Dissolved Solids
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USGS	U.S. Geological Survey
VEF	Vulnerability Evaluation Framework

CHAPTER 1

INTRODUCTION

Geologic sequestration[1] (GS) of carbon dioxide (CO_2), a greenhouse gas (GHG), has been identified as one of several approaches to reduce atmospheric concentrations of CO_2, thereby contributing to the mitigation of climate change (IPCC, 2005). A large body of literature indicates that GS is a viable technology that can be conducted in a safe manner when coupled with a comprehensive approach to ensure protection of human health and the environment (see text box). Nonetheless, there are potential risks and uncertainties associated with GS. To systematically identify those conditions that could increase the potential for adverse impacts from GS, the U.S. Environmental Protection Agency (EPA) has developed a Vulnerability Evaluation Framework (VEF).

> "With appropriate site selection based on available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geologic storage would be comparable to risks of current activities such as natural gas storage, [enhanced oil recovery], and deep underground disposal of acid gas."
>
> –IPCC (2005)

1.1 Background on Climate Change and Geologic Sequestration

In its 2007 scientific assessment, the Intergovernmental Panel on Climate Change (IPCC) concluded that "warming of the climate system is unequivocal" (IPCC, 2007). This warming trend has been linked to shrinking glaciers, rising sea levels, alterations in plant and animal habitats, and other global impacts. The IPCC concluded that it is very likely that most of the increase in the average global temperature since the mid-20th century has been caused by emissions of GHGs from human activities. Continued GHG emissions at or above current rates will lead to further warming and very likely to global impacts, some of which may be irreversible (IPCC, 2007).

The IPCC examined several scenarios to reduce and soon reverse increase in emissions of GHGs and thus limit future climate change; most studies find that a range of strategies will need to be employed. In its Special Report on Carbon Dioxide Capture and Storage, the IPCC identified CO_2 capture and storage (CCS) as one of several approaches with the potential to address climate change (IPCC, 2005). CCS is intended to mitigate climate change effects by decreasing emissions from stationary sources such as power plants (IPCC, 2005). Although several CCS technologies have been proposed, including ocean storage and mineral carbonation, GS has been identified as the most technically viable approach (IPCC, 2005). GS involves injecting captured CO_2 into deep, subsurface rock formations for long-term storage. It has been estimated that available capacity for GS in the United States ranges from 1,300 to 3,900 gigatons of CO_2, with most of the capacity in deep saline formations (NETL, 2007). For reference, the total energy-related CO_2 emissions in the United States in 2005 was 5.9 gigatons, with fossil fuel combustion accounting for 5.8 gigatons (U.S. EPA, 2007).

[1] Note, sequestration is also sometimes referred to as storage, see for example, IPCC 2005.

1.2 Vulnerability Assessment Approach

The vulnerability assessment incorporated in the VEF was developed to systematically identify those conditions that could increase the potential for adverse impacts from GS, regardless of likelihood or broad applicability. It is not a quantitative, probabilistic risk assessment tool. Vulnerability assessment examines conditions that lead to increased or decreased susceptibility to consequences, whereas risk assessment measures the probability and severity of consequences. It is recommended that assessing vulnerability be an iterative process where new information is incorporated into the evaluation as it is generated. Many of the principles, approaches, and areas of focus in the VEF, discussed in this report, are similar to and reflect conclusions reached in other GS assessments (see, for example, Oldenburg et al., 2002a, 2002b; Friedman and Nummedal, 2003; Maul et al., 2003; Celia and Radonjic, 2004; Celia et al., 2004; Le Gallo et al., 2004; Quintessa, 2004; Walton et al., 2004; Zhang et al., 2006).

The VEF described in this report is not designed to be a generalized site selection tool, to establish performance standards for GS sites, or to specify data requirements. The VEF represents a first step toward a conceptual framework designed to aid regulators, and other technical experts, in framing key site-specific considerations and in identifying key areas that require in-depth evaluation for project design, site-specific risk assessment, monitoring, and management. It could serve as a reference document for regulators responsible for approving environmental impact statements, approving GS sites, or issuing permits for GS projects. Applying the VEF would necessitate detailed technical information on the proposed GS site extracted from existing data sources or specifically collected by a project operator.

Current challenges to developing a quantitative risk assessment that is applicable across all GS sites are related to limited field experience and the heterogeneity of GS sites. Attempting to quantify risks before sufficiently understanding GS systems could result in understating or overstating the risks associated with GS. Development of a high-level quantitative risk analysis will become more feasible as information is generated from pilot- and commercial-scale projects. Due to the inherent heterogeneities of GS systems, site-specific quantitative risk assessments similar to approaches taken at the Weyburn (Canada), Gorgon (Australia), and Otway (Australia) sites provide invaluable insight into understanding and managing potential risks. (Zhou et al., 2004; Chevron, 2005; U.S. DOE, 2007a; CO2CRC, 2008).

As with all such frameworks, the VEF is limited in that only vulnerabilities based on currently known or understood physicochemical or biological processes are considered. Uncertainties that go beyond current understanding of these fundamental processes or are related to issues of scale are not explicitly incorporated into this vulnerability framework. Uncertainties associated with models may also present challenges to both operators and regulators. Acknowledging these uncertainties and employing a strategy to manage them is a critical aspect of any assessment. Probabilistic approaches may be applied to handle uncertainties that arise from variability in the GS system (e.g. description of deep geologic storage systems, variation in types of cement materials used in wells, uncertainty regarding the location of existing wells, etc). Uncertainties from incomplete characterization of the GS site may be addressed through incorporating additional information as it is generated, thus reducing uncertainty and increasing the precision of the evaluation. It may be more difficult to address uncertainties arising from a lack of understanding of processes involved, and from potentially unreliable, inexplicable, or conflicting data. Approaches are being developed that can be applied to manage uncertainties associated with GS (see Benbow et al, 2006).

The VEF concept was developed based on an extensive literature review as well as input from EPA's Regional and Headquarters offices, researchers at the DOE national laboratories, experts from academia, and members of nongovernmental organizations working on issues related to GS. The IEA GHG R&D Programme also facilitated a peer review of this document by GS experts.

It is important to emphasize that the use of the VEF in framing site-specific considerations for site selection does not replace or supersede other statutory or regulatory requirements for the protection of human health and the environment. Owners and operators must obtain all necessary permits from appropriate state and federal authorities under the Safe Drinking Water Act (SDWA) and any other applicable statutes and regulations.

1.3 Report Organization

The goals of this report are to:

1. Outline key characteristics of a GS system that need to be evaluated to understand potential impacts to human health and the environment.

2. Provide approaches for conducting "first-order" assessments of GS systems to identify circumstances where additional study and/or monitoring may be warranted.

3. Identify potential mechanisms for unanticipated migration[2], leakage[3], and or pressure changes that could cause adverse impacts.

4. Describe potential impacts of unanticipated migration, leakage, and pressure changes based on available literature.

The report chapters address these goals as follows:

Chapter 2: For GS to be an effective climate change mitigation tool, large volumes of CO_2 must remain underground for long periods of time (hundreds, if not thousands, of years). Chapter 2 discusses the types of geologic formations that are currently being considered for GS and the types of mechanisms that could trap CO_2 underground. The VEF was developed with a focus on deep saline formations (described in Chapter 2), but many of the concepts apply to other geologic settings under consideration for GS. The chapter also provides background on GS as a climate change mitigation strategy by identifying natural and industrial analogs for GS and reviewing U.S. experience in regulating subsurface injection.

Chapter 3: Chapter 3 describes geologic attributes that could influence (i.e., increase or decrease) the vulnerability of a GS system to unanticipated migration, leakage, or pressure changes. This chapter also discusses the GS footprint component of the spatial area of evaluation.

[2] The term "migration" refers to subsurface movement of CO_2 (or other fluids) within or out of the injection zone.

[3] The term "leakage" refers to the movement of CO_2 (or other fluids) to the surface (for example, to the atmosphere or oceans).

Chapter 4: Five impact categories and associated key receptors are described that could be affected by unanticipated migration and leakage or pressure changes: human health and welfare, atmosphere, ecosystems, groundwater and surface water, and the geosphere. Chapter 4 identifies approaches to evaluate adverse impacts to receptors (human and environmental) that might occur in the event of unanticipated migration, leakage, or pressure change, and to evaluate spatial area of evaluation with respect to the receptors that may be impacted.

Chapter 5: The overall vulnerability of a GS site to adverse impacts is not dependent on the presence of a single attribute or receptor, but is a combined function of the identified geologic attributes and receptors. Chapter 5 provides a qualitative discussion of this concept of an holistic approach, the linkage between attribute vulnerabilities and impacts, and how vulnerabilities may change over time. This chapter also elaborates on two key attributes considered likely conduits, wells and faults/fracture zones (both existing and pressure-induced). The discussion highlights that even for these individual attributes, it is the interplay of multiple characteristics that will determine the level of vulnerability, and not their simple presence.

Chapter 6: The VEF assists in identifying situations that could result in elevated vulnerability to adverse impacts from GS and often recommends monitoring in such instances. The potential for adverse impacts may be minimized in many cases by careful monitoring and mitigation. Chapter 6 reviews monitoring technologies that can be used to measure how much CO_2 is injected, to track the location of stored CO_2, and to detect any CO_2 releases[4] to the atmosphere. This chapter also discusses potential mitigation actions in the event of leakage, unanticipated migration, or pressure changes.

Chapter 7: Chapter 7 provides a summary of the VEF, its structure, development, purpose, and potential applications. The chapter also describes next steps that may be taken to further develop, refine, and validate the VEF.

[4] Release is another term used for leakage.

CHAPTER 2

BACKGROUND ON GEOLOGIC SEQUESTRATION

The value of GS as a climate mitigation tool is, in part, contingent on CO_2 remaining stored underground for a long period of time. Long-term storage could be accomplished by injecting CO_2 into appropriate geologic formations with effective trapping mechanisms that will not be compromised over the storage period. It has been estimated that CO_2 storage will need to function for at least several hundred years (Chalaturnyk and Gunter, 2004; IPCC, 2005; Holloway et al., 2007). While a desirable timeframe for effective sequestration of CO_2 may be as much as thousands of years, effective storage of CO_2 for even several hundred years may provide valuable flexibility in reducing CO_2 emissions and addressing climate change impacts.

This chapter describes likely formations where CO_2 might be injected and the mechanisms that can trap CO_2 underground. It reviews natural and industrial analogs and related field experience that are often cited to support the view that GS can be an effective climate change mitigation technology (Benson et al., 2002; Heinrich et al., 2003; IEA, 2004; IPCC, 2005, 2007; Dooley et al., 2006; MIT, 2007). U.S. regulation of subsurface injection of fluids also provides relevant experience that is summarized here.

The chapter is organized into the following sections:

- Section 2.1 outlines the kinds of geologic formations being considered for GS, including deep saline formations, depleted oil and gas reservoirs, coal seams, and other geologic formations.
- Section 2.2 explains the various mechanisms and properties of CO_2 and geologic formations that control the underground movement and trapping of CO_2.
- Section 2.3 examines practical experience relevant to sequestration, including existing GS projects, natural and industrial analogs for GS, and relevant EPA regulatory experience.
- Section 2.4 summarizes the chapter.

2.1 Geologic Settings under Consideration for Sequestration

The behavior of CO_2 in the subsurface and potential vulnerabilities of a GS project are functions of both the type of geologic formation into which CO_2 would be injected and the prior uses of the geologic setting, if any. Figure 2.1 is a general illustration of how GS could be implemented in a variety of geological settings. The VEF was developed mainly to evaluate deep saline formations, but many of the concepts also apply to other geologic settings.

Geologic formations and operational processes typically considered for GS include the following:

- **Deep saline formations**: In these sedimentary formations, the pore space between the formation rock is filled with water containing elevated concentrations of dissolved salts (brines). These formations are being considered for GS because they form very large basins, are located at significant depth (generally below 800–1,000 meters), and typically are not considered viable sources of potable groundwater because of their salinity and depth.

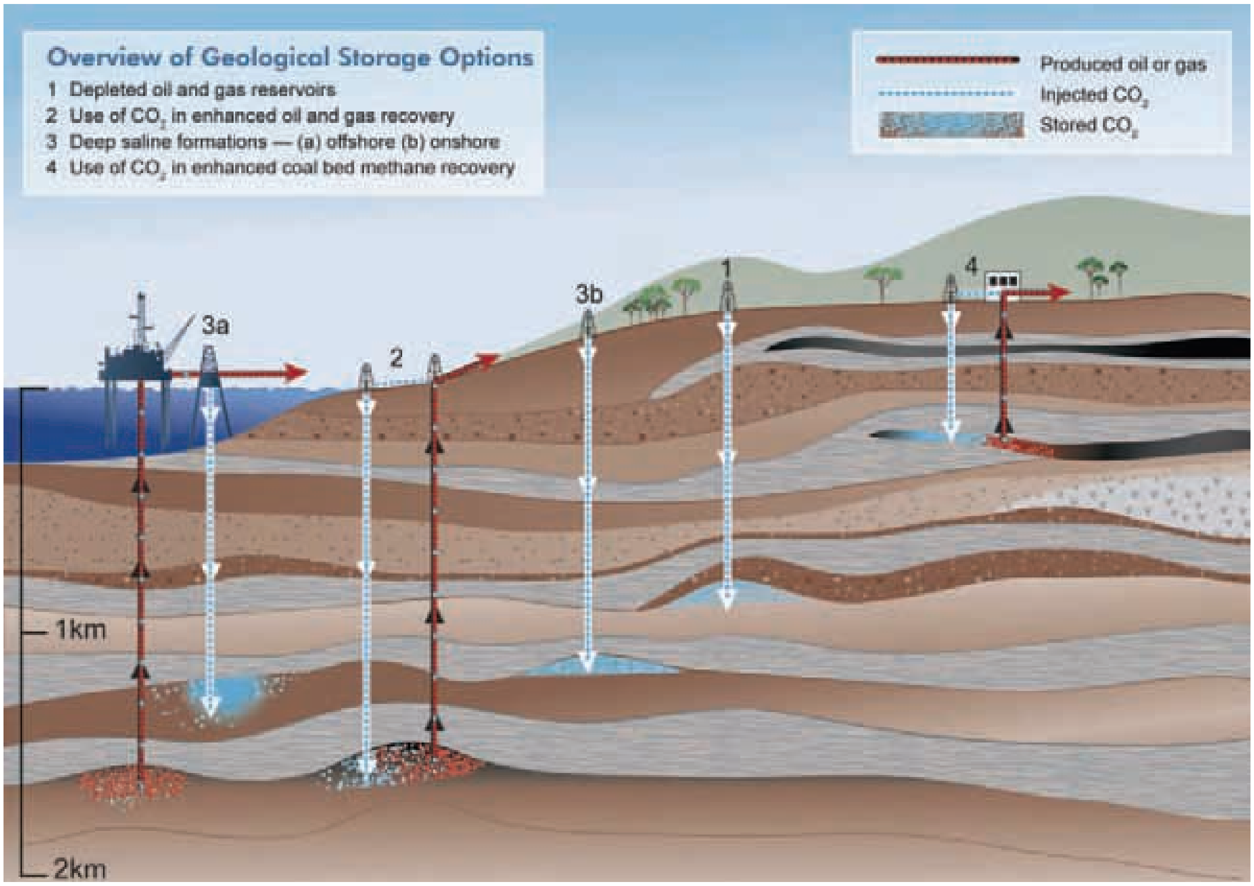

Figure 2.1. Examples of Geologic Formations Being Considered for GS. Source: CO2CRC, 2007

Deep saline formations are believed to have the greatest potential storage capacity and are more widespread than other storage options (Dooley et al., 2006; NETL, 2007), and therefore are the primary focus of the VEF. Stacked reservoirs, in which multiple formations are overlain vertically, separated by lower permeability rock, may be considered particularly advantageous for GS. For a given surface area, such settings would provide greater vertical storage space, and the multiple layering may provide additional CO_2 structural and stratigraphic traps (see section 2.2 for a discussion of CO_2 trapping mechanisms). In addition, because of their depth, deep saline formations are penetrated by few wells or other artificial penetrations that could serve as pathways for CO_2. Furthermore, the pressure and temperatures typically encountered at such depths are sufficient to maintain CO_2 as a supercritical fluid; and supercritical CO_2 requires much less storage space than it does in gaseous form. Finally, there is currently little competing demand for the resources contained in these formations, including saline pore waters (IPCC, 2005; Dooley et al., 2006). However, advances in desalination technologies and increasing water demand in certain regions could lead to increased competition in the future. A challenge in this GS option is the displacement of large volumes of water to create the pore space for CO_2. The Sleipner Project in the North Sea is an example of a commercial operation in which captured CO_2 is injected into a saline formation.

- **Depleted oil and gas reservoirs**: These formations have effectively stored oil and natural gas for hundreds of thousands to millions of years before human extraction (Benson et al., 2002; IPCC, 2005; Haszeldine, 2006). As a result, there is reason to believe these same formations could effectively store injected CO_2. Although a wealth of geologic data are available on the characteristics of these reservoirs, they are also known to have many abandoned oil and gas production and exploration wells that could be conduits for CO_2 to escape from the subsurface. Chapter 5 contains more information on the potential for such wells to be unanticipated migration or leakage pathways.

- **Enhanced oil/gas recovery**: CO_2 is currently injected in some U.S. oil fields to enhance oil production. Because these formations effectively stored oil for hundreds of thousands to millions of years, it is believed that they can be used to store injected CO_2 for long periods of time. However, enhanced oil recovery (EOR) operations are not currently designed to maximize CO_2 storage but rather to increase production of oil (Advance Resources International, 2006). The Weyburn site in Saskatchewan, Canada, is an example of an EOR operation using CO_2 that is captured and shipped via pipeline from a commercial coal gasification plant in Beulah, North Dakota. Geologic sequestration in EOR fields faces the same issues associated with depleted oil and gas reservoirs. Specifically, EOR fields have substantial geological information, but are known to have active and abandoned oil and gas production and exploration wells that could be unanticipated migration and leakage pathways (Celia et al., 2004; Heller, 2005).

- **Coal seams**: Coal seams are being considered for GS because of coal's high affinity for CO_2 (Haszeldine, 2006). Micropores in the coal matrix, made more accessible through coal seam fractures, can adsorb gases, including CO_2 and methane (CH_4). However, the fine cleats that create coal micropermeability can become plugged as CO_2 replaces CH_4, thereby restricting flow and causing localized matrix swelling. Matrix swelling around an injection wellbore may reduce permeability and injectivity and, if reduced injectivity is not overcome, may lead to reduced effective storage capacity.

  Methane is a GHG that can contribute to climate change effects if discharged into the atmosphere (IPCC, 2007). While there are few examples in practice, the CH_4 released by the adsorption of CO_2 could be recovered for commercial use. Coal seams are sometimes underground sources of drinking water (USDWs), and may therefore be subject to additional requirements. Though coal seams are considered an option for CO_2 storage, considerable research and development is still needed to understand coal seam CO_2 sequestration.

- **Other geologic settings**: Other rock types such as basalts and oil or gas rich shale, geologic repositories such as salt caverns, and abandoned mines may also be considered for GS, but are not the subject of current focus. Each of these settings has advantages and disadvantages with regard to its potential to effectively store CO_2 based on its specific geologic characteristics. For example, basalt has the disadvantage of low porosity, permeability, and fractures that may result in the unanticipated movement of CO_2 out of the injection zone; but has the advantage that CO_2 could be permanently trapped in mineral form through chemical reactions of the CO_2 with silicates in the basalt to form carbonate minerals (IPCC, 2005). Additionally, these settings may not accommodate the anticipated scale of GS.

2.2 Subsurface CO_2 Movement and Storage Mechanisms

Knowledge of subsurface movement and trapping of CO_2 assists in understanding the potential for CO_2 to migrate out of the injection zone.

2.2.1 Factors that Control the Rate of CO_2 Movement in the Subsurface

The rate of CO_2 fluid flow depends on the properties of CO_2 and other fluid phases present in the injection formation, properties of the formation itself, and physical and geochemical interactions that may occur in the subsurface. The primary fluid transport mechanisms that control the rate of movement of CO_2 in the subsurface include:

- Fluid flow caused by injection-induced pressure gradients (where higher gradients result in faster flow rates).
- Fluid flow caused by existing hydraulic gradients in the injection formation.
- Buoyancy-driven flow caused by the density differences between CO_2 and the formation fluids (which may result in upward migration of CO_2).
- Dispersion and fingering caused by formation heterogeneities and viscosity contrasts between CO_2 and the formation fluid(s) (CO_2 is less viscous than water and will preferentially “slide” over saline waters and channel into high permeability zones).
- Diffusion (this has a relatively minor effect).

Properties of the injection zone formation(s) that affect the rate of CO_2 movement include its permeability, thickness, and heterogeneity. A higher permeability results in faster CO_2 migration, and a greater thickness means that a greater total volume of CO_2 can migrate at the given rate. Geologic heterogeneities also can control CO_2 flow. For example, zones of high permeability such as a sand lens or an open fracture can act as conduits that allow CO_2 to move much faster than would be expected based on the bulk properties of the rock. In contrast, low permeability zones such as shale can slow down or even stop flow. Some of these physical and geochemical processes also can affect the movement of CO_2 in the subsurface by retarding CO_2 flow and acting as CO_2 trapping mechanisms, as discussed below.

2.2.2 Physical and Geochemical Trapping Mechanisms

Geologic sequestration of CO_2 occurs through a combination of structural and stratigraphic trapping, residual CO_2 trapping, solubility trapping, mineral trapping, and preferential adsorption trapping. These mechanisms are functions of the physical and chemical properties of CO_2 (see Appendix A for a summary of these properties) and the geologic formations into which the CO_2 is injected. Figure 2.2 illustrates the relative effectiveness of the different mechanisms (with the exception of preferential adsorption trapping) in trapping CO_2 over time. Impermeable physical barriers are considered to be the most effective physical trap in the near term. Although mineralization is the most permanent trapping mechanism, it occurs relatively slowly compared to the others. The various trapping mechanisms, based on the discussion in the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005), are as follows.

- Structural and stratigraphic trapping occurs when injected CO_2 rises within the storage formation because of its relative buoyancy and/or the applied injection pressure and then reaches a physical barrier that inhibits further upward migration. The physical barrier could be a stratigraphic trap (a formation or a group of formations that act as a permeability and capillary barrier which impedes or prevents upward migration of supercritical CO_2) or a structural trap such as one formed by folded or faulted rocks (IPCC, 2005).

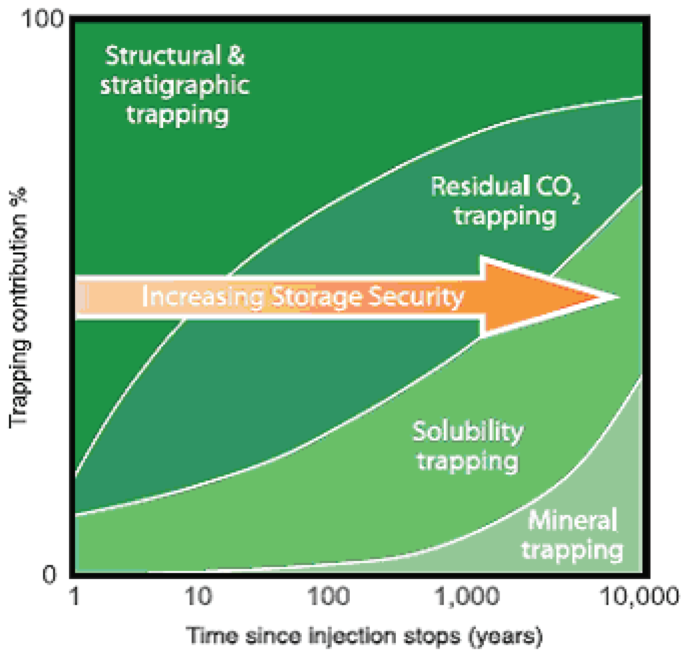

Figure 2.2. Effectiveness of Trapping Mechanisms Over Time. Source: IPCC, 2005, Figure 5.9.

- Residual CO_2 trapping occurs when CO_2 moving through the formation(s) is retained in the pore space by capillary forces. This retention, also called capillary trapping, may range from 15% to 25% for typical storage formations (Holtz, 2002), but could exceed 25%, depending upon the porosity and permeability of the formation(s). When the degree of capillary trapping is high and CO_2 is injected at the bottom of a thick formation or group of formations, capillary trapping can prevent CO_2 from reaching overlying structural and stratigraphic traps (IPCC, 2005; Kumar et al., 2005).

- Solubility trapping occurs when injected CO_2 contacts a fluid formation (e.g., saline water) and dissolves into the fluid (also known as dissolution trapping). CO_2 that is dissolved in a formation fluid is not buoyant; it is instead trapped within the formation fluid. The density of formation fluids with dissolved CO_2 increases, so formation fluids containing dissolved CO_2 may sink within the formations (GEO-SEQ Project Team, 2004; Streit and Watson, 2004; IPCC, 2005), though this effect may be limited by geologic heterogeneities (Lindeberg and Wessel-berg, 1997; Ennis-King and Paterson, 2003).

- Mineral trapping occurs when the injected CO_2 reacts with the formation waters or formation rocks, or both, to form carbon-containing minerals such as carbonates. Although some of the injected CO_2 may react relatively quickly to form solid mineral phases, it is generally believed that converting all the injected CO_2 into solid minerals could take several thousand years. Nevertheless, the permanence of mineral trapping makes it a desirable feature for long-term storage (Wilson, 2004; IPCC, 2005).

- Preferential adsorption trapping occurs when coal and certain organic-rich shales have a high affinity for CO_2, meaning that CO_2 can be adsorbed to the coal and shale surfaces. Coal may contain up to 25 cubic meters of CH_4 per metric ton of coal (IPCC, 2006). Because coal has a greater affinity for CO_2 than CH_4, CO_2 injected into coal seams can displace CH_4, be adsorbed and trapped, and the released CH_4 could be recovered for commercial use, though application of this concept is still in early developmental stages. Carbon dioxide will remain trapped in coal and certain organic-rich shales under stable pressure and temperature (IPCC, 2005; Haszeldine, 2006).

2.3 Practical Experience Relevant to Geologic Sequestration

Existing project experience, natural and industrial analogs, research and current regulatory experience with underground injection contribute to the understanding of CO_2 behavior in geologic systems.

2.3.1 Existing Projects

Ongoing GS projects show that CO_2 can be successfully injected and sequestered in geologic formations (see, for example, IEA, 2004). Currently operating commercial CCS sites include the Sleipner Project in the North Sea (Norway), the Weyburn Enhanced Oil Recovery Project (Canada), and the In Salah Gas Formation (Algeria). These projects provide valuable field experience which will help improve understanding of GS systems, CO_2 behavior, and storage mechanisms. For example, they provide information that different geologic formations have the injectivity, containment, and storage effectiveness needed for long-term sequestration. These projects have practically applied site selection tools and monitoring techniques and programs. The existing projects have also highlighted the importance of establishing a baseline as a part of an effective monitoring program (see chapter 6), and have provided insight into the use of models to help predict the behavior of CO_2 in the subsurface. However, it should be noted that these sites have been operating for only a relatively short period of time (up to a decade), and hence do not demonstrate the efficacy of GS over the longer required storage time periods of hundreds to thousands of years.

A new set of commercial GS projects will be implemented in the very near future, including the Gorgon Joint Venture (Barrow Island, Australia). In addition, U.S. field experiments, including the Frio Brine Experiment (Texas) and regional projects supported by DOE's Regional Carbon Sequestration Partnerships Program, will contribute valuable information about GS in coming years (see U.S. DOE [2007b] for a summary of this program). For a more comprehensive list of current and planned GS projects, see NETL's CO_2 Storage Web site[5].

Existing projects indicate that GS is a viable technology. However, commercial-scale deployment of GS will involve substantially larger volumes of CO_2, and individual GS projects will need to inject greater volumes of CO_2 than current DOE pilot projects and other international sites. Commercial-scale GS projects will encompass areas that may be miles in diameter (as opposed to the small fraction of a mile encompassed by most pilot projects). Therefore, current analogs may not demonstrate the full range of scenarios that are likely to be encountered in commercial-scale deployment. Commercial-scale projects may be more likely to:

- Encounter geologic heterogeneities that may serve as unanticipated migration and leakage pathways, including faults and fractures and other geologic features such as high permeability sand lenses or "pinches" in the confining system.

- Intersect potential anthropogenic pathways such as unplugged wells.

[5] http://www.netl.doe.gov/technologies/carbon_seq/core_rd/world_projects.html

- Experience adverse pressure effects that can cause fracturing or regional effects on groundwater flow.

- Encounter basin-wide effects, and influences of neighboring projects.

It is also noteworthy that pilot demonstration projects are generally designed to exhibit the viability of the technology (e.g., minimal unanticipated migration of CO_2). Sites are chosen for these projects because they are anticipated to successfully contain the smaller volumes of CO_2, and hence may not portray the full range of geologic and anthropogenic features that could be encountered in commercial-scale deployment (Friedmann, 2003). However, pilot projects can nevertheless provide useful information, and some of their inherent limitations may be overcome by evaluating multiple projects implemented across a variety of geologic settings.

2.3.2 Natural and Industrial Storage Analogs

Natural and industrial systems that have stored or are storing CO_2 and other fluids (e.g., liquids and gases) may also provide insights into the feasibility of GS. Although, as noted in the previous section, the quantity of CO_2 that may need to be injected for GS may be much greater than these analogs, the evaluation of these analogs has improved the understanding of storage mechanisms and processes.

Carbon dioxide accumulates underground naturally in a variety of geologic settings. For example, 200 million metric tons of naturally occurring CO_2 have remained trapped in the Pisgah Anticline in central Mississippi, northeast of the Jackson Dome, for more than 65 million years with no evidence of unanticipated migration or leakage (IPCC, 2005). Such natural analogs provide information about the ideal conditions for long term storage.

Industrial practices of injecting and storing fluids underground may also serve as analogs for GS. The oil and gas industry, for example, has been storing natural gas in underground reservoirs for nearly 100 years (IPCC, 2005). Experience from natural gas storage operations suggests that it is possible to store gases effectively in the subsurface. However, there are examples of gas escaping through wells, faults, and fracture zones (Perry, 2005). Furthermore, these sites are generally used for temporary storage and hence only provide insight, but not a demonstration of, the long-term feasibility of underground storage of fluids and gases. These sites also provide valuable evidence that confining systems can be exposed to repeated stress cycling (i.e. depressurizing and pressurizing) without adverse effects on seal integrity.

The oil and gas industry also has more than 35 years of experience in site characterization and injection of CO_2 through enhanced product recovery projects (Benson et al., 2002; Heinrich et al., 2003; IPIECA, 2007). EOR projects contribute substantial knowledge about the design of CO_2 injection wells and technologies for handling, injecting, and monitoring injected supercritical CO_2. However, such projects are designed to maximize oil production rather than provide storage of CO_2 for long periods.

2.3.3 Regulatory Experience

Federal and State regulations protecting underground sources of drinking water under SDWA address the injection of fluids into the subsurface (including liquids, gases and semisolids). These regulations are designed to ensure that injected fluids do not endanger USDWs and address siting, well construction, monitoring and site closure. For example, the program regulates the injection of CO_2 for enhanced oil and gas recovery. The EPA Underground Injection Control (UIC) regulations reflect a great deal of technical expertise by operators and regulators on relevant geological issues and well construction and operations associated with injection. The UIC Program has been successfully regulating the injection of billions of gallons of fluids annually into tens of thousands of injection wells for more than 30 years (Benson et al., 2002). This regulatory experience will provide useful insight for GS projects and is seen as a clear indication that GS projects will be addressed through an established and effective regulatory system. For more information, please visit http://www.epa.gov/safewater/uic/wells_sequestration.html.

2.4 Chapter Summary

This chapter described the geologic formations and trapping mechanisms necessary for the effective storage of CO_2. It also examined the feasibility of GS as a climate mitigation technology by reviewing natural and industrial analogs as well as EPA's current regulatory experience in subsurface injection. The next chapter provides an overview of the VEF and discusses the geological attributes that could result in vulnerabilities to adverse impacts.

CHAPTER 3

VULNERABILITY EVALUATION FRAMEWORK FOR GEOLOGIC SEQUESTRATION: GEOLOGIC SYSTEMS AND ATTRIBUTES

The VEF identifies attributes of GS systems that may lead to increased vulnerability to adverse impacts, identifies potential impact categories, and provides a series of decision-support flowcharts that are organized, systematic approaches to assess the attributes and impacts. These attributes and impact categories were carefully selected by EPA as the key factors of GS systems to be included in a vulnerability evaluation, through the process described in Chapter 1 of literature review, consultation with experts, and professional knowledge. The conceptual approach to the VEF shown in Figure 3.1 has the following components:

- The GS system first is characterized in terms of the injected CO_2 stream, the confining system, the injection zone, and a series of geologic attributes that could influence (i.e., increase or decrease) the vulnerability of the GS system to unanticipated migration, leakage, and undesirable pressure changes (first column).

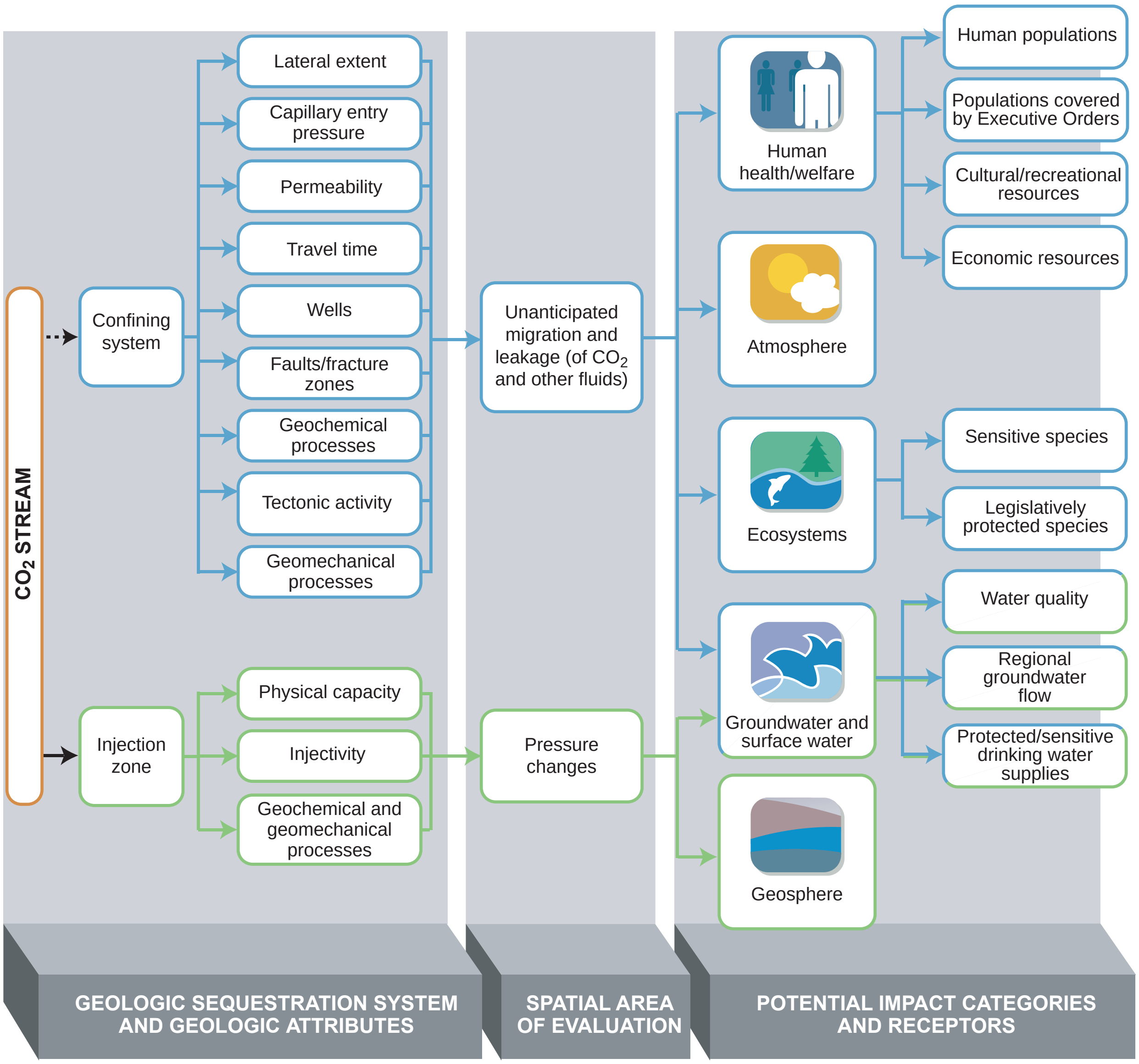

Figure 3.1. VEF Conceptual Model

- An approach is then provided for defining the spatial area that should be evaluated for adverse impacts associated with unanticipated migration, leakage, or undesirable pressure changes (middle column).

- Potential impact categories and associated key receptors are then identified, including human health and welfare, the atmosphere, ecosystems, groundwater and surface water, and the geosphere (last column).

Though not explicitly shown in Figure 3.1, the VEF further recognizes that pressure changes in the injection zone and overlying geosphere may be linked to unanticipated migration or leakage pathways and the associated impacts depicted in Figure 3.1, through processes like induced fracturing, fault reactivation, and the exceedence of capillary entry pressure. These concepts are also discussed in this chapter. Furthermore, the VEF also recognizes that impacts to the geosphere, groundwater and surface water, ecosystems, and the atmosphere may also impact human health and welfare.

This chapter is an overview of the geologic sequestration system, the geologic attributes that have been identified as affecting vulnerability, and the related spatial area that would be evaluated for unanticipated migration, leakage, and pressure changes. These are represented in the first two columns of the conceptual framework shown in Figure 3.1. Chapter 4 discusses the potential adverse impacts of GS and potentially affected receptors, the last column of the VEF conceptual framework.

For the purposes of the VEF and this report, a binary classification of low and elevated vulnerability are qualitatively defined as follows:

- **Low vulnerability**: Adverse impacts are not expected to be associated with the attribute or receptor under evaluation.

- **Elevated vulnerability**: Particular attention should be paid to the attribute or receptor under evaluation. In some cases, adverse impacts may occur if actions are not taken to further examine and/or manage the vulnerability associated with the attribute or receptor. Examples of actions that may be taken include corrective action at wells, targeted monitoring, and the development of mitigation plans.

The metrics and binary classification schemes for each attribute in this chapter can be used to qualitatively evaluate the level of vulnerability associated with each attribute. The classification schemes indicate whether vulnerability is expected to be low or elevated on a qualitative basis. Elevated vulnerability associated with a single attribute does not imply that overall vulnerability associated with the GS site is elevated. In some cases, there may be actions that could be taken to minimize vulnerability (e.g., targeting questionable wells for corrective action). These instances are indicated where applicable in the accompanying decision-support flowcharts that have been developed for the components of the GS system.

The flowcharts represent first-order evaluation approaches and, as such, should be used only with additional information and analysis to support more comprehensive risk assessment and/or decision-making. In the future, binary classification schemes could be further developed to reflect a more refined, multiscaled classification scheme, as warranted by available information, data, and expert opinion. Future steps could also include developing the decision-support flowcharts into an integrated evaluation tool that has a more quantitative and numerical basis, presented in a user-friendly format.

This chapter contains the following sections:

- Section 3.1 describes the GS system and geologic attributes that may affect unanticipated migration, leakage, and pressure changes.
- Section 3.2 discusses the spatial area of evaluation.
- Section 3.3 summarizes the chapter.

3.1 Geologic Sequestration System and Geologic Attributes

Descriptions of geological attributes that can influence the vulnerability of a GS system to unanticipated migration, leakage, or pressure changes include a variety of metrics and classification schemes. The metrics and schemes can be used to determine whether there is low or elevated vulnerability to unanticipated fluid migration, leakage, and/or pressure changes associated with each attribute. The attributes presented here are organized according to those that are relevant to the confining system and those that are relevant to the injection zone. The section also describes evaluation processes (decision-support flowcharts) for the confining system, the injection zone, and the CO_2 stream.

3.1.1 Confining System and Related Geologic Attributes

A confining system is defined as a geologic formation, group of formations (e.g., shale or siltstone), or part of a formation (sometimes referred to as an aquitard) that is composed of impermeable or distinctly less permeable material which acts as a barrier to the upward flow of fluids stratigraphically overlying the injection zone. Geologic attributes of the confining system identified as influencing the potential for unanticipated migration and leakage include the following.

- **Lateral extent**. Lateral extent is defined in the VEF as the surface area of the confining system that overlies the GS footprint. This attribute can be evaluated using a metric of total surface area measured in appropriate units such as square miles. Elevated vulnerability is associated with a confining system with a lateral extent that is less than the GS footprint.
- **Capillary entry pressure**. The capillary entry pressure is defined in the VEF as the added pressure that is needed across the interface of two immiscible fluid phases (e.g., supercritical CO_2 and water or brine) for CO_2 to enter the confining system. Appropriate evaluation metrics for determining sufficient capillary entry pressure include CO_2 column height and injection pressure (Harrington and Horseman, 1999). Elevated vulnerability may be associated with the exceedence of the confining system capillary entry pressure.
- **Permeability**. Permeability refers to the ability of a geologic material to allow transmission of fluid through pore spaces. Appropriate metrics for evaluating permeability include the darcy unit. Elevated vulnerability may be associated with geologic materials with a permeability greater than clay, shale, or siltstone.
- **Travel time**. Travel time refers to the interval of time that is required for a fluid (e.g., CO_2 or brine) to migrate across the thickness of the confining system. Factors that will influence travel time include the confining system thickness, permeability, diffusion, retardation (as a

result of sorption or desorption), and geochemical reactions. Thus, all other parameters being equal, GS systems at greater depth will have longer associated travel times. The metric for travel time is a unit of time such as years. Travel times that compromise the integrity of the project are considered to result in elevated vulnerability.

- **Wells**. Wells (and other artificial penetrations such as boreholes) may serve as conduits for fluid movement and hence could result in elevated vulnerability to adverse impacts. Numerous metrics have been identified as relevant to the evaluation of vulnerability associated with wells, including well depth, well integrity (including construction materials, and seal and plug materials), and spatial density of well occurrence. The level of vulnerability associated with wells can be evaluated by considering all of these metrics. Wells and faults have been identified as one of the most likely unanticipated migration and leakage pathways in GS systems; as such, they are discussed in greater detail in Chapter 5 of this report, which also includes an evaluation approach.

- **Faults/fracture zones**. Faults are breaks in the Earth's crust that occur when the crustal rock is either compressed or pulled apart. A fracture is any local separation or discontinuity plane in a geologic formation that divides the rock into two or more pieces. Fractures are commonly caused by stress exceeding the rock strength. For the purposes of this report, fractures are defined as distinct from faults by their smaller scale. Faults may serve as either barriers or conduits to fluid flow (Omre et al, 1994; Lewicki et al., 2006; Wilkens and Naruk, 2007). Numerous metrics may be appropriate for evaluating faults and/or fracture zones, including density, stratigraphic position, connectivity, sealing/conductive (transmissive), stress level, orientation, and fault reactivation pressure (multiplied by a safety factor). The level of vulnerability associated with faults and fractures can be evaluated by considering all of these metrics. Chapter 5 discusses faults and fracture zones in greater detail.

- **Geochemical processes**. Geochemical processes are chemical reactions that may cause alterations in mineral phases. A number of different geochemical processes could influence the confining system. Acidity caused by the reaction of CO_2 with water may partially dissolve confining zone geologic materials, which could have the unfavorable effect of opening fluid migration pathways within the confining zone. Geochemical reactions could also have favorable effects, such as the formation of mineral phases as result of the reaction of CO_2 with the geologic material of the confining system and/or formation waters that could help to improve the seal of the confining system, by plugging pores and fractures (Johnson et al., 2005). Appropriate metrics for evaluating geochemical processes include dissolution rates, buffering capacity, molar volume, and pH level. Mineralogy and pH that favor the formation of conduits in the confining system through dissolution and/or decreases in molar volume increase vulnerability; those that do not favor the formation of conduits through dissolution and/or increases in molar volume decrease vulnerability.

- **Tectonic activity**. Tectonically active settings may be more likely to have transmissive faults and/or fractures, and may be unsuitable for GS (IPCC, 2005). Seismic activity can be used as a measure for tectonic activity. Seismic activity is defined as the shifting of the Earth's surface due to changes at depth, and it may cause seismicity or earthquakes. An appropriate metric for evaluating tectonic activity is the seismic hazard rating. Areas with seismic hazard ratings that indicate the potential for seismicity to cause adverse impacts are considered to have elevated vulnerability (see USGS, 2007).

Tectonic activity also covers volcanism, which is the process by which magma and gases are transferred from the Earth's interior to the surface. Hotspots are shallow areas of molten rock below the surface that persist long enough to leave a record of uplift and volcanic activity. Distance to volcanic activity or hotspots serves as a metric for vulnerability, and the presence of active volcanoes or hotspots within the spatial area of evaluation may indicate whether there is low or elevated vulnerability.

- **Geomechanical processes**. These are processes that may result in alterations of the structural integrity of geologic material. Appropriate evaluation metrics for this attribute include fracture pressure, fracture/fault reactivation pressure, and orientation of the fracture or fault relative to the orientation of the principal regional stress regime. If the fracture pressure and the fracture/fault reactivation pressure (multiplied by a safety factor) are exceeded, vulnerability is considered to be elevated. It should be noted that geomechanical processes occur at a continuum of scales, and potential impacts, such as deformation of geologic formations, can occur without necessarily adversely affecting the integrity of the confining system.

Confining System Evaluation Process

An evaluation process that can be used to examine the confining system based on the attributes described above is shown in Figure 3.2. In the flowchart, elevated vulnerability reflects a determination that the confining system is inadequate and may increase the potential for adverse impacts, and low vulnerability indicates that the confining system is anticipated to be adequate for the proposed project. Elevated or low vulnerability determinations in the VEF refer to a specific attribute, system, or impact being evaluated and not to the GS site as a whole. Chapter 5 discusses key considerations in assessing the overall vulnerability of a GS site.

The confining system evaluation provides an approach for assessing and reducing vulnerability through:

- **Establishing that a confining system is present over the necessary lateral extent**. To ensure the confining system acts as an effective barrier to fluid flow, it is important that the geologic formations (rock layers) of the confining system are sufficiently laterally extensive and continuous to cover the entire area affected by the CO_2 injection. This includes the area occupied by the CO_2 and a potentially larger area affected by pressure changes associated with injection[6]. The continuity of the barrier can be maintained, despite pinch-outs or other discontinuities, if such features in one rock layer are blocked by overlying layers of the confining system. In some cases, there may also be a confining system underlying the injection zone that serves as a lower barrier to the GS system. If the lateral extent is insufficient, it may be possible to alter operational conditions to improve site suitability, for example, by injecting into multiple formations of the injection zone, thereby reducing the surface area of the CO_2 plume.

- **Evaluating the physical properties of the confining system to determine if it provides adequate confinement of fluids under the proposed operating conditions**. Attributes of a confining system that will help to prevent the upward movement of fluids include

[6] Deep saline formations that are laterally unconstrained may in particular have larger areas affected by pressure, in contrast for example, to depleted oil and gas fields, where the extent of pressure changes may be limited by the geologic structures of the system.

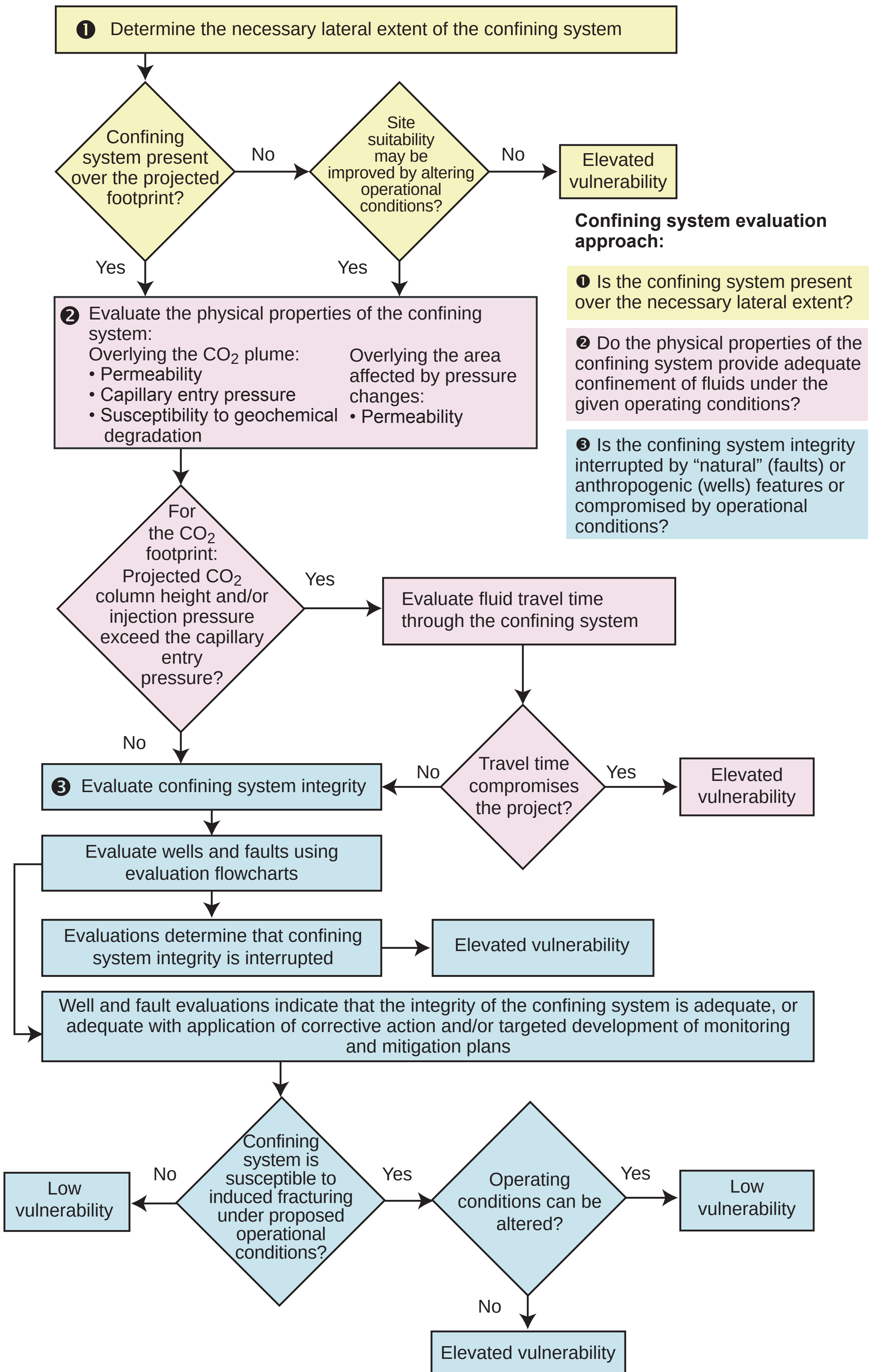

Figure 3.2. Confining System Evaluation

its capillary entry pressure[7]. A high capillary entry pressure will make it difficult for CO_2 and other fluids to enter the confining system. Travel time, a function of the permeability and thickness of the confining system, may also contribute to an effective barrier. A long travel time would ensure that if any CO_2 or other fluids entered the confining system, they would travel only minimal distances within the confining system over the timeframes that are relevant to GS systems. A low permeability will contribute to a long travel time. A low susceptibility to dissolution and other geochemical degradation processes will also contribute to an effective confining system, thus avoiding thinning of the barrier and the opening of potential fluid pathways.

- **Evaluating the integrity of the confining system**. Another important factor that may limit the ability of the confining system to act as a barrier to fluid flow includes the presence of fluid-conducting perforations such as unsealed or unplugged wells, and transmissive faults and fractures (both natural and those induced/reactivated by injection). Vulnerabilities associated with wells and faults may be managed through altering operational conditions such as injecting at a lower rate at a greater number of wells to reduce injection pressure. The integrity of the confining system could also be interrupted by other high permeability zones such as sand lenses, and other discontinuities, such as pinchouts in the confining system formation(s). Targeted monitoring can also detect unanticipated migration and leakage and pressure changes, and inform the development of mitigation actions and plans. Mitigation actions, such as corrective action for wells, are discussed in more depth in Chapter 6.

3.1.2 Injection Zone and Related Geologic Attributes

The injection zone is a geologic formation, group of formations, or part of a formation of sufficient areal extent, thickness, porosity, and permeability to accommodate CO_2 injection volume and injection rate. The injection zone is characterized by several geologic attributes identified to have the potential to influence pressure changes and are described below.

- **Physical capacity**. Physical capacity is defined as the volume within a geologic formation that is available to accept CO_2. Injected CO_2 will occupy the pore space between the grains of the rock that makes up the injection zone by displacing the fluids that are already occupying these pores. If storage capacity is found to be insufficient for the proposed operation due to pressure constraints capacity could be increased by dewatering. Appropriate metrics for evaluating this attribute include thickness, surface area, effective (or interconnected) porosity, CO_2 density (CO_2 density generally increases with depth, because density increases with pressure, and pressure generally increases with depth), and residual water saturation also referred to as irreducible water saturation. Induced pressure changes can also affect physical capacity. For example, if a geologic system is constrained laterally, the pressure buildup associated with the CO_2 injection may restrict how much CO_2 can be stored without exceeding fracture pressure, sometimes referred to as effective pore volume vs. absolute pore volume (Zhou, et al., 2008). Other non-technical considerations could also potentially affect storage capacity, including economic considerations such as competing demands for the injection zone.

- **Injectivity**. Injectivity characterizes the ease with which fluid can be injected into a geological formation. It will be influenced by both properties of the injection zone and

[7] This is true for CO_2 and other nonaqueous displaced fluids. However, in the case of brines, there is no capillary entry pressure to overcome because the fluid in the confining system and the brine are both aqueous.

operational factors. The properties of the injection zone that control injectivity include injection zone thickness, permeability, and pressure within the injection zone[8]. Though the VEF is focused on the geologic system, operational factors that influence injectivity, and which may be altered to reduce vulnerability, are discussed below in the description of the injection zone evaluation process.

- **Geochemical and geomechanical processes**. The geochemical and geomechanical processes may influence vulnerability to pressure changes by affecting injection zone capacity to store CO_2 and injectivity.

  - **Geochemical processes**. Geochemical processes are the chemical reactions that may cause alterations in mineral phases. A number of different geochemical processes could influence the injection zone. Dissolution of CO_2 into the formation waters (e.g., brine) will reduce the volume of CO_2 that is stored as a supercritical fluid, thus reducing needed storage volume (Doughty et al., 2001). Acidity caused by the reaction of CO_2 with water may partially dissolve injection zone geologic materials, which could improve porosity and injectivity. Geochemical processes may also have unfavorable impacts. For example, new mineral phases may form as a result of the reaction of CO_2 with the geologic materials and/or formation waters. These new minerals may partially plug pores and thereby have the unfavorable impact of reducing permeability and porosity (Knauss et al., 2003).

    Appropriate metrics for evaluating the geochemical processes that could lead to pressure changes include dissolution rates, buffering capacity, molar volume, and pH level. Unfavorable geochemical processes are defined as involving pH and mineralogy that favor precipitation of minerals and/or increases in molar volume, resulting in elevated vulnerability. Favorable geochemical processes, those with low vulnerability, are defined as involving pH and mineralogy that favor increased injection zone porosity through dissolution and/or decreases in molar volume.

  - **Geomechanical processes**. These are processes that may result in alterations in the structural integrity of a geologic material. If pressure in the injection zone is increased because of CO_2 injection, the injection zone geologic material may be deformed, and in the extreme, crack or fracture, or faults might be reactivated. Fracturing of the injection zone is intentionally used to increase production in oil and gas operations, and whether or not this method should be used for GS could be considered based on further study of the applicability of this technique to GS and site-specific factors. As a result, appropriate metrics and thresholds for injectivity may be site-specific.

Injection Zone Evaluation Process

An evaluation process that can be used to examine the injection zone based on the attributes just described is shown in Figure 3.3. As indicated in the flowchart, the vulnerability to adverse impacts associated with the injection zone of a GS system may be considered low if the storage capacity is adequate, the injectivity is sufficient, and geochemical and/or geomechanical processes produce favorable conditions for injection and storage. In particular, this evaluation provides an approach for assessing and reducing vulnerability through:

[8] To introduce CO_2 into the injection zone, the downhole injection pressure must be higher than the injection zone formation(s) fluid pressure.

- **Determining that the injection zone capacity is sufficient**. The physical capacity of the injection zone is proportional to the total pore volume of the injection zone. Total pore volume can be determined by multiplying the injection zone thickness by the injection zone surface area and by the fraction of the injection zone that is taken up by pores (i.e., its porosity). However, only a fraction of this total pore volume will actually be available for CO_2 storage.

  Numerous factors will influence the physical capacity of the injection zone. Carbon dioxide will enter only interconnected pores. Most of the pores in rocks such as sandstones are interconnected, but some fraction of the pore volume will be "dead space" and not interconnected. Carbon dioxide will displace only a fraction of the water in the pores, because of residual water saturation. Furthermore, CO_2 is not likely to occupy the entire thickness of the injection zone because of its buoyancy and heterogeneities within the injection zone. Being relatively buoyant, it will tend to rise upward in the injection zone and spread out laterally under the confining system or under lower permeability lenses within the injection zone. Vertical features such as sealed faults or other discontinuities may also limit the pore volume that is accessible to CO_2, and may put pressure constraints on the system that could also limit the physical capacity.

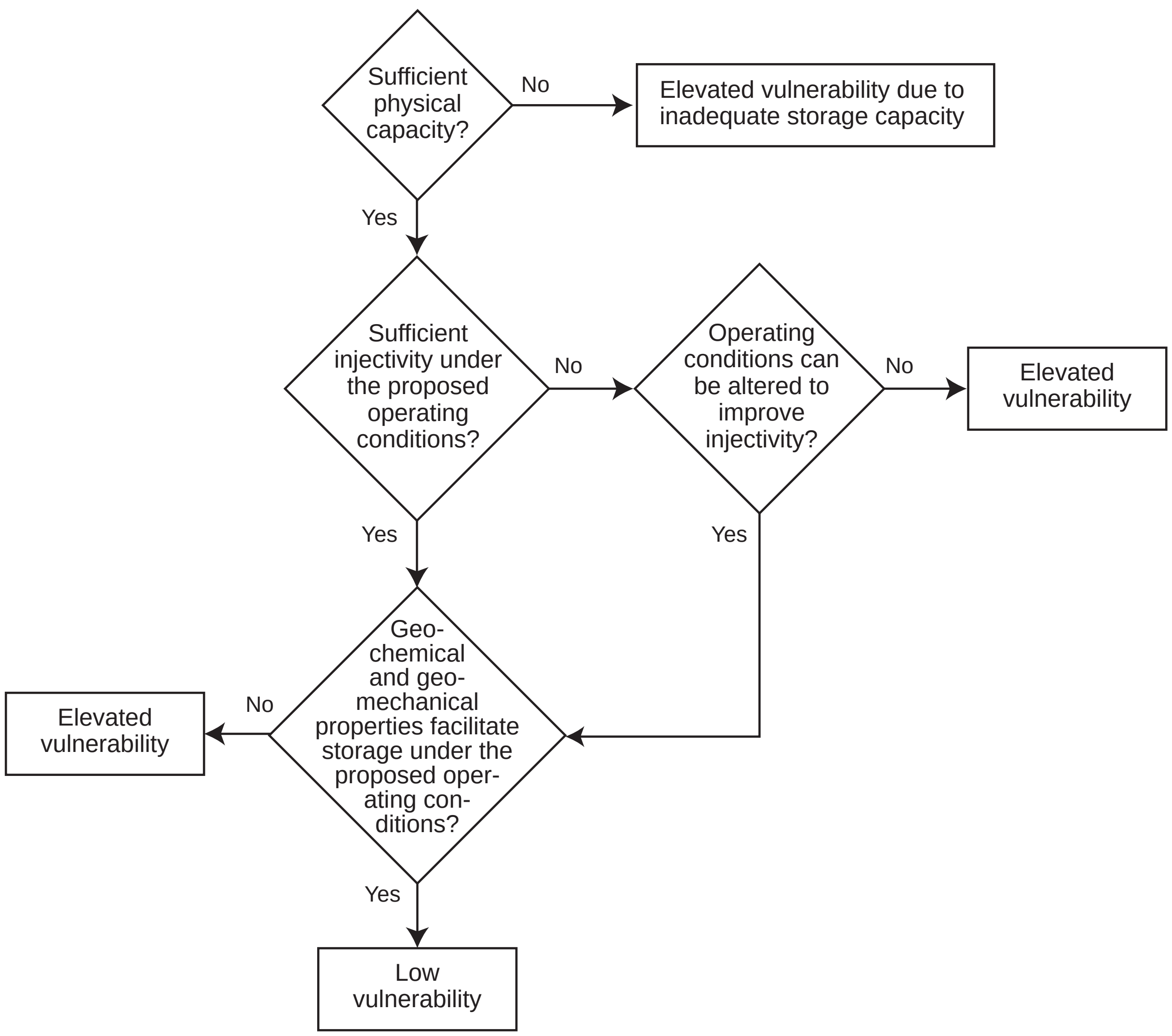

Figure 3.3. Injection Zone (IZ) Evaluation

Properties of CO_2 that will influence the amount of space it occupies include its density and ability to dissolve in water. The space needed to store a given amount of CO_2 will decrease with increasing density. Density increases with increases in pressure and depth and decreases with increases in temperature. Dissolution will be greater at higher temperatures and pressures, and less dissolution occurs at higher salinities.

- **Determining that the injectivity is sufficient**. As described above, injectivity is the rate at which CO_2 injection can be sustained over the duration of injection, and is a function of properties of the injection zone and operational conditions. The former include injection zone thickness, permeability, and pressure within the injection zone. Operational factors that may influence injectivity include the length and orientation of the injection well. Injectivity may be increased by maximizing the slotted length of the injection wells (i.e., the part of the well that is open and allows passage of CO_2 into the injection zone), installing horizontal wells that are slotted over much longer reaches than their vertical counterparts, or increasing the number of wells used for injecting CO_2.

- **Evaluating the geochemical and geomechanical properties of the injection zone**. By virtue of their impact on porosity, geochemical and geomechanical processes may also affect the physical capacity of the injection zone. Depending on whether there is net dissolution or precipitation of minerals associated with the injection of CO_2, injectivity may be improved or decreased correspondingly. Impurities in the CO_2 stream may also react with the injection zone rock and formation waters to form new minerals that may locally decrease porosity. Fracturing is intentionally used to increase production in oil and gas operations, and intentional fracturing of the injection zone could improve permeability and hence injectivity of the injection zone. However, the appropriateness of this technique for GS applications may need further study.

  Initial estimates of physical capacity can be made using equations such as those in the NETL Carbon Sequestration Atlas (NETL, 2007), or the approaches developed by Bachu et al. (2007) and Brennan and Burruss (2003). More refined evaluations of the attributes of the confining system, the physical capacity, injectivity, and geochemical and geomechanical processes within the injection zone are likely to rely on use of numerical modeling and site characterization data (Xu et al., 2003; Pruess et al., 2004; Celia et al., 2005; IPCC, 2005).

3.1.3 Carbon Dioxide Stream

The CO_2 stream and its characteristics may affect geologic attributes within the GS system and ultimately contribute to increased vulnerability to adverse impacts. A captured CO_2 stream from a power plant or industrial source would probably not be pure CO_2. The specific impurities and their concentrations in the CO_2 stream will differ depending on the fuel source, the capture process, constraints (i.e., concentration limits) associated with the mode of conveyance to the injection site (e.g., pipeline), and injection concentration limits. For example, trace amounts of sulfur dioxide (SO_2), nitrogen oxide (NO), hydrogen sulfide (H_2S), hydrogen (H_2), carbon monoxide (CO), methane (CH_4), nitrogen (N_2), argon (Ar), mercury (Hg), cyanide (Cn), and oxygen (O_2) could be found in a captured CO_2 stream (IPCC, 2005; U.S. DOE, 2007c). Some of these may be of potential concern because of their toxicity (e.g., Cn, Hg), others because of their potential to accelerate corrosion processes (e.g., H_2S), and still others simply because they may increase the total amount of needed storage space (e.g., Ar). Under different capture scenarios, the volumes of these impurities can vary significantly. For example, the concentration of impurities as a percentage of total CO_2 volume for post-combustion capture at coal-fired power generation plants is approximately 0.01%. In contrast, the concentration of impurities for precombustion capture at gas-fired power generation plants is approximately 4.4% (IPCC, 2005).

Given the potential presence of these impurities, characterization of the CO_2 stream is very important. Impurities could create more acidic conditions, possibly accelerating the formation of fluid-conducting pathways through the corrosion of well seal materials and the dissolution of geologic materials in the subsurface. Impurities could also impact storage capacity and well integrity. The CO_2 Stream Evaluation, depicted in Figure 3.4, outlines key considerations for evaluating CO_2 stream impurities. Though not a focus of the VEF, it is acknowledged that impurities may also impact surface infrastructure (see, for example, Rhudy 2004). Chapter 4 discusses potential receptors that might be affected by those impurities, and these receptors include human populations in general, populations covered by Executive Orders, economic and cultural/recreational resources, legislatively protected species and other sensitive species, and groundwater and surface water. The CO_2 Stream Evaluation will help identify where impurity-specific targeted monitoring could indicate the need for mitigation actions and help reduce the potential for adverse impacts.

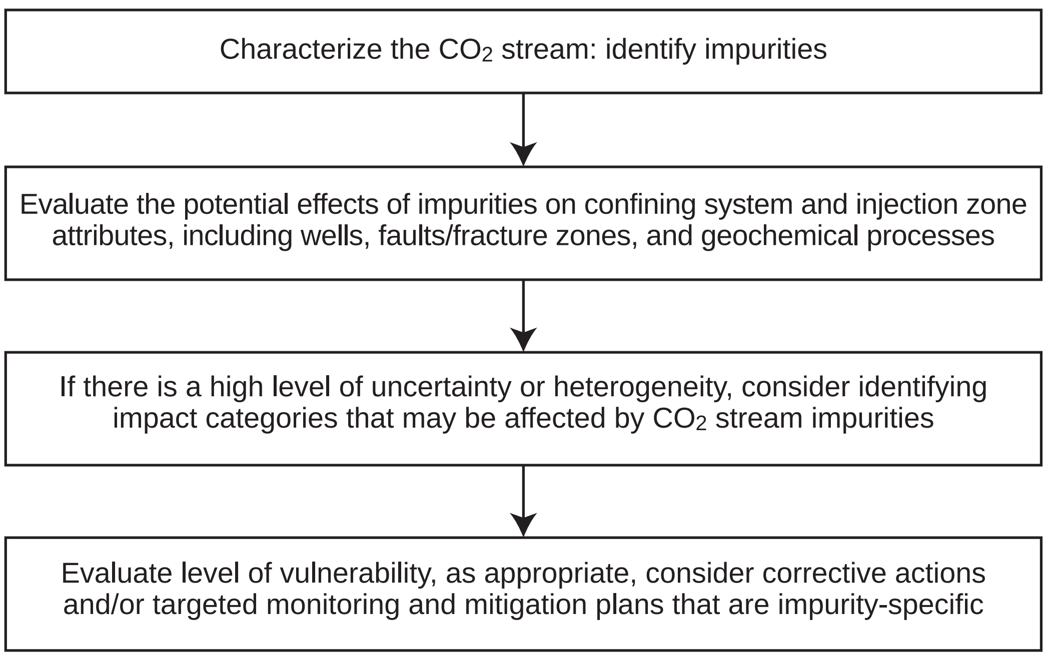

Figure 3.4. Carbon Dioxide Stream Evaluation

3.2 Spatial Area of Evaluation: Geologic Sequestration Footprint

Determining the full geographical extent of a GS system is essential for site characterization and for establishing the spatial area to be monitored for potential adverse impacts. The size and shape of the CO_2 subsurface plume and associated pressure front will depend on the total volume of CO_2 injected over the duration of the injection, operational factors, and the geologic characteristics of the confining system and injection zone, including their geometry, heterogeneities, and other geologic features. The size of the CO_2 plume will increase during the period of injection, which might last 25 to 50 years. Because CO_2 is relatively buoyant and has lower viscosity than water and brine, the plume may also continue to change position and shape for some time after injection ceases. However, secondary storage mechanisms, including dissolution, capillary, and mineral trapping, are anticipated to eventually minimize the size and immobilize the CO_2 plume (see Chapter 2 for a discussion of secondary storage mechanisms).

The pressure front[9] associated with the injected CO_2 may extend significantly farther than the CO_2 plume itself. This is particularly true in saline aquifers, where the geographical area affected by elevated pressure may be several orders of magnitude larger than the area occupied by CO_2 (Nicot et al., 2006; Birkholzer et al., 2007). As discussed in Chapter 5, the pressure front may dissipate after injection stops, or may remain elevated, depending on the lateral boundaries of the system.

For the purposes of this VEF, the spatial area encompassed by the CO_2 plume and associated pressure front is termed the GS footprint. Figure 3.5 provides different geologic scenarios that might be encountered, and approaches to delineate the footprint for each scenario. Estimates of the size of the footprint associated with the total amount of CO_2 to be injected over the lifetime of a project are anticipated to be an element of the initial evaluation of the adequacy of a GS system. This footprint may also serve as the basis for defining the area where baseline conditions are established prior to injection at a GS site (see chapter 6 for more discussion on monitoring and baseline). Delineation of the footprint may also be performed at multiple stages of the project, as the footprint expands and changes shape during injection and due to buoyancy driven flow, and to predict the effect of secondary trapping mechanisms. In most instances, modeling in combination with site-specific data will most likely be used to delineate the GS footprint. Data collected during monitoring can be used to refine and calibrate models and confirm the location and dimensions of the CO_2 plume and the pressure front.

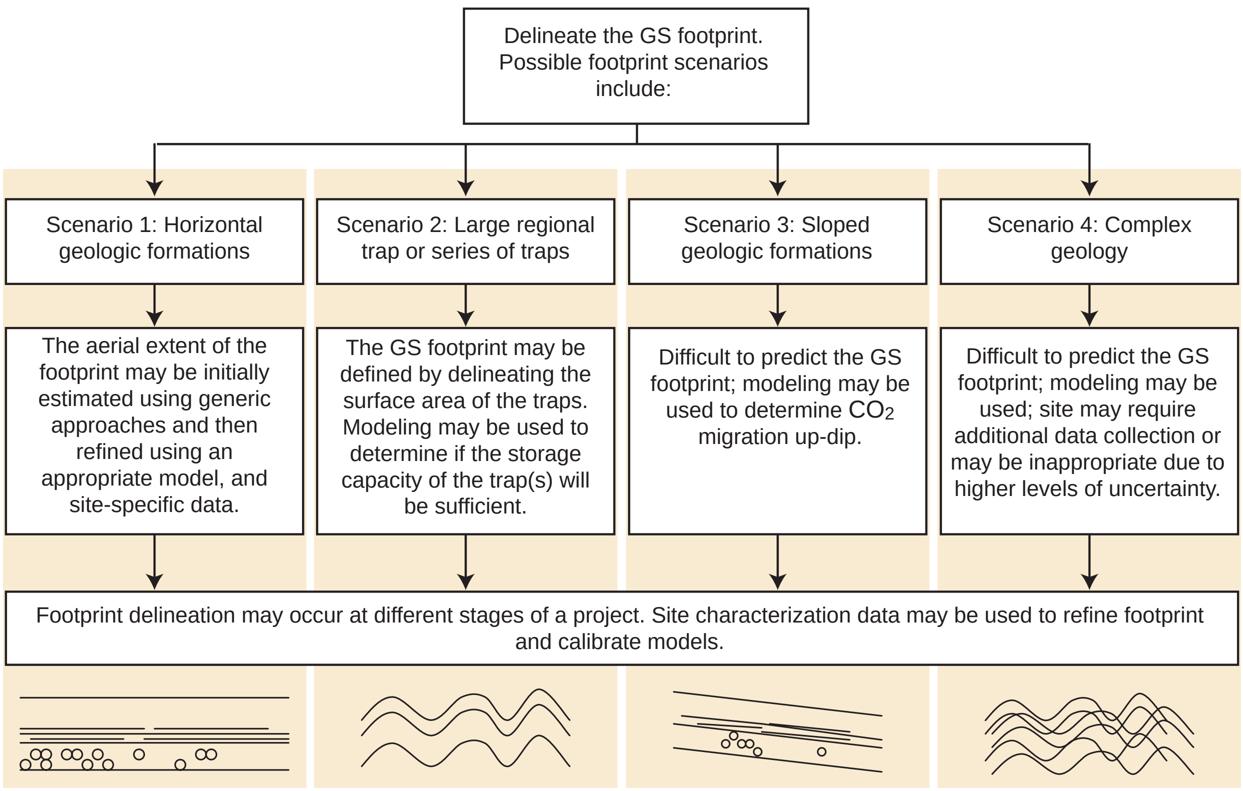

Figure 3.5. Geologic Sequestration (GS) Footprint Delineation

[9] The pressure front can be defined by the pressure differential that is significant enough to cause adverse impacts to overlying receptors (e.g., fluid displacement into an overlying aquifer).

The spatial area to be evaluated for potential adverse impacts is dependent on geologic characteristics and potential receptors. Depending on the particulars of a GS system, the area to be evaluated may be larger than the GS footprint itself. Chapter 4 describes receptors and how they may influence the spatial area of evaluation.

All of the attributes of the confining system and injection zone should be considered within the GS footprint. However, it is particularly important to understand the pathways that could serve as conduits for CO_2 and other fluids, and to understand the causes and changes in subsurface pressure. These pathways are introduced below and described in further detail in Chapter 5. Appendix B summarizes and compares some VEF geologic attributes with critical CO_2 unanticipated migration and leakage pathways or characteristics that would affect the suitability of a proposed storage site identified by the IPCC (2006) and IPIECA (2007).

Migration and Leakage Pathways

To understand the potential for unanticipated migration and leakage, it is necessary to identify pathways that could allow the movement of CO_2 and fluids displaced by the CO_2 (e.g., brines) and other geologically stored fluids (e.g., oil and CH_4). The IPCC (2005) identifies three principal pathways:

- The pore system of the confining system if it is of low permeability, or around the lateral extent of the confining system if it is insufficient.
- Anthropogenic artificial penetrations such as abandoned wells.
- Openings in the confining system, such as fractures or faults, which may be natural or induced by pressure changes.

Pressure Changes

Injecting CO_2 into geologic formations will, in most cases, cause subsurface changes in pressure. Increased pressure can lead to the unanticipated migration of fluids either through existing pathways or induced fracturing. It can also have impacts on overlying receptors, even if the CO_2 remains contained within the injection zone. The applied pressure could force CO_2 and other fluids through existing conduits, such as abandoned wells and faults. Induced fracturing and fault reactivation can also occur if injection pressure exceeds formation pressures. Even if the CO_2 and other fluids remain contained, pressure changes associated with the injection may still cause adverse impacts to groundwater and surface water, including causing changes in groundwater flow direction and water table levels, and pressure-induced displacement of brine and other fluids through the pore structure of the rock into overlying aquifers. The nature of pressure changes in the subsurface associated with injection will be determined by both geologic attributes of the GS system and operational factors. These effects can be minimized through an understanding of the relevant geologic attributes, careful site characterization, careful operation of GS systems, and monitoring.

3.3 Chapter Summary

This chapter presented an overview of the geologic sequestration system, which comprises the confining system, the injection zone, and the CO_2 stream. Geologic attributes that may influence the vulnerability to unanticipated migration, leakage, and pressure changes and evaluation processes for the confining system, the injection zone, and the CO_2 stream were described. Finally, the spatial area that may be evaluated for unanticipated migration, leakage, and pressure changes was discussed, and a flowchart that depicts GS footprint delineation scenarios was presented. Chapter 4 discusses the potential adverse impacts of GS and potentially affected receptors.

CHAPTER 4

VULNERABILITY EVALUATION FRAMEWORK FOR GEOLOGIC SEQUESTRATION: IMPACTS AND RECEPTORS

Unanticipated migration, leakage, and changes in subsurface pressure could potentially cause adverse impacts to human health and welfare, the atmosphere, ecosystems, groundwater and surface water, or the geosphere. Furthermore, impacts to the latter four categories could in turn impact human health and welfare. For example, groundwater contaminated via unanticipated migration could have adverse impacts to human health. Adverse impacts to forests or fisheries or other harvested natural resources could also result in adverse economic (welfare) impacts to humans.

The vulnerability of a GS system to these adverse impacts is a function of both the presence of the key receptors in the impact categories and the levels of exposure. A number of factors affect exposure, including but not limited to the concentration and volume of the release, the rate of release (i.e., slow vs. sudden), the proximity of the release to the receptor, and wind or wave dispersion. Impacts are also affected by whether the release is acute but limited (in time or spatial extent) or chronic. Unanticipated migration of CO_2 from the injection zone will not necessarily result in leakage and/or subsequent adverse impacts. A qualitative discussion of the links between geologic attributes and potential impacts and receptors is provided in Chapter 5.

The VEF includes decision-support flowcharts for evaluating the impact categories, which can help identify key receptors and applicable qualitative exposure thresholds. Additionally, the VEF may be further developed to quantitatively account for exposure and threshold levels.

This chapter focuses on the last component of the VEF conceptual model: potential impact categories and key receptors associated with each category (last column of Figure 3.1). Building on the GS footprint described in Chapter 3 the spatial area of evaluation is expanded to take the receptors that may be impacted into account. This chapter includes the following sections:

- Section 4.1 discusses potential human health and welfare receptors and impacts.
- Section 4.2 presents potential impacts to the atmosphere.
- Section 4.3 covers potential ecosystems receptors and impacts.
- Section 4.4 presents potential groundwater and surface water receptors and impacts.
- Section 4.5 considers potential impacts to the geosphere.
- Section 4.6 examines how receptors may influence the area of evaluation.
- Section 4.7 summarizes the chapter.

4.1 Potential Human Health and Welfare Impacts

Adverse health effects caused by high levels of CO_2 can range from minor, reversible effects to mortality, depending on the concentration of CO_2 and the length of the exposure. Release of CO_2 may also adversely impact recreational and economic resources by restricting access or use or by changing the quantity and quality of the resource.

The Human Health and Welfare Evaluation, depicted in Figure 4.1, outlines the components of human health and welfare impacts for the purposes of the VEF. Key receptors that could be adversely impacted in the event of unanticipated migration and leakage and the associated potential impacts are identified. Suggestions are made for assessing and managing vulnerability of these receptors to adverse impacts.

Adverse health effects from the release of high levels of CO_2 (and other fluids) could be experienced by the general human population and sensitive subpopulations, which, for the purposes of the VEF, are identified as those subpopulations covered by Executive Orders. In addition, cultural, recreational, and economic resources (human welfare) could be negatively affected by CO_2. Potential impacts to these key receptors are detailed below.

4.1.1 Human Populations

The vulnerability of a human population to the release of CO_2 (and other fluids) is affected by the population's size and sensitivity to CO_2 (and other fluids that may leak from the GS system), and the proximity to and concentration of the release.

Carbon dioxide is a naturally occurring gas present in ambient air at a concentration of roughly 0.04% [i.e., 380 parts per million (ppm)]. However, exposure at much higher concentrations can have a variety of impacts on human health[10]. These impacts result when concentrations of CO_2 or other constituents in the sequestered stream exceed toxicity threshold concentrations, and can range from mild discomfort to more permanent effects, including death (Benson et al., 2002).

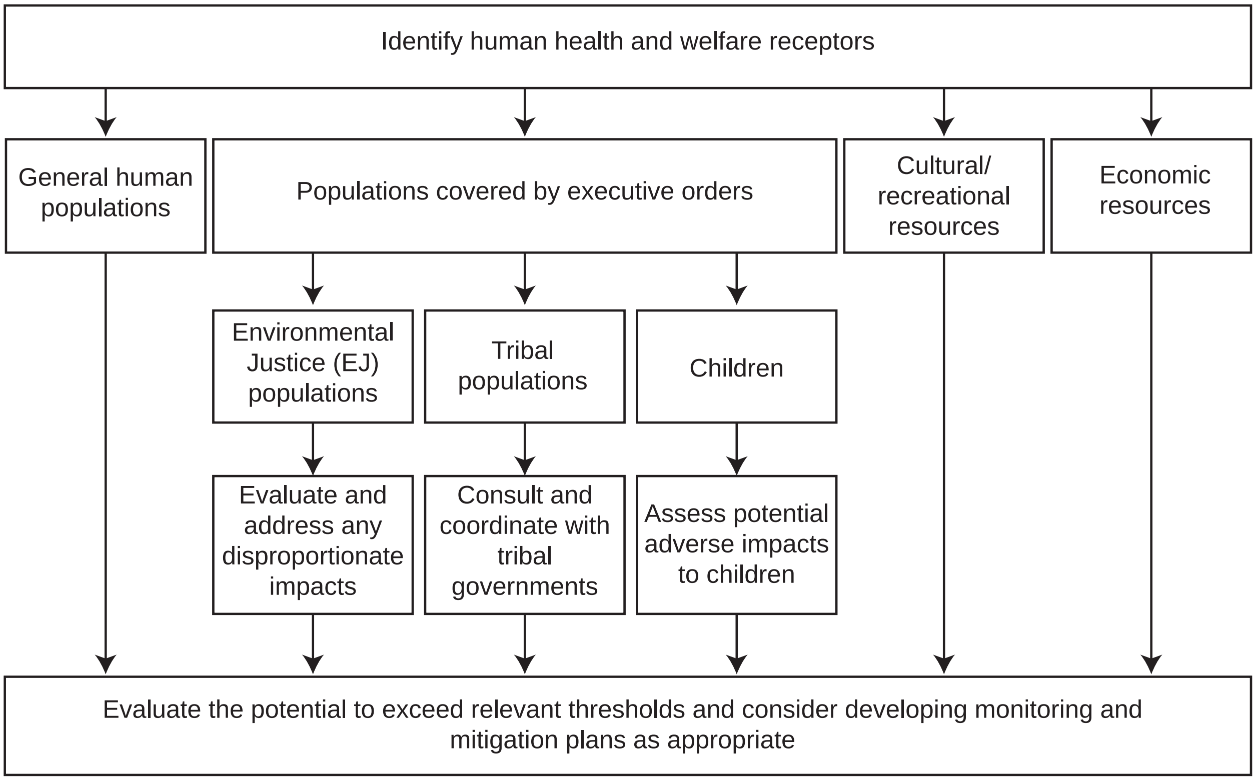

Figure 4.1. Human Health and Welfare Evaluation

[10] Projected increases in CO_2 concentrations from anthropogenic emissions range from 41 to 158 % above present levels or 535 to 983 ppm by 2100 (Meehl et al., 2007). Such increases would result in atmospheric CO_2 concentrations of 0.054 to 0.098 % by volume in 2100, which is well below published thresholds for adverse health effects.

Short-term (acute) exposure to CO_2 levels at or below 3% causes only temporary and reversible health effects such as increased breathing rate, mild headache, and sweating. When CO_2 levels exceed 3%, breathing rate increases substantially (e.g., from 11 liters per minute at 3% to 26 liters per minute at 5%), hearing and vision may become impaired, and headaches can occur. Symptoms become more severe as CO_2 levels exceed 5% (Benson et al., 2002; CEC, 2007). At high concentrations, CO_2 can be fatal to humans following a relatively short exposure, because CO_2 displaces oxygen, causing suffocation (Benson et al., 2002; Oldenburg et al., 2002a; Rice, 2003; Rice and Rhudy, 2004). When CO_2 levels reach 10%, unconsciousness can occur after one to several minutes of exposure, and at levels exceeding 15%, unconsciousness occurs in less than one minute. When CO_2 levels reach 30%, death occurs within a few minutes (Benson et al., 2002).

Measuring the effects of long-term (chronic) exposure to elevated CO_2 levels is more complicated, but studies have found no evidence of any adverse health impacts from chronic exposure to levels below 1% (IPCC, 2005). Furthermore, there is evidence that exposure to air with up to a 3% CO_2 concentration can result in physiological adaptation with no negative long-term health effects (Benson et al., 2002).

Small (low-flux), continuous leaks are less likely to result in adverse impacts unless there are topographic lows where CO_2 could accumulate (Oldenburg and Unger, 2004; Shipton et al., 2005) and a lack of dispersion based on wind patterns (Heller, 2005). Anthropogenic features may also accumulate CO_2, such as basements and other underground structures, including mines. There is a greater potential for adverse affects to human health associated with higher flux leaks such as those observed at natural analogs like Mammoth Mountain in California, and Latera and Ciampino in Italy (Chiodini and Frondini, 2001; Eichhubl et al., 2005; NASCENT, 2005; Shipton et al., 2005). However, Holloway et al. (2007) report that natural analogs underline the significance of understanding the nature of a release and subsequent dispersion, rather than focusing exclusively on the volume of CO_2 released; for example, the impacts of large sudden releases may be minimized by atmospheric dispersion. Furthermore, large sudden releases are anticipated to be unlikely if GS systems are appropriately characterized, designed, and monitored (Benson et al., 2002; IPCC, 2005; Lewicki, 2006; Holloway et al., 2007). Hence, events such as the 1986 fatal occurrence at Lake Nyos, Cameroon, in which 0.24 million metric tons of CO_2 (Benson et al., 2002) were suddenly released, are highly unlikely to occur in association with GS[11].

Impurities in the CO_2 stream (introduced in Chapter 3) may independently pose a health risk to humans, but these health risks are not currently well characterized. For example, H_2S is of particular significance because of its toxicity. Therefore, the release of stored CO_2 with H_2S to the atmosphere could have greater health and safety impacts than the release of pure CO_2.

To mitigate adverse impacts to the general population, it may be necessary to identify proximate populations and develop monitoring plans that reference appropriate exposure thresholds. Appropriate thresholds can be defined as the lowest concentration identified by a regulatory agency as causing adverse health effects in humans. Regulatory agencies that prescribe short-term and chronic exposure thresholds for humans include the National Institute for Occupational Safety and Health and the Occupational Safety and Health Administration.

[11] A Lake Nyos type event is even less likely to occur with GS, because it occurred as a result of a set of relatively unique conditions associated with the accumulation of CO_2 at the bottom, and turnover of, a deep stratified lake, and there are very few deep, stratified lakes in the United States.

4.1.2 Populations Covered by Executive Orders

Additionally, it may be necessary to give special consideration to the potential for adverse impacts to populations covered by Executive Orders. Although these groups may experience impacts similar to general human populations, Executive Orders require proposed federal regulations and programs to specifically address potential impacts to environmental justice populations, children, and tribal governments; therefore they may need to be given particular attention.

- **Environmental justice populations**. Executive Order 12898, Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations, establishes requirements to ensure enhanced protection from disproportionate impacts for minority and low-income populations. The order directs federal agencies to identify and address disproportionately high adverse human health or environmental effects of its activities on minority and low-income populations (Executive Order 12898, 1994).

  If there is a potential for disproportionate impacts to environmental justice populations, it may be necessary to address these impacts by using targeted monitoring, altering the project design, or using other mitigation methods.

- **Tribal populations**. Executive Order 13175, Consultation and Coordination with Indian Tribal Governments, establishes requirements to ensure enhanced protection from disproportionate impacts for American Indian tribal populations. This order requires that federal agencies consult and coordinate with tribal governments in formulating or implementing policies that have substantial direct effects on tribal governments (Executive Order 13175, 2000). Thus, it may be necessary to consult and coordinate with potentially affected tribal governments.

- **Children**. Children are more sensitive than adults to many substances. Therefore, safety thresholds for areas occupied by children (e.g., schools, day-care centers) may need to be more stringent than those set for the general population. Executive Order 13045, Protection of Children from Environmental Health Risks and Safety Risks, establishes requirements to ensure enhanced protection from disproportionate impacts for children. The order requires federal agencies to prioritize identification and assessment of environmental health and safety risks that may disproportionately affect children, and requires federal agencies to ensure that these risks are addressed (Executive Order 13045, 1997).

Other specific population subgroups that may need to be considered can be defined by conditions that lead to increased vulnerability to CO_2 exposure. These populations can include individuals with pulmonary disease, panic disorder patients, and patients with cerebral disease or trauma (Rice, 2003; Rice and Rhudy, 2004). For example, exposure to elevated levels of CO_2 is an increased risk to those with head trauma injuries or who have certain cerebral diseases, because CO_2 can inhibit blood clotting. As with the general human populations, monitoring and mitigation plans can be developed for these subpopulations that take into account relevant exposure thresholds.

4.1.3 Cultural and Recreational Resources

Unanticipated migration and leakage resulting from GS activities could adversely affect cultural and recreational resources by precluding human use (e.g., due to elevated CO_2 levels) or by impacting the resource itself (e.g., chemical degradation of historical artifacts by reaction with CO_2 or other stream constituents). Cultural sites include places of archaeological, historic, or natural significance; American Indian resources; and other cultural resources, including cemeteries and paleontological resources (U.S. DOE, 2007c). In addition, certain recreational activities that are dependent on the health and welfare of ecological receptors (e.g., fish and game) could be affected if those ecological receptors are adversely impacted. If cultural or recreational resources are present, it may be necessary to develop a monitoring and mitigation plan, based on appropriate exposure thresholds.

4.1.4 Economic Resources (Surface and Subsurface)

Unanticipated migration and leakage resulting from GS activities has the potential to adversely affect certain surface or subsurface economic resources such as forestry, agriculture, mineral resources (mining), and oil and gas reservoirs. Impacts resulting from unanticipated migration, leakage, or pressure changes from GS might include restricted access to resources, restricted use of resources, or changes in the quantity and/or quality of resources.

A GS project could also indirectly impact human welfare even in the absence of fluid migration and/or release, if it precludes alternative land use or subsurface activities (e.g., resource extraction). This would include, for example, future restrictions on the use of saline formations as drinking water sources (if appropriate desalination technologies became available) or for the extraction of metal ions such as lithium. In addition, access to overlying or underlying oil and gas reservoirs and storage space for other substances (e.g., natural gas) could be limited because of GS operations. Further, changes in underground pressure caused by GS could increase seismic activity (discussed in Section 4.5) or change quantities and qualities of groundwater by altering some combination of flow rate and/or direction (discussed in Section 4.4).

It may be necessary to address these potential adverse impacts with, for example, targeted monitoring using appropriate thresholds and/or alteration of the GS project design.

4.2 Potential Atmospheric Impacts

According to the National Oceanic and Atmospheric Administration, atmospheric concentrations of CO_2 in 2006 totaled approximately 382 ppm (NOAA, 2007), and the current rate of increase in atmospheric CO_2 concentrations is approximately 1.9 ppm per year (IPCC, 2007). Geologic sequestration is intended to mitigate local and global climate change impacts by providing long-term storage of CO_2 emissions that would otherwise have contributed to global atmospheric CO_2 concentrations.

In some cases, small releases of CO_2 or other GHGs (e.g., CH_4) as a result of releases from GS may not adversely impact local environmental receptors (e.g., ecological receptors, groundwater and surface water, the geosphere, and human health). However, releases can reduce the climate benefits of capturing CO_2, thus decreasing the overall effectiveness of GS as a climate change mitigation strategy.

An effective monitoring plan can help minimize adverse atmospheric impacts as a result of GS by ensuring that releases of CO_2 or other GHGs are quickly identified and remedied. (For more information on GS monitoring approaches, see Chapter 6.) In addition to identifying and remedying releases, it is important to record and account for them. The IPCC develops and publishes guidelines for estimating and inventorying national GHG emissions. The 2006 IPCC inventory guidelines for the first time included transport, injection, and GS of CO_2 as sources of GHG emissions that should be considered in national inventories (IPCC, 2006). The EPA is currently evaluating how to implement the guidelines and accurately account for emissions associated with these activities.

The purpose of the Atmosphere Evaluation, depicted in Figure 4.2, is to identify fluid-conducting pathways and identify approaches that can be used to evaluate their potential to conduct CO_2 to the atmosphere. Monitoring strategies can be implemented to reduce the potential for CO_2 to reach the atmosphere in the event of unanticipated migration.

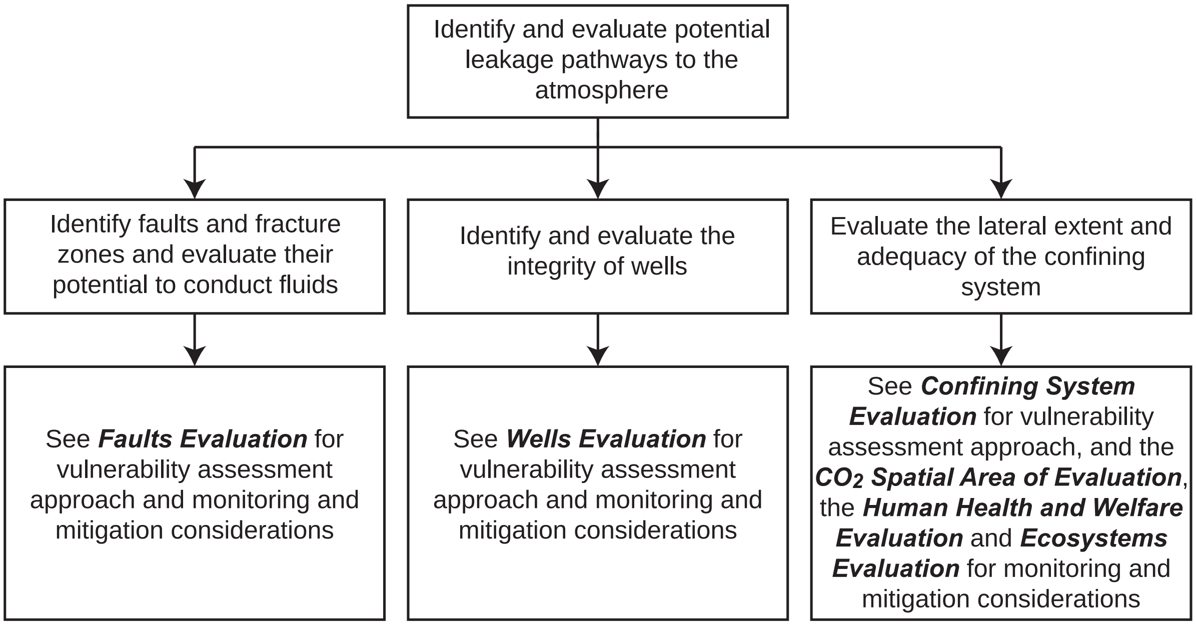

Figure 4.2. Atmosphere Evaluation

4.3 Potential Ecosystems Impacts

The Ecological Receptors Evaluation, Figure 4.3, is used to frame the discussion of ecosystems impacts in the following sections. As shown in Figure 4.3, legislatively protected species and other sensitive species are key ecological receptors that could be adversely impacted by unanticipated migration, leakage, or pressure changes resulting from GS activities. There are very few studies on the effects of CO_2 at an ecosystem level (West et al., 2005), and adverse impacts to ecosystems from GS is currently an active area of research (West et al., 2006). Additional receptors not identified in the VEF may also be impacted by GS. As the VEF is a iterative evaluation process, these may be included as new information comes to light.

4.3.1 Sensitive Species

Sensitive species are organisms that are especially vulnerable to high CO_2 concentrations. Numerous ecological receptors may be sensitive to exposure to CO_2, other stream constituents, brine, or other gases that may be released as a result of GS activities either because of their behavior (e.g., burrowing mammals, ground-nesting birds, reptiles that preferentially occupy low-lying areas, and soil-dwelling microorganisms) or because their physiology makes them unusually sensitive to increased concentrations.

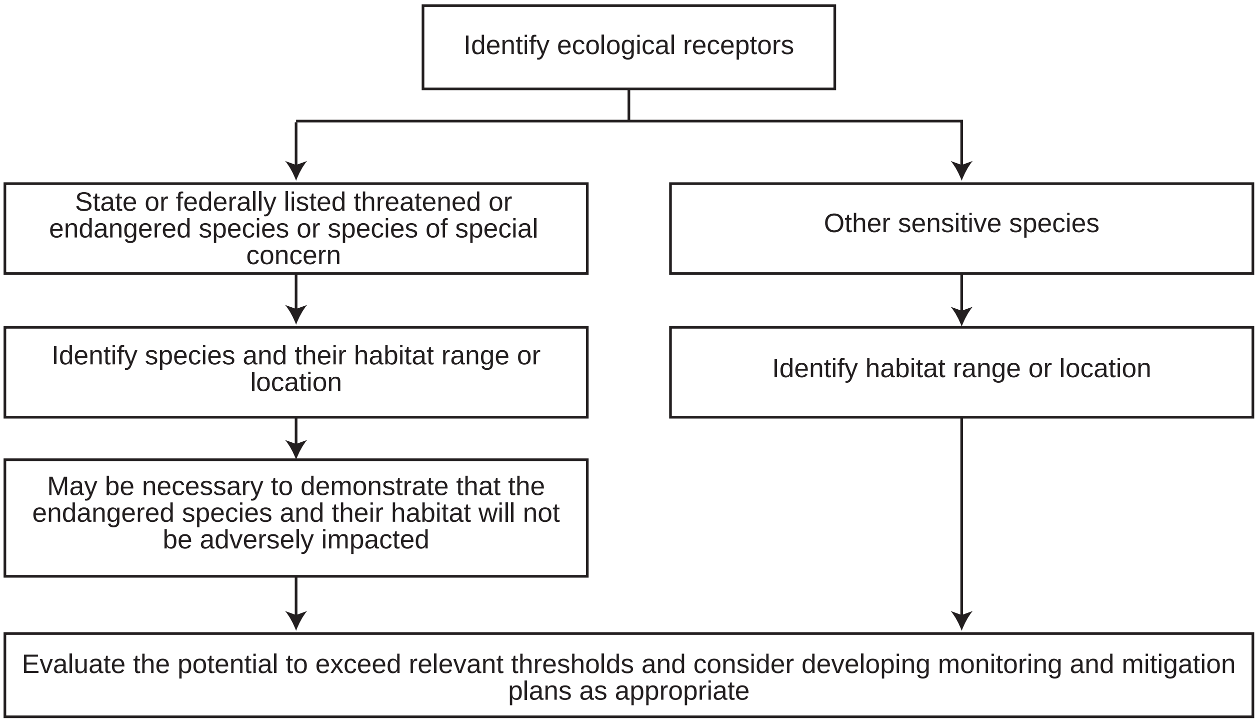

Figure 4.3. Ecological Receptors Evaluation

It is important to understand the condition (e.g., stressed by other factors or not) of these receptors as well as their potential ranges or stationary locations. Sensitive species can serve as sentinels for potential impacts to a wider array of organisms. If sensitive species are protected, then a reasonable assumption could be made that less sensitive species within that area are protected as well. Some species may also be sensitive to secondary effects of CO_2, including increased acidity (in aquatic environments and in terrestrial soils), mobilization of metals caused by increased acidity, and loss of food resources and habitat in the case of vegetation loss caused by CO_2 (e.g., fish and other species that are sensitive to increased acidity and aqueous metal concentrations, and mollusks and other species that are reliant on precipitation of carbonates).

It may be necessary to identify habitat range or location for each identified sensitive ecological receptor, and to consider targeting for monitoring and mitigation plans. Sensitive species and potentially relevant thresholds are summarized below.

Soil-dwelling animals and microbes. Soil CO_2 concentration varies between 0.2% and 4% (Benson et al., 2002) and is a function of depth, water content, soil type, and time of year (Bouma et al., 1997). Soil CO_2 concentrations between 20% and 30% are thought to be sufficient to significantly alter the dynamics of ecosystems (Benson et al., 2002). There is a relatively wide range, and some overlap, in the CO_2 concentrations causing different adverse effects in burrowing invertebrates such as worms and insects. For example, depending on the specific species, behavioral changes may be exhibited at CO_2 concentrations between 2% and 39%, paralysis at concentrations between 10% and 59%, and death at concentrations between 11% and 50% (Sustr and Simek, 1996; Benson et al., 2002). Soil-dwelling animals may begin experiencing negative physiological effects at 2% CO_2, and concentrations of approximately 15% CO_2 can be lethal (Benson et al., 2002). In another study examining CO_2 tolerance of dung insects, 80% CO_2 was the threshold for paralysis (Holter, 1994). Microbes have a wide range of sensitivity to CO_2. For fungi, significant inhibitory effects are observed at 30% CO_2, with concentrations of 40% CO_2 generally lethal (Benson et al., 2002).

Plants. Elevated atmospheric CO_2 can enhance plant photosynthesis if adequate amounts of other nutrients are available. However, because plant roots take in O_2 and expel CO_2, elevated CO_2 in the soil can inhibit root respiration. The specific physiological limits for plant roots (the time and concentration required for CO_2 toxicity) are unclear (USGS, 2001). However, plant growth at a natural CO_2 spring site was accelerated at concentrations up to 10%, but inhibited at concentrations between 30% and 55% (Vodnik et al., 2006). At Mammoth Mountain, California, a soil concentration of 30% caused death of all trees, regardless of age or species (Saripalli et al., 2002). Evaluations at landfill sites show that soil CO_2 concentrations as low as 10% may inhibit root function, but that some species can tolerate concentrations up to 20% CO_2 without detrimental effects on root function (Flower et al., 1981; Ehrlich, 2002). In addition to inhibition of root respiration, increased CO_2 concentrations may increase soil acidity. Increased soil acidity can make potentially toxic metals more bioavailable, which can affect the dynamics of soil ecosystems (McGee and Gerlach, 1998; Saripalli et al., 2002).

Surface-dwelling animals. Few data are available indicating the toxic thresholds of CO_2 in surface-dwelling animals, except for humans. Research suggests that birds may begin exhibiting behavioral changes or paralysis when CO_2 concentrations reach 40% (U.S. Patent 5435776), and reptiles (and possibly amphibians) have a higher CO_2 tolerance than other ground-dwelling vertebrates (Benson et al., 2002). Additionally, thresholds for human exposure to CO_2 may be appropriate proxies for surface-dwelling animals (Benson et al., 2002; IPCC, 2005). As noted above, wildlife that rely on vegetation for food, cover, or nesting/breeding habitat can suffer secondary, habitat-related effects if plants are affected adversely.

Aquatic organisms. Adverse impacts to aquatic organisms can result if CO_2 leaks into overlying water bodies, including lakes, streams, and oceans. High concentrations of CO_2 reduce the amount of oxygen reaching the blood in aquatic organisms with gills, causing suffocation (Maina, 1998). Fish, for example, are likely to experience negative effects with a three-fold increase of ambient aquatic CO_2 concentrations. Aquatic organisms and ecosystems are also vulnerable to changes in pH resulting from increased CO_2. In general, a pH level of less than 5 or greater than 10 is lethal for most fish; low pH can cause acidification of body tissues (Benson et al., 2002; Turley et al., 2004, 2006; Miles et al., 2007).

Other invertebrates may be sensitive to increased CO_2 as well. Miles et al. (2007) examined CO_2 tolerance of the sea urchin (Psammechinus miliaris), an ecologically important organism with a sensitive pH balance, and found that a pH of 6.16 was lethal to 100% of the test organisms after 7 days, and a pH below 7.5 was severely detrimental to the test organisms. Negative effects included hypercapnia (excess CO_2 in the blood) due to elevated CO_2 concentrations and decreased pH in coleomic fluid (Miles et al., 2007). Turley et al. (2004) reported that in saltwater, a pH ranging from 5 to 6.7 was lethal for zooplankton in 72 hours, and a pH ranging from 4.8 to 6.2 was lethal in 24 hours. However, they also found that a pH ranging from 5.6 to 7.8 was not lethal after 96 hours.

An increase in aquatic CO_2 concentration is unlikely to significantly reduce aquatic photosynthetic productivity in phytoplankton that have CO_2-concentrating mechanisms (Turley et al., 2004). However, some organisms' photosynthetic rate is more sensitive to CO_2 concentration, meaning that they may be more susceptible to changes in CO_2 (Turley et al., 2006).

Calcifying aquatic organisms. Calcifying organisms are dependent on dissolved carbonate in the water to produce their protective shells. As CO_2 concentrations in water increase, pH decreases (a process sometimes referred to as ocean acidification) and carbonate becomes less available in the aquatic environment. Organisms such as corals may be severely affected by acidic conditions if they are either unable to form shells or if the shells are dissolved by the acidic water. Turley et al. (2006) found reduced calcification in cultures of coccolithophore species that were in water in contact with atmospheric concentrations of 750 ppm CO_2. Spicer et al. (2007) examined the effects of elevated CO_2 and low pH on the velvet swimming crab (Necora puber) and found that after 16 days at a pH level of 6.74, the animal experienced hypercapnia. To compensate, the test animals dissolved their exoskeletons to make bicarbonate available in their blood (Spicer et al., 2007).

Deep geologic ecosystems. Deep geologic ecosystems support significant communities of microbial life but are poorly characterized. Microbial life is ubiquitous and extends several miles into the Earth's crust (as deep as 4,000 meters), and in all of the types of locations being considered for GS (IPCC, 2005). At extreme depths, microbes are adapted to very high pressures and temperatures and can catalyze reactions that involve compounds such as hydrogen sulfide (H_2S), sulfate (SO), nitrate (NO), iron (Fe), and CO_2 to derive energy (West and Chilton, 1997; Ehrlich, 2002). The effect of a change in CO_2 concentration at extreme depths is unknown; deep-earth organisms may not respond to CO_2 as organisms living nearer the atmosphere do, unless the organism uses CO_2 in its metabolism. Relatively little is known about the importance or unimportance of such organisms in ecosystems and carbon cycles. Further research is needed to address this uncertainty.

Microbial activity could also potentially impact the GS system (Quintessa, 2004). For example, microbes could catalyze the precipitation of minerals, thus decreasing storage capacity. Alternatively, they could produce organic acids, thereby enhancing the corrosion of well seals and the dissolution of geologic materials.

4.3.2 Legislatively Protected Species

State and federal government agencies use legislation to identify certain species populations as threatened or endangered (i.e., as defined in the Endangered Species Act of 1973). Impacts similar to those listed in the previous section are possible for these species as well. Because of their increased sensitivity, it is important to understand the legal status of these species (e.g., endangered or threatened) as well as their potential ranges or stationary locations. Further, it may be necessary to demonstrate that an endangered species and its habitat will not be adversely impacted by evaluating the potential for adverse impacts and targeting the species for appropriate monitoring based on current and known thresholds.

4.4 Potential Groundwater and Surface Water Impacts

Geologic sequestration could potentially impact groundwater and surface water. EPA is mandated to protect the nation's waters (both USDWs and surface waters) under the SDWA and the Clean Water Act. USDWs could potentially be more susceptible to adverse impacts than surface waters because of their closer proximity to the injection zone. Although this discussion focuses on groundwater impacts, many of the concepts can be also be applied to evaluating surface waters. The evaluation depicted in Figure 4.4 identifies key receptors, including protected and/or sensitive water bodies, water quality, and regional groundwater flow, and identifies appropriate monitoring and mitigation strategies.

Groundwater and surface water may be vulnerable to adverse impacts associated with unanticipated migration of CO_2 (and other fluids) and pressure changes, including the water quality and groundwater flow effects described below.

4.4.1 Water Quality

Geologic sequestration could impact groundwater if CO_2 escapes the GS system or if brine or other fluids are displaced as a result of pressure changes into overlying or underlying aquifers. Impacts include changes such as increased salinity, increased acidity (reduced pH), and mobilization of metals or other impurities. The effect of GS on a water body may be indicated by a change in specific relevant water quality parameters. Relevant water quality parameters that can be used to evaluate groundwater include:

- **Total dissolved solids (TDS)**. Migration of brine into overlying aquifers as a result of CO_2 injection could potentially endanger human health and the environment. Though there is not an EPA primary drinking water standard for TDS, water with TDS greater than 500 milligrams per liter (mg/L) is not recommended for human consumption. EPA also considers aquifers with TDS below 10,000 mg/L to be underground sources of drinking water, therefore migration of brine into these sources may have potential implications if this threshold is exceeded.

- **Buffering capacity**. Systems made of geologic materials with lower buffering capacities (e.g., sandstones as opposed to limestones) may be more susceptible to acidification in the event of migration of CO_2.

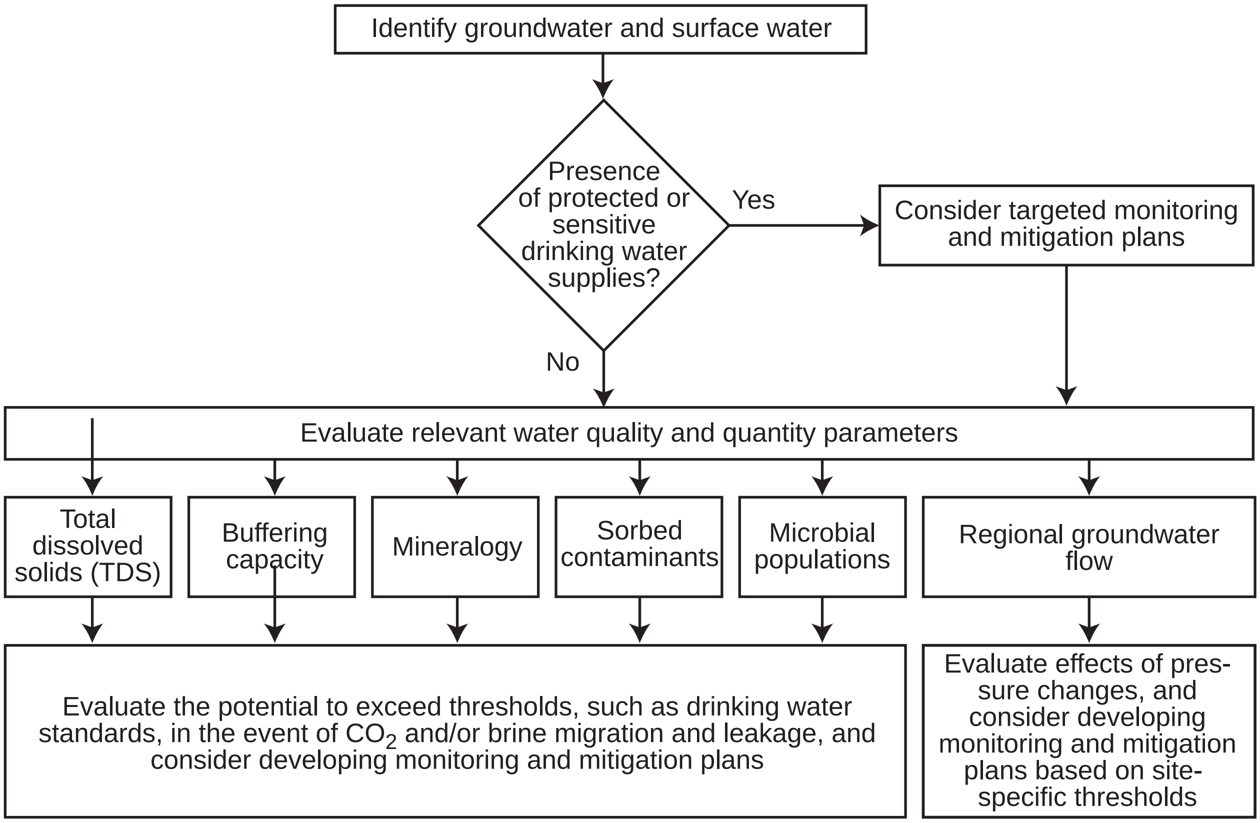

Figure 4.4. Groundwater and Surface Water Evaluation

- **Mineralogy**. Migration of CO_2 into overlying aquifers could cause acidification, which in turn may cause dissolution of metal-containing minerals and desorption of metals and organic species from the aquifer matrix (Jaffe and Wang, 2003; Kolak and Burruss, 2003, 2004; Wang and Jaffe, 2004). If metal and metalloid-bearing mineral phases (e.g., metal oxides, sulfides, carbonates) are determined to be present, geochemical modeling may be necessary to evaluate whether metal aqueous concentrations will exceed drinking water standards in the event of migration into an overlying aquifer. The mobilization of metals and other contaminants within the injection zone could also potentially impact drinking water sources, if the metal-containing fluids leaked into an overlying aquifer, or could preclude the use of the injection zone as a future drinking water source without treatment.

- **Sorbed contaminants**. Sorbed metals, organic contaminants, and gases could be released under acidic conditions created by CO_2 and other geochemical processes (e.g. competitive desorption). If impurities (e.g., organics, metals, gases) are present, geochemical modeling may be necessary to evaluate if aqueous concentrations will exceed drinking water standards in the event of migration of CO_2 and other fluids into overlying aquifers.

- **Microbial populations**. As noted in Section 4.3.1, microbial populations may catalyze geochemical reactions. As such, their influence may need to be considered when determining aqueous concentrations of metals and other impurities.

In addition, impurities in the CO_2 stream, such as H_2S, SO_2, and other sulfur- and nitrogen-containing species, can increase the acidification of groundwater compared to pure CO_2.This could lead to increased mobilization of trace amounts of hazardous metals if a CO_2 stream leak comes into contact with groundwater (IPCC, 2005). However, the concentrations of sulfur and nitrogen bearing gaseous constituents in the CO_2 stream are likely to be low, and hence their impacts on injection zone rocks and groundwater may be relatively minor (Apps, 2006).

The migration of CO_2 through overlying soils may also cause mobilization of contaminants in the vadose zone. For example, the FutureGen risk assessment identifies radon mobilization as a potential secondary effect of migration of CO_2 and other impurities through soils. Radon is a naturally occurring element in some soils and might be mobilized if CO_2 and other potential impurities diffuse through soils at high enough rates (U.S. DOE, 2007c). However, this impact may be minimal because such elements are likely to be present only at trace concentration levels (Apps, 2006). Consideration may also need to be given to the possible entrainment of organic species by migrating CO_2 in the case of injection into oil and gas fields. Though Apps (2006) reports that concentrations of such organic species is likely to be low.

For surface water (including oceans), biotic water quality criteria may also need to be considered. For example, fish and other species may be sensitive to increased concentrations of metals such as copper, cadmium, and zinc, and increased acidic conditions may inhibit precipitation of calcareous shells in surface water and oceans.

Geologic sequestration that involves injection into subseabed geologic formations raises the potential for water quality impacts in the ocean. If sufficient volumes of leaked CO_2 were to come into contact with sea water, it could locally increase the acidity of the water and potentially induce a secondary set of water quality impacts (e.g., changes in concentrations of metals through interaction with surface sediments). Impurities and substances added to the CO_2 stream (e.g. to enable or improve capture) could also impact marine water quality. Finally, the effects of supercritical CO_2 on marine water quality parameters may need to be considered under certain circumstances. At great enough depths, the CO_2 may be more dense than the surrounding seawater, and hence may tend to sink, rather than being dispersed through buoyancy–driven upward migration and dispersion.

4.4.2 Regional Groundwater Flow

Groundwater flow directions, water table levels, and the distribution of groundwater (areas where groundwater is gained and lost) could all be affected in shallower aquifers sensitive to pressure changes caused by CO_2 injection (Nicot et al., 2006; Tsang et al., 2007). This could influence the quantity of water available for groundwater-based municipal water supplies and cause interferences with injection wells. Further, a rise in the water table level under a stream or lake fed by groundwater could result in elevated water levels, changes in flow rates, and changes in the geometry of the water bodies. Finally, there may be effects on intertidal zones, where displaced brine may ultimately be discharged into oceans.

Groundwater flow direction, flow rate, and quantity are metrics for this receptor in the VEF, and the determination of elevated vulnerability thresholds for these metrics is likely to be site specific. Physical groundwater and surface water modeling is likely to be necessary to evaluate effects of pressure changes.

4.4.3 Protected and Sensitive Drinking Water Supplies

Protected and sensitive drinking water supplies may be particularly vulnerable to adverse impacts associated with migration of CO_2 and other fluids and pressure changes, including the water quality and groundwater flow effects described above. Because of their increased vulnerability, it is important to identify the presence or absence of such water supplies, and it may be necessary to consider targeted monitoring and the development of mitigation plans if these water bodies are present.

4.5 Potential Geosphere Impacts

Changes in subsurface pressure from GS could have direct impacts on the geosphere. Subsurface pressure changes that cause an exceedence of the subsurface geologic formation's geomechanical strength could cause fracturing or reopening of faults and fracture zones (Quintessa, 2004; IPCC, 2005). This in turn could cause unanticipated movement of CO_2 and other fluids and increase the potential for the impacts discussed above. Other potential impacts include induced seismic activity such as earthquakes in the extreme case (Healey et al., 1968) and land deformation through uplift (Quintessa, 2004; Birkholzer et al, 2007).

4.6 Spatial Area of Evaluation: Influence of Receptors

Chapter 3 introduced the GS footprint, the geographical area that may be impacted by unanticipated migration, leakage, and pressure changes, and is the focus of site characterization and monitoring (column two of Figure 3.1). Under certain circumstances, it may be necessary to extend site characterization and monitoring beyond the GS footprint. Receptors outside the footprint might be adversely impacted if leakage occurs near or at the footprint boundary. For example, it might be appropriate to extend monitoring into the habitat of an endangered species that straddles the boundary of the CO_2 plume. In addition, concentrating features such as topographic lows, wind patterns, or ocean current patterns could transport CO_2 beyond the boundary of the GS footprint (Bogen et al., 2006; U.S. DOE, 2007c). Furthermore, site characterization and monitoring for pressure effects, including displacement of brine into overlying aquifers, are likely to extend over an even larger area.

It is also important to note that areas of evaluation are not expected to be static entities. As discussed in Chapter 3, the CO_2 plume and pressure front will grow and change shape over the lifetime of a project, as will the corresponding spatial area of evaluation.

This section introduces two evaluation processes for spatial area evaluation processes. The first focuses on characterization of the area that may be affected by the injected CO_2, and the second focuses on the area that could be affected by pressure changes. Separate CO_2 and pressure spatial areas of evaluation are delineated because of the anticipated much larger areal extent of pressure changes (particularly for deep saline formations). Additionally, a smaller set of potential impacts will be associated with pressure changes. The evaluation processes suggest approaches on how to delineate the geographical extent of the area affected by CO_2 and pressure changes, and also recommend monitoring and mitigation plans. It is important to note that the geographical area affected by pressure may be evaluated for pressure-driven displacement of brine into overlying aquifers, as described below, but it will not need to be evaluated for direct adverse impacts of CO_2 (and other impurities) on human health and welfare and ecological receptors.

4.6.1 Carbon Dioxide Spatial Area of Evaluation

The flowchart depicted in Figure 4.5 represents an approach for delineating and examining the CO_2 spatial area of evaluation.

Spatial Area of Evaluation Delineation

The lateral extent of the CO_2 spatial area of evaluation can be delineated by first using the areal extent of the CO_2 plume as the base and then expanding on that base to include the spatial extent over which adverse impacts to physical features and receptors within a determined distance of its perimeter may occur. Physical features can include CO_2 -concentrating features such as topographic lows and dispersing features such as atmospheric conditions and ocean current patterns. As discussed in Sections 4.1 through 4.5, potentially affected receptors can include human populations, populations covered by Executive Orders, cultural and recreational resources, economic resources (surface and subsurface), legislatively protected and other sensitive species, and groundwater and surface water sources.

Identification of Receptors and Development of Monitoring and Mitigation Plans

It can be useful to specifically locate potentially affected receptors within the expanded CO_2 spatial area of evaluation and identify their vulnerability to adverse impacts, taking into account CO_2-concentrating physical features and geologic attributes. Four potential scenarios highlighted in Figure 4.5 suggest different types of monitoring and mitigation plans. For example, if the location of receptors does not coincide with CO_2-concentrating physical features or with elevated geologic attribute vulnerabilities, then generic monitoring may be implemented. However, if the location of receptors coincides with CO_2-concentrating physical features, a receptor-specific monitoring and mitigation plan may be developed that takes those features into account. The scenarios highlight that the overall vulnerability associated with a GS system is determined based on a combination of multiple factors. This concept is discussed further in Chapter 5.

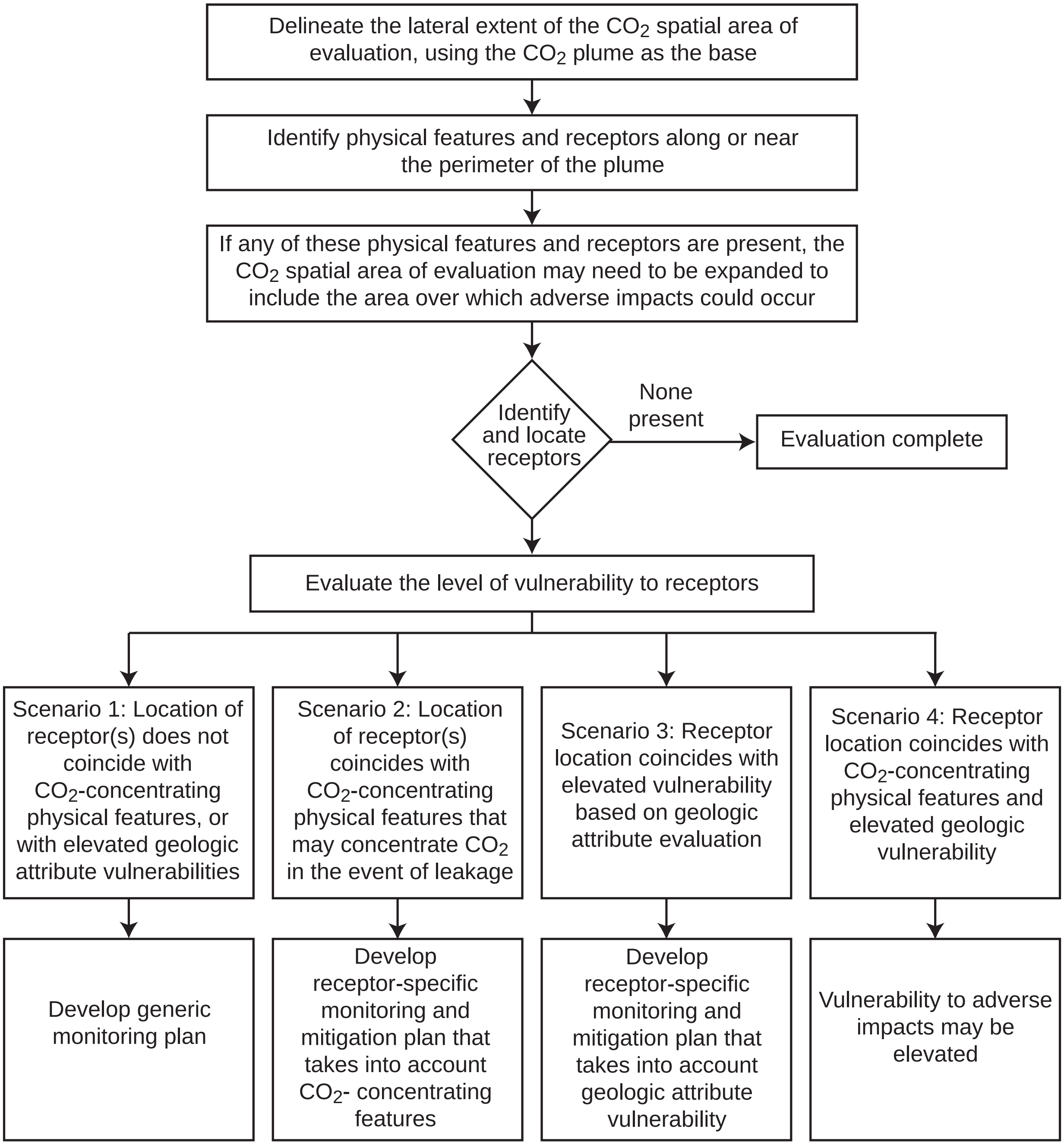

Figure 4.5. Carbon Dioxide Spatial Area of Evaluation

4.6.2 Pressure Spatial Area of Evaluation

The flowchart depicted in Figure 4.6 provides an approach for delineating and examining the pressure spatial area of evaluation.

Spatial Area of Evaluation Delineation

The lateral extent of the pressure spatial area of evaluation can be delineated using the GS footprint as the base. In this case, the boundary of the GS footprint is defined by the pressure change that is significant enough to cause adverse impacts to overlying receptors (e.g., fluid displacement into an overlying aquifer). The perimeter can then be expanded to include the spatial extent over which receptors within a determined distance of the perimeter of the GS footprint could be affected. As noted in the previous section, receptors can include human populations, populations covered by Executive Orders, cultural/recreational resources, economic resources (surface and subsurface), legislatively protected and other sensitive ecological species, and groundwater and surface water sources.

Identification of Receptors and Development of Monitoring and Mitigation Plans

Potentially affected receptors within the expanded pressure spatial area of evaluation can then be considered. It is important to evaluate the potential impacts to these receptors, taking into account geologic attributes, and then develop monitoring and mitigation plans for receptors susceptible to adverse impacts associated with pressure changes.

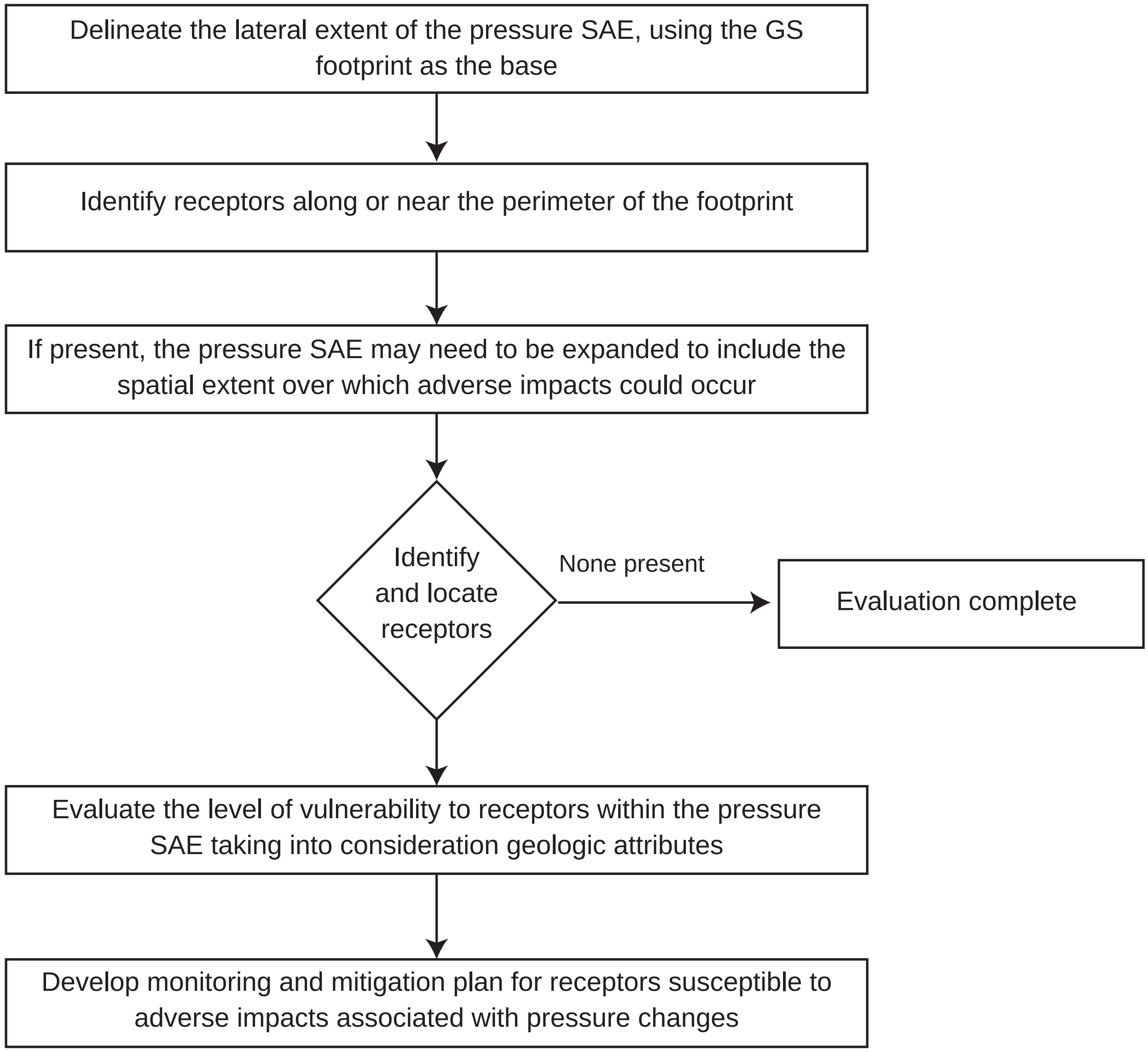

Figure 4.6. Pressure Spatial Area of Evaluation

4.7 Chapter Summary

This chapter examined categories of potential adverse impacts resulting from unanticipated migration, leakage, and pressure changes, and associated receptors. Impact categories include human health and welfare, atmosphere, ecosystems, groundwater and surface water, and the geosphere. The chapter then discussed the delineation of spatial areas of evaluation for site characterization and monitoring, taking into account the receptors discussed in the previous sections. Chapter 5 incorporates elements from Chapters 3 and 4 into a holistic approach for vulnerability evaluation and highlights key geologic attributes that should be considered carefully when characterizing a potential GS site.

CHAPTER 5

VULNERABILITY EVALUATION FRAMEWORK FOR GEOLOGIC SEQUESTRATION: KEY CONSIDERATIONS

Adopting a holistic approach to vulnerability assessment is important because the overall vulnerability of a GS site is a combined function of all of the identified geologic attributes and receptors. In most instances, evaluating a single attribute will not provide sufficient information to characterize overall vulnerability. Rather, the entire site needs to be evaluated as a whole. The individual and combined influence of attributes on vulnerability as well as the presence, proximity, and sensitivity of receptors is likely to change over time. Generally, vulnerability and uncertainty will decrease after injection ceases and as monitoring data are incorporated into the assessment.

Key attributes that have been identified as particularly important when evaluating the potential vulnerability to unanticipated migration and leakage from a GS system include wells and faults/fracture zones, as well as pressure changes that may induce fracturing or reactivate faults. However, even for these key attributes, it is the interplay of multiple characteristics that will determine the level of vulnerability that may be associated with them; the simple presence of a well or a fault does not automatically indicate elevated vulnerability. The prioritization of vulnerabilities associated with receptors, geologic attributes and their characteristics is an important, but challenging endeavor that is beyond the current scope of the VEF. However, vulnerabilities can nevertheless be managed by carefully evaluating and managing these key attributes, thus reducing the likelihood of adverse impacts.

Chapters 3 and 4 identified and described the geologic attributes that could contribute to vulnerability and the receptors that may be adversely impacted. They also presented evaluation processes and suggestions as to how particular vulnerabilities may be addressed. This chapter examines key considerations when examining the vulnerabilities of a GS site as a whole and contains the following sections:

- Section 5.1 discusses a holistic approach to vulnerability evaluation in terms of GS system characteristics and temporal scales.
- Section 5.2 provides additional detail on attributes that are key to determining GS site vulnerability, specifically wells, faults, and pressure changes. Evaluation flowcharts for these attributes are introduced as well as suggestions for reducing vulnerabilities.
- Section 5.3 provides a summary of the chapter.

5.1 Holistic Approach to Evaluating Vulnerability

The overall vulnerability to adverse impacts is determined by the combination of geologic attributes and receptors that are associated with a GS site. Further, since storage of CO_2 is intended for a long time period, it is important to examine how the influence of different attributes may change over time.

5.1.1 Interplay of Geologic Attributes and Receptors

The overall vulnerability of a GS site to adverse impacts is a function of the vulnerability of a system to unanticipated migration, leakage, or pressure changes in combination with the vulnerability of specific receptors of concern. The highest level of vulnerability emerges when there is a high potential that there are unanticipated migration or leakage pathways in the presence of important vulnerable receptors, such as a sensitive drinking water supply. If the vulnerability to unanticipated migration or leakage is low (for example, the confining system is laterally extensive, has a very low permeability, is not known to be perforated by wells or faults, and has a low vulnerability to induced fracturing or other pressure-related effects) then the overall vulnerability to adverse impacts may be relatively low, despite the presence of sensitive receptors such as drinking water supply. Therefore, an evaluation of the combined presence and condition of GS attributes together with the presence and sensitivity of receptors is required for a clear understanding of overall vulnerabilities.

5.1.2 Evaluation of Vulnerability at Different Temporal Scales

The importance of different attributes for affecting the probability and severity of adverse impacts is likely to change over the lifetime of a GS project. Although a quantitative discussion of the relative contribution of different attributes and how this may change over the duration of a project is not possible at this time, some qualitative comments can be made. For example, during the injection phase, injectivity and geomechanical processes are anticipated to be key attributes in the evaluation of vulnerability to adverse impacts. The mechanical integrity of the injection wells is also very important, particularly the ability to withstand applied pressures. The vulnerability to induced fracturing is expected to be much higher during injection than post-injection. Post-injection, wells might continue to represent potential unanticipated migration or leakage pathways. However, the concern may be more for slow/small leaks that develop through slow geochemical degradation pathways (thus primarily affecting atmospheric vulnerability) as opposed to high-intensity pressure blow-outs that could also affect human health and welfare and environmental receptors.

In general, the overall vulnerability to adverse impacts is expected to decline over time, as illustrated in Figure 5.1. This is based on a combination of factors, including the greater permanence of secondary trapping mechanisms such as dissolution, which also decreases buoyancy (see Chapter 2),

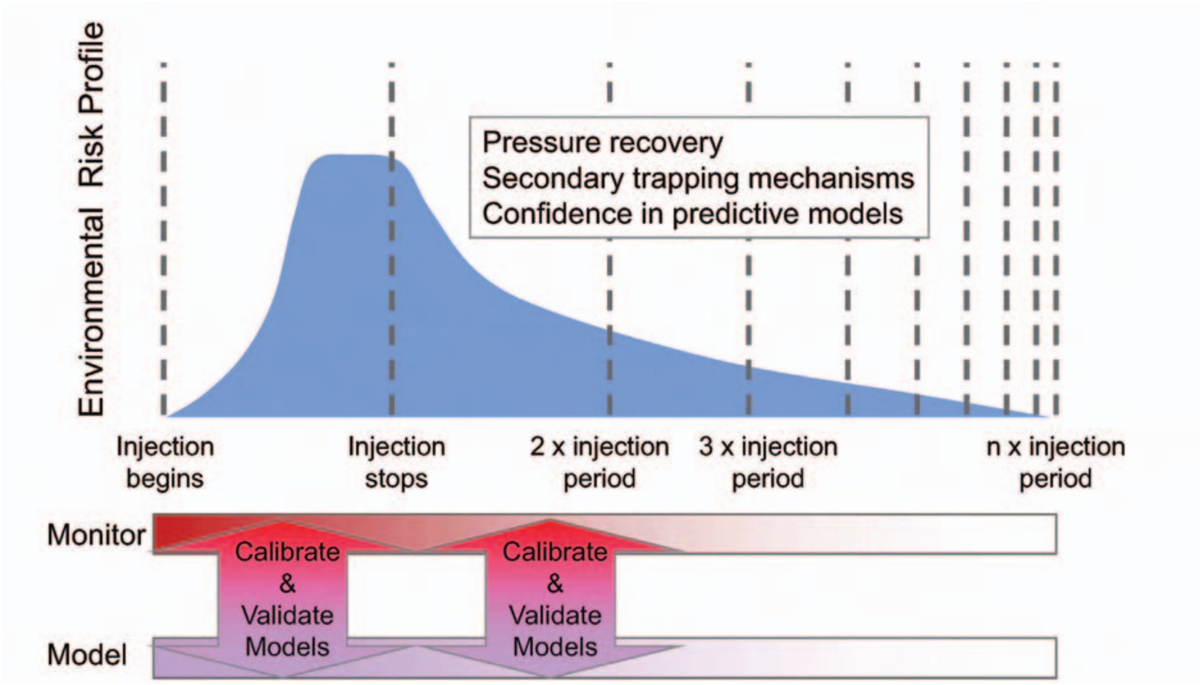

Figure 5.1. Risk Profile for CO_2 Storage. Source: Benson, 2007.

pressure recovery once injection stops, and improved characterization and modeling of GS system attributes over time.

In some cases, however, vulnerabilities associated with certain aspects of a GS system may not decrease appreciably over time. For example, in open systems where the injected CO_2 and associated induced pressure changes do not reach the lateral boundaries of the injection zone formation(s), pressure is expected to drop significantly when injection ceases (Pawar et al, 2006; Birkholzer et al., 2007), thus decreasing the vulnerabilities to induced seismic activity and faulting and fracturing. However, in closed systems where pressure remains elevated at the lateral boundaries of the system (for example in EOR geologic settings, where boundaries may be defined by geologic features such as an anticline or sealed fault), it may take much longer for pressure to dissipate. This can result in elevated vulnerability for a prolonged period of time after injection stops. It should be noted that this example re-emphasizes the necessity of evaluating the vulnerabilities associated with a GS system as a whole. Although pressure may remain elevated for a longer period of time in the closed system, this does not necessarily mean that the system has an overall elevated level of vulnerability. For example, EOR settings have withstood elevated pressure for geologic timescales in the past, thus demonstrating an effective confining system with low vulnerability to unanticipated migration or leakage.

5.2 Key Attributes in Evaluating GS System Vulnerability

Although the overall vulnerability of a GS site is determined through a holistic evaluation of the interactions among all elements of a GS site, certain key attributes have been identified as central to evaluating the vulnerability associated with a GS system. It is unlikely that any one of these single attributes alone will determine the overall vulnerability of a GS site. However, there are some basic screening considerations:

- Is the physical capacity of the injection zone sufficient to store the total CO_2 volume?
- Is the confining system present and of sufficient lateral extent?
- Is the injectivity of the injection zone sufficient?
- Is tectonic activity (earthquakes, volcanoes, hotspots, etc.) not a concern?
- Are wells, faults, fracture zones not a concern?

If one or more of these conditions is not met, there may be elevated vulnerability to unanticipated migration, leakage, or adverse pressure changes that render a GS system less suitable. As described in the evaluation processes presented in Chapter 3, the suitability of the GS system can be improved, for example, by altering operational plans and injecting less, through targeted monitoring and mitigation, and/or corrective actions at vulnerable wells. The discussion below focuses on wells and faults because they have been identified as being the most likely attributes to contribute to unanticipated fluid migration out of the injection zone. However, the presence of these attributes alone may not indicate elevated vulnerability; and it is important to examine them thoroughly to ascertain the level of vulnerability associated with a GS system.

5.2.1 Wells as Fluid-Conducting Pathways

Wells and other artificial penetrations such as boreholes have been identified as one of the most probable conduits for the escape of CO_2 and other fluids from the injection zone (Gasda et al., 2004; Benson, 2005; IPCC, 2005; Carey et al., 2007). Industrial analogs indicate that while gases such as CH_4 can be stored effectively in the subsurface, there are examples of unanticipated gas leakage through poorly completed or improperly plugged and abandoned wells (Gurevich et al., 1993; Lippmann and Benson, 2003; Perry, 2005). Hence, if not properly sealed and plugged, wells can provide an open conduit from depth to the surface. Even wells that are properly sealed may have fluid-conducting pathways along the outside of the casing, where a complex environment involving well cements, drilling muds, and possibly damaged rock zones can provide opportunities for fluid flow (Gasda et al., 2004). Further, the acid generated when CO_2 contacts water could degrade well construction materials, possibly creating pathways for fluid flow (Scherer et al., 2005). The relative depth of wells is also an important consideration when evaluating their potential to serve as fluid pathways. Only wells that penetrate the injection zone can serve as direct leakage pathways to the surface. However, well characterization should include all wells within the area anticipated to be affected by CO_2 injection, because shallower wells could be connected to faults or other features that do penetrate the injection zone. Thus, the combination of wells and faults can serve as a pathway for unanticipated migration and leakage.

Experience from industrial processes underlines the importance of evaluating the potential for active and abandoned wells to serve as fluid pathways and conducting a detailed GS site characterization before injection (Cawley et al., 2005). As illustrated in Figure 5.2, evaluating the potential for wells to act as conduits for CO_2 and other fluids involves considering multiple factors, including determining whether wells are present, measuring their depth relative to injection zone, and evaluating the integrity of the well construction materials and seal.

While operational factors are not the focus of the VEF, injection and monitoring wells may also have implications for the creation of fluid-conducting pathways. Principal design considerations for CO_2 injection wells include pressure, production and injection rates, and corrosion. There is substantial knowledge about the design of CO_2 injection wells developed for EOR operations (IPCC, 2005). Equipping injection wells with packers can help isolate pressure effects to the injection interval. The slotted length of wells, use of horizontal wells (slotted over much longer reaches than vertical wells), and the number of injection wells used for injecting CO_2 are all operational factors that may minimize pressure. Using corrosion-resistant well construction materials can help maintain the integrity of the well. Numerous monitoring and mitigation techniques also exist and could be applied to GS systems (Jarell et al., 2002; Skinner, 2003).

Identifying and evaluating active and abandoned wells may be particularly challenging in certain geologic settings, such as depleted oil and gas fields, where there may be numerous active and abandoned production and exploration wells of different ages, depths, and general condition. Industry and state records exist that can help locate such wells, and determine their depth and mechanisms of sealing and plugging. However, the completeness of such records, particularly for historical (pre-1950s) wells, may be limited, and may need to be supplemented by field verification. Nevertheless, site characterization that includes the considerations outlined in Figure 5.2 may reduce uncertainties and manage vulnerability by helping identify those conditions involving wells that may be of concern and by providing approaches to address them. For example, a well that penetrates the injection zone and is not sealed properly, or for which records do not exist on abandonment

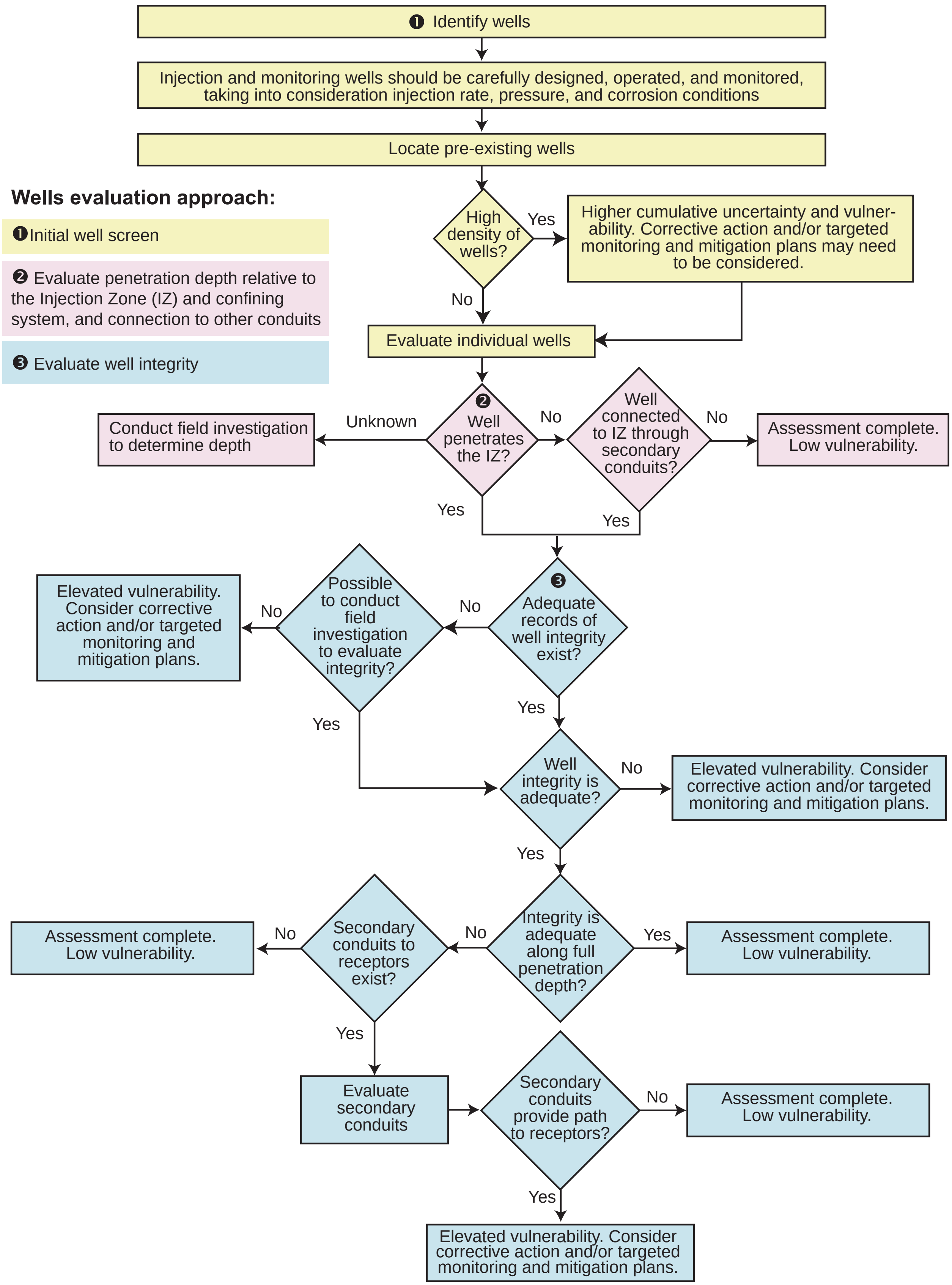

Figure 5.2. Wells Evaluation

methods, could be managed by targeting the well for monitoring and taking mitigative steps such as those described in Chapter 6. Decisions may need to be made on a site-specific basis regarding whether corrective action or targeted monitoring, or a combination of both, may be most appropriate to address conditions at a given well, in addition to the development of mitigation plans.

5.2.2 Faults and Fractures as Fluid-Conducting Pathways

Although faults and fractures have been identified, along with wells, as one of the most likely fluid conduits in GS systems, the simple presence/absence of fault in many cases will not be sufficient to evaluate the vulnerability to unanticipated migration and leakage. The potential for faults and fractures to act as fluid pathways in GS systems is a function of numerous factors, including stratigraphic position. For example, a fault that does not cut across the full thickness of the confining zone may not pose the same level of vulnerability as a fault that is continuous from the injection zone to the surface.

Whether a fault is sealed or conductive will also determine its ability to allow passage of CO_2 and other fluids; faults may serve as either barriers or conduits to fluid flow (Omre et al., 1994; Lewicki et al., 2006; Wilkens and Naruk, 2007). Existing faults and fractures that are sealed may remain stable or may be reactivated by induced pressure changes and geochemical conditions caused by CO_2 injection. The orientation and geometry of the fault relative to regional stresses will also influence whether it may be re-activated (Rutqvist et al., 2007a, 2007b). New fractures could form if the fracture pressure of the formation(s) is exceeded (Healy et al., 1968; Gibbs et al., 1973; Raleigh et al., 1976; Sminchak et al., 2002; IPCC, 2005; Streit et al., 2005; Wo et al., 2005). However, currently available geomechanical methods can assess the stability of faults and estimate the maximum sustainable pore fluid pressures for CO_2 storage (e.g., Streit and Hillis, 2003).

The potential for induced fractures and re-opened faults to result in adverse impacts will depend on numerous additional factors, including whether they are connected to an overlying receptor, whether they are connected to other fluid-conducting pathways (e.g., wells), and whether or not they may be resealed by geochemical processes. In addition, an adverse impact will occur only if the amount of CO_2 that is transported along the fault is sufficient to impact a receptor such as a drinking water supply. For example, if a small fault reopened that connects the injection zone to an overlying aquifer, the amount of CO_2 transported along the fault may not adversely affect drinking water or other resources.

Identifying and evaluating how faults and fractures will behave presents a particular challenge in the characterization of GS systems. Figure 5.3 presents some of the factors that can be considered when evaluating the potential for faults and fractures to act as fluid-conducting pathways. The figure highlights the need to identify whether faults are continuous from the injection zone to secondary conduits, overlying aquifers, or other receptors. This evaluation can be strengthened if multiple techniques for site characterization are used, such as surface mapping, interpretation of well bore data, and seismic techniques. Use of seismic techniques is generally the more comprehensive approach, because not all faults at injection zone depths have surface expressions allowing surface mapping to locate them, and the spatial discreteness of well bore data is generally insufficient to properly characterize fault and fracture zones. Three-dimensional seismic data may provide advantages for complete fault characterization, because two-dimensional seismic data have associated spacing and resolution constraints. As work progresses, additional methods may be identified for fault characterization techniques within GS systems.

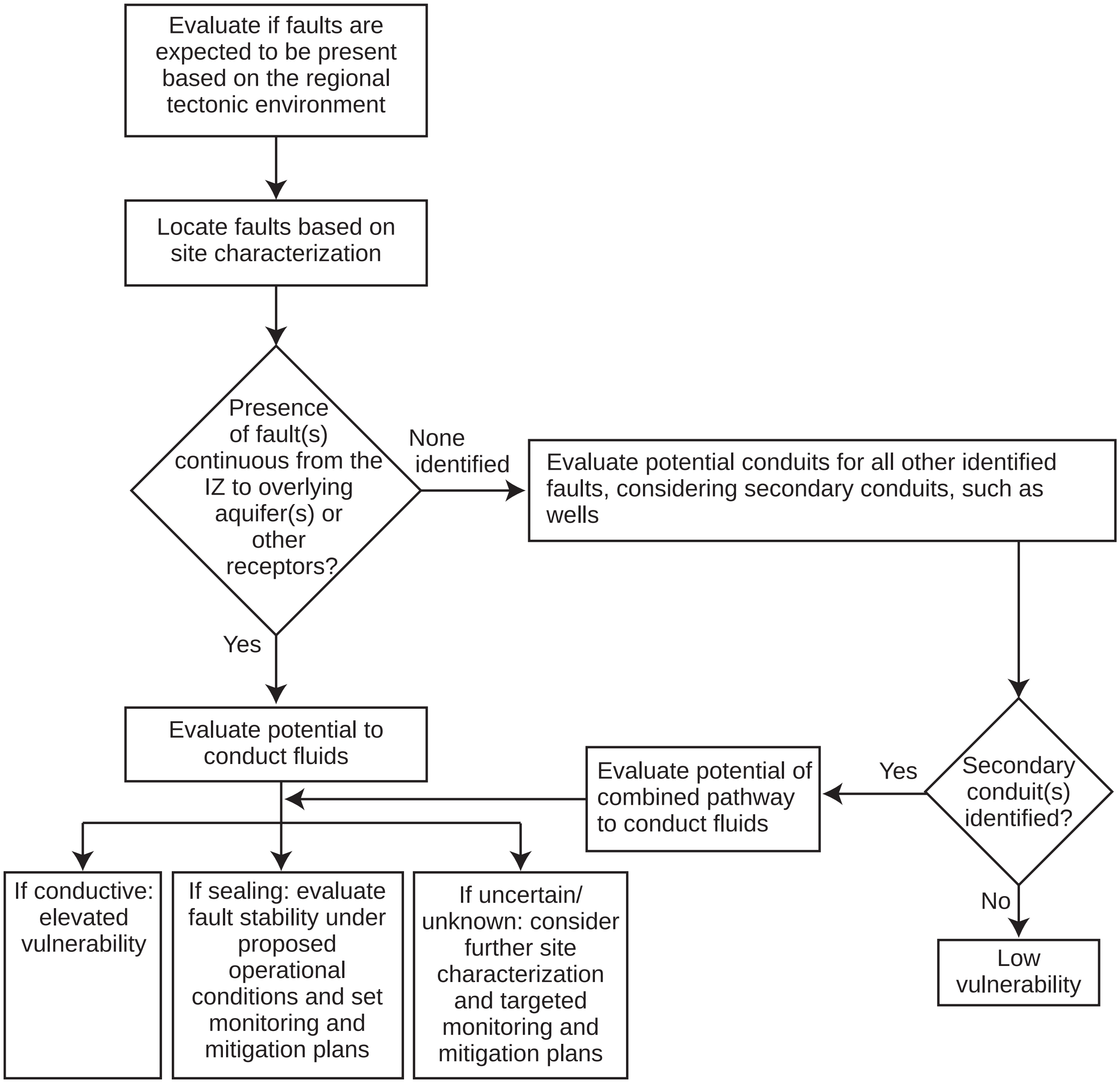

Figure 5.3. Faults Evaluation

Evaluating the stability of faults and fracture zones in GS systems also presents particular challenges. Faults and fractures are often associated with complex zones with altered properties, rather than being simple discontinuities. There may be significant uncertainty in being able to predict how they will behave under the conditions induced by GS. However, as described in Figure 5.1, careful design and monitoring can help manage vulnerabilities associated with faults and fractures. Approaches include using multiple site characterizing technologies and setting monitoring at a level appropriate to the level of uncertainty. Furthermore, the existing knowledge base is likely to improve as more data are acquired from field projects.

5.2.3 Pressure-Induced Physical Effects

Injecting CO_2 into geologic formations will in most cases cause subsurface changes in pressure. As discussed above, induced fracturing and fault reactivation can occur if injection pressure exceeds fracture pressures, which may in turn result in the opening of fluid migration pathways. If pressures are great enough, they could in extreme cases cause earthquakes (Healey et al., 1968). However, these effects could be minimized through an understanding of the relevant geologic attributes, careful site characterization, careful operation of GS systems, and monitoring. As summarized in Chapter 3, the geologic attributes that will influence pressure changes include physical capacity of the injection zone, its injectivity, and geomechanical and geochemical processes. Operational factors that influence pressure changes, and that can be managed, include the rate of injection, the slotted length of the injection well, the number of injection wells, and their orientation.

There may be greater uncertainty about evaluating pressure effects in GS systems when examining the potential for pressure-induced regional scale impacts that do not involve fracturing or faulting. As discussed in Chapter 4, pressure changes in the injection zone could cause regional impacts on overlying aquifer systems, including changes in groundwater flow directions and water table levels. These may result in alterations in the distribution and fluxes of groundwater. This could in turn have other impacts, for example, changing the quantity of groundwater that is available for municipal drinking water supplies. There also could be pressure-induced migration of brines and other fluids through the pore structure of overlying formations into groundwater receptors, which may impact water quality. Furthermore, pressure-induced fluid displacement could result in the release of brine at locations where injection zone formations outcrop at the land surface. Regional pressure effects have been the focus of relatively few studies, and uncertainties and vulnerabilities associated with this subject should be addressed through additional research.

5.3 Chapter Summary

This chapter discussed the importance of a holistic evaluation of vulnerability associated with GS systems and highlighted key attributes (i.e., wells, faults, and pressure changes) that should be examined extensively in a vulnerability evaluation. Chapter 6 summarizes monitoring and mitigation strategies to help decrease or avoid the potential adverse impacts of GS summarized in Chapter 4.

CHAPTER 6

MONITORING AND MITIGATION

Careful site selection and site characterization of GS systems and accompanying spatial areas of evaluation can help minimize the potential for adverse impacts. However, in the event of unanticipated migration and leakage, early detection through monitoring and application of mitigation techniques can help prevent or minimize adverse impacts. Data collected from monitoring can also help refine our understanding of GS systems and overlying receptors, thereby enhancing operations while minimizing vulnerabilities.

The VEF identifies the key attributes that are important to site selection and site characterization (geologic attributes and receptors described in Chapters 3 and 4), and approaches to delineate the spatial extent of the GS system (also described in Chapters 3 and 4). Although monitoring and mitigation are not the focus of the VEF, application of the VEF can inform and prioritize monitoring and mitigation approaches, focused on both the subsurface geologic attributes, and overlying receptors.

This chapter contains the following sections:

- Section 6.1 presents a brief overview of the purposes of monitoring, different applicable monitoring technologies, and the timeframe for monitoring activities.
- Section 6.2 provides a brief summary of mitigation strategies in the event of unanticipated migration, leakage, and pressure changes.
- Section 6.3 provides a summary of the chapter.

6.1 Monitoring

6.1.1 Purposes of Monitoring

Most of the geologic attribute evaluation processes provided in the VEF qualitatively identify those conditions that may lead to low or elevated vulnerability, and recommend the development of monitoring and mitigation plans in instances of elevated vulnerability. Monitoring can provide an early warning mechanism in the event of unanticipated movement of CO_2 and other fluids from the injection zone (Oldenburg et al., 2003; IPCC, 2005). It can also be used to detect pressure changes in the subsurface. Early detection of unanticipated fluid migration and increases in pressure provides the opportunity to put into place mitigation strategies to avoid or minimize adverse impacts. The goals of monitoring include regularly confirming the location and containment of the injected CO_2. Hence, the data collected during monitoring can also be used to develop a more comprehensive understanding of the GS system, and to calibrate and refine models of the behavior and location of CO_2 in the subsurface. Operations may be modified and enhanced based on the interpretation of monitoring data.

An important element of monitoring is establishing baseline conditions by collecting monitoring data prior to the injection of CO_2. Measurements taken before injection will help evaluate how the subsurface might change in response to injection. Interpreting the data gained through many monitoring techniques (such as the seismic measurements discussed in the next section) can be greatly facilitated if post- and pre-injection data can be compared.

Monitoring can also be used to ensure proper functioning of injection wells and to optimize injection. Specific techniques can also be targeted at attributes and receptors of a GS site identified during site characterization that may be of particular interest, including abandoned wells, faults and fracture zones, and sensitive overlying receptors (IPCC, 2005).

6.1.2 Monitoring Technologies

Several types of monitoring technologies can be used to meet the purposes identified above. The IPCC, in its Special Report on Carbon Dioxide Capture and Storage, describes monitoring technologies for the different monitoring purposes:

- **Location and movement of stored CO_2**. The location and movement of stored CO_2 and other underground fluids and gases can be monitored using direct or indirect approaches. Direct approaches, which are employed at many EOR projects, involve measuring the volume of injected quantities of CO_2 at multiple production wells. A second direct approach to monitoring movement of stored CO_2 and other underground fluids and gases is to drill monitoring wells. Monitoring wells can also be used in other assessments of subsurface fluid migration, including tracer tests. Injecting unique tracers (e.g., gases not found within the injection zone) and detecting for them at monitoring wells can help characterize CO_2 migration in the subsurface (IPCC, 2005).

  Indirect approaches for monitoring movement of stored CO_2 and other underground fluids and gases include using seismic and non-seismic technologies (IPCC, 2005). Seismic technologies measure the velocity and absorption of energy waves through rock and provide a picture of underground layers of rocks and reservoirs. Non-seismic techniques such as electrical and electromagnetic techniques measure the relative conductivity of subsurface layers of various solids and fluids (IPCC, 2005). A comprehensive list of technologies for monitoring movement of stored CO_2 and other underground fluids and gases is given in Table 5.4 of the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005).

- **Injection rates and pressures**. The oil and gas industry has a long history of monitoring injection rates and pressures. Technologies used for this purpose are mature and commercially available. Gauges at wellheads are used to measure injection rates. Injection pressure is typically measured at most injection wells, and downhole formation pressure measurements are also routine, though the latter measurements may only be made on a periodic basis. Pressure gauges at injection wells are often linked to shut-off mechanisms that will slow or cease injection if injection pressure deviates from a determined range (IPCC, 2005).

- **Well integrity**. Wells are often subjected to extensive induced-pressure testing for mechanical integrity before use. Continued integrity of the well during injection can be evaluated by monitoring pressure. The injection pressure can be continuously monitored at the wellhead by meters (IPCC, 2006). The pressure in the injection well annulus can also be monitored during injection to ensure the integrity of the injection well packer and casing. A decrease in pressure in the annulus may indicate unanticipated subsurface migration. In addition, temperature and "noise" logs can be used to detect well failures. Such logs have historically been used in natural gas storage projects. The integrity of the casing material can also be monitored using corrosion monitoring techniques such as caliper logs (IPCC, 2005).

- **Local environmental impacts**. In addition to technologies for monitoring CO_2 movement underground, several technologies are available for monitoring the local environmental impacts of unanticipated migration and leakage. Several reviews have been published on near-surface monitoring technologies that can evaluate local environmental impacts, including both conventional and unconventional technologies (IPCC, 2005; Benson et al., 2002; Oldenburg et al., 2003).

  Monitoring CO_2 levels at the surface is a common practice in many occupational applications. Many heating, ventilation, and air conditioning systems, for example, have CO_2 sensors. In addition, the literature on CO_2 concentrations in soil and air is extensive (as described in Oldenburg et al., 2003; Miles et al., 2005) and monitoring occurs frequently in many areas (e.g., regular CO_2 flux measurements by the U.S. Geological Survey at Mammoth Mountain, California) (USGS, 2001).

  Satellite-based remote sensing and airborne imaging measurements of CO_2 levels are also possible technologies for monitoring CO_2 levels at the surface. However, these technologies may not be sensitive enough to detect the small CO_2 fluctuations that may be associated with GS. Monitoring ecosystems for exposure to CO_2 is another technique for assessing local environmental impacts at the surface. Such monitoring often involves measuring the productivity and biodiversity of flora and fauna and measuring pH levels in aquatic ecosystems. Impacts on USDWs can be monitored by water sampling that tests levels of major ions and gases that may be carried by the leaked plume or mobilized by the plume's constituents (IPCC, 2005). Hyperspectral imaging is also being considered for the detection of stressed vegetation.

6.1.3 Timeframe Implications for Monitoring

The long timeframe over which GS needs to be effective underlines the importance of regular monitoring. It is suggested that monitoring periods for GS can be divided into three periods: injection and operation; storage during pressure equilibration; and long-term storage (Chalaturnyk and Gunter, 2004).

The length of the injection and operation period will depend on the capacity of the injection zone and the rate of injection, but is generally expected to be 25–50 years. The period of time required for pressure equilibration after injection stops will be site specific. For open systems, where the injection zone formation is very large compared to the volume of the CO_2 plume, the time period for pressure to decay back to the regional formation pressure may be 100 years or less (Birkholzer et al., 2007). For closed systems, pressure may remain elevated for a much longer period of time. After pressure stabilization (either with a return to the regional pressure regime in the case of open systems or a long-term stabilization at elevated pressures in closed systems), if unanticipated migration and leakage has not occurred, the GS system may be considered stable, and the formation of pressure-related fluid conduits no longer anticipated (Chalaturnyk and Gunter, 2004). Geochemical changes, however, can continue over a longer timeframe. The integrity of the caprock or wellbore cements, for example, may be affected by reactions with injected CO_2 (IPCC, 2005).

Monitoring may be more intensive in the earlier stages, with more frequent measurements and specific targeting of operational infrastructure. The frequency of monitoring may decrease as the system stabilizes post-injection, and eventually cease (Chalaturnyk and Gunter, 2004; IPCC, 2006).

Additionally, the area requiring monitoring is also likely to change over time, expanding during the injection period as the CO_2 plume grows. The continued mobility of CO_2 post-injection, because of its relatively high buoyancy and lower viscosity compared to water and brine, may also result in a dynamic post-injection area of evaluation, necessitating adaptive monitoring. The area to be monitored for pressure impacts will also expand during injection and may be significantly larger than the area covered by the CO_2 plume. Post-injection, if the pressure dissipates (e.g., in the case of open systems), the area requiring monitoring for pressure changes may decrease correspondingly.

6.2 Mitigation

Unanticipated migration, leakage, and adverse pressure changes identified through monitoring may be addressed in many cases with mitigation actions. For the purposes of this report, mitigation refers to actions taken to prevent unanticipated migration, leakage, or pressure changes that have the potential to cause adverse impacts. It also includes actions taken to prevent or reduce impacts once unanticipated migration, leakage, or pressure changes have been detected by monitoring. This report does not address actions taken to address impacts that have already occurred. Several important mitigation concepts are discussed below. Some of these approaches are routine within the oil and gas and other industries, while others are more experimental, and will likely require further study prior to implementation.

Wells. According to the IPCC, the development of mitigation plans for active or abandoned wells is particularly important, because they are known vulnerabilities (Gasda et al., 2004; IPCC, 2005; Perry 2005). Standard mitigation techniques, also referred to as corrective actions, exist to stop unanticipated migration and leakage from injection and abandoned wells. These include injecting a heavy mud to plug the opening. If the well is not accessible at the surface, a new well can be drilled to intercept the casing of the compromised well below the ground surface and cement can be pumped in from the interception well.

Further mitigation techniques also exist for injection wells. The integrity of CO_2 injection wells can be repaired by replacing injection tubing and packers. If the space between the casing and the formation borehole leaks, the casing can be perforated to allow injection of cement behind the casing to seal the leak. If the well cannot be repaired, it can be plugged and abandoned using the standard procedures cited above, and replaced with a new injection well.

Faults and fractures. The unanticipated migration of CO_2 and other fluids along faults (and fractures) could be mitigated by lowering the pressure driving flow along the fault by injecting at a lower rate, or through more wells. Alternatively, the pressure in the injection zone could be lowered by removing water or other fluids, or by possibly creating a pathway to access additional formations within the injection zone. Further, extraction wells could be used to intersect the pathway, or a hydraulic barrier could be created by increasing the reservoir pressure upstream of the fault. It may also be appropriate to consider ceasing injection to stabilize the project and, in the extreme case, the CO_2 could be recovered from the formation and re-injected in a more suitable formation (IPCC, 2005).

Accumulation in indoor environments. Slow releases of CO_2 can accumulate in confined spaces (e.g., basements) and cause harm to human health. These slow releases into structures can be eliminated using techniques designed to dilute the CO_2 before it enters indoor environments, such as basement/substructure venting or pressurization (IPCC, 2005).

Large releases to the atmosphere. For very large releases to the atmosphere spread over large areas, natural attenuation through atmospheric dispersion may be the main mitigation option. Smaller localized releases at wellheads or in buildings could be addressed using fans or venting (Benson and Hepple, 2005; IPCC, 2005).

Accumulation in soil gas. As discussed in chapter 4, accumulation of CO_2 in soil gas can be detrimental to ecological receptors. Removing the CO_2 from the vadose zone would also prevent its escape to the atmosphere. CO_2 can be extracted from the vadose zone and soil gas using standard vapor extraction techniques that use horizontal or vertical wells to collect the CO_2. Additionally, it may be possible to decrease or stop releases to the atmosphere from the vadose zone by the use of caps or gas vapor barriers. The CO_2 accumulated under the cap could then be removed using extraction wells. Since CO_2 is denser than air, it may be possible to collect it in subsurface trenches. The CO_2 captured via these approaches could then be reinjected into the subsurface. Finally, in some cases, acidification of the soils from contact with CO_2 could be remediated by irrigation and drainage, acid-neutralizing substances such as lime could be applied to the soil (IPCC, 2005).

Groundwater and surface water. Fluids that reach groundwater could be captured using extraction wells and reinjected into the subsurface. Carbon dioxide that reaches a groundwater aquifer and then becomes immobile through residual trapping could be removed by flushing the aquifer with water, thereby enhancing CO_2 dissolution, and then extracting the dissolved CO_2 using groundwater extraction wells. Additionally, CO_2 that has dissolved in shallow groundwater can similarly be removed with groundwater extraction wells. The mobilization of metals or other contaminants as a result of CO_2 migration into groundwater could be addressed through pump and treat technologies, the creation of hydraulic barriers, or by in situ passive methods such as enhanced bioremediation (IPCC, 2005).

Shallow surface water bodies that have significant turnover (shallow lakes) or turbulence (streams) may be naturally attenuated, due to their relatively quick release of dissolved CO_2 back into the atmosphere. For deep, stably stratified lakes, active systems for venting gas accumulations have been developed and applied (IPCC, 2005).

6.3 Chapter Summary

Chapter 6 summarized the importance of delineating the geographical extent of GS systems for site characterization and monitoring purposes, how monitoring can be used to achieve multiple goals, the types of monitoring technologies, and the timeframe for monitoring activities. It also described mitigation strategies that can be employed in the event of unanticipated migration and leakage of fluids in order to avoid or minimize adverse impacts.

CHAPTER 7

SUMMARY AND NEXT STEPS

The VEF approach was developed by EPA to systematically identify those conditions that may increase or decrease susceptibility to adverse impacts from GS. The VEF is a reference document that can assist regulators and other technical experts in identifying key areas for in-depth site-specific risk assessment, monitoring, and management. The vulnerability assessment introduced in the VEF is intended to be an iterative process where new information is incorporated into the evaluation as it is generated. It is not intended to be broadly applicable or to measure the severity of an outcome, to establish performance standards for GS sites, or to specify data requirements.

The VEF identifies attributes of GS systems that may lead to increased vulnerability to adverse impacts, identifies potential impact categories, identifies thresholds that may indicate low versus elevated vulnerability, and provides a series of decision-support flowcharts that are organized, systematic approaches to assess the attributes and potential impacts. Though certain attributes or receptors may increase the overall susceptibility of a GS site to adverse impacts, it is important to recognize that assessing overall vulnerability is dependent on the interplay between individual attributes and receptors.

The VEF, as described in this report, represents the first step toward the development of a conceptual framework to evaluate potential vulnerabilities of GS projects and as such is a work in progress. Numerous reviewers have encouraged further development and refinement of the VEF as well as demonstration of its practical applicability. Future work could also involve developing the decision-support flowcharts into an integrated evaluation tool that has a more quantitative and numerical basis. This could include refining the binary vulnerability classification (low versus elevated) into a multiscaled classification scheme as warranted by available information, data, and expert opinion. In addition, the VEF may be validated and refined by applying it to case studies that represent a range of likely scenarios in which various aspects of the VEF framework can be tested. These scenarios may be based on real, successful demonstration projects as well as more challenging situations where risk may be higher. Applying the VEF in this manner would improve the framework and could be an instructive exercise for regulators, operators and other stakeholders and can provide a means to test approaches developed to manage uncertainties.

The VEF is designed to focus on vulnerabilities of GS systems that could increase adverse impacts associated with GS. It could be expanded to include vulnerabilities to adverse impacts associated with the capture or transport of CO_2, operational aspects of GS such as surface infrastructure (e.g., buildings, pipelines, well construction), and specific monitoring techniques to ensure the integrity of the GS system recommended. Though not currently included in the VEF, these elements need to be considered because they may play an important role in defining a proposed project's overall vulnerability.

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GLOSSARY

Term	Definition
Abandoned Well	A well that is no longer in use and has been closed according to standardized procedures, which may often include placing cement or mechanical plugs in all or part of the well.
Adsorption	The adhesion of molecules on the surface of a solid or a liquid.
Artificial Penetration	Man-made perforations that penetrate the subsurface (e.g., wells, boreholes, and mines).
Aquifer	An underground geological formation or group of formations, containing water. Aquifers are sources of groundwater for wells and springs.
Attribute	A characteristic of the geologic system that may influence the vulnerability to adverse impacts. Geologic attributes are characteristics that can affect the vulnerability to unanticipated migration, leakage, or pressure changes.
Borehole	A hole drilled into the subsurface, typically to collect soil samples, water samples or rock cores. A borehole may be converted to a well by installing a vertical pipe (casing) and well screen to keep the borehole from caving.
Brine	Water containing a high concentration of dissolved salts.
Buffering Capacity	A measure of the ability of a solution to resist change in pH when acid or base are added.
Capillary Entry Pressure	The additional pressure needed for a liquid or gas to enter a pore occupied by a different phase. For example, for CO_2 to displace water and enter the pores of the confining system.
Capillary Trapping	Retention of CO_2 in pore spaces by capillary forces.
Caprock	See confining system.
Carbon Dioxide Capture And Storage	A climate change mitigation strategy that involves capturing CO_2 emissions from large stationary sources, transporting the CO_2 to a storage location, and sequestering the CO_2 for long periods of time.
Closed System	A system where elevated pressure levels associated with the injection of CO_2 do not dissipate to background levels, but remain elevated at its physical boundaries, and may remain elevated for a long period of time after injection stops.
CO_2 Plume	The extent, in three dimensions, of an injected carbon dioxide stream.
CO_2 Spatial Area Of Evaluation	The CO_2 spatial area of evaluation is delineated based on potential adverse impacts resulting from unanticipated migration or leakage. The CO_2 spatial area of evaluation is typically larger than the CO_2 plume, because unanticipated migration or leakage of CO_2 right along the boundary of the plume may affect areas beyond the plume.
CO_2 Stream	The content of the CO_2 stream captured from large point sources for injection. The CO_2 stream may include trace amount of impurities in addition to CO_2.

Confining System	The confining system is a geologic formation, group of formations (e.g., shale or siltstone), or part of a formation that is composed of impermeable or distinctly less permeable material stratigraphically overlying the injection zone that acts as a barrier to the upward flow of fluids.
Corrective Action	Use of methods to assure that wells do not serve as conduits for unanticipated migration or leakage.
Cultural/Recreational Resources	Cultural resources include gathering places for human populations, including places of archaeological, historic, or natural significance; American Indian resources, cemeteries and paleontological resources. Recreational resources include ecological features that provide fishing, hunting, and hiking to the public.
Dip	The angle between a planar feature, such as a sedimentary bed or a fault, and the horizontal plane.
Dissolution Rate	The rate at which a substance is dissolved in a fluid.
Dissolution Trapping	The trapping of CO_2 when it contacts the fluid formation and dissolves into the fluid. Also referred to as solubility trapping
Downhole Injection Pressure	Injection pressure at the point where CO_2 exits the well and is introduced to the injection zone formation(s).
Economic Resources	Surface and subsurface resources with economic value, including mineral and hydrocarbon reservoirs, forests, and croplands.
Endangerment	The construction, operation, maintenance, conversion, plugging, or abandonment of an injection well, or the performance of other injection activities, by an owner or operator in a manner that allows the movement of fluid containing any contaminant into a USDW, if the presence of that contaminant may cause a violation of any primary drinking water regulations or may adversely affect the health of persons.
Enhanced Coal Bed Methane Recovery	The process of injecting a gas (e.g., CO_2) into coal, where it is adsorbed to the coal surface and methane is released. The methane can be captured and produced for economic purposes; when CO_2 is injected, it adsorbs to the surface of the coal, where it remains sequestered.
Enhanced Gas Recovery	Typically, the process of injecting a fluid (e.g., water, brine, or CO_2) into a gas bearing formation to recover residual natural gas. The injected fluid thins (decreases the viscosity) or displaces small amounts of extractable gas, which is then available for recovery.
Enhanced Oil Recovery	Typically, the process of injecting a fluid (e.g., water, brine, or CO_2) into an oil bearing formation to recover residual oil. The injected fluid thins (decreases the viscosity) or displaces small amounts of extractable oil, which is then available for recovery.

Fault	Faults are breaks in the Earth's crust that occur as a result of when the crustal rock is either compressed or pulled apart. Faults may either serve as barriers or conduits to fluid flow, depending upon whether they are transmissive or sealed.
Flux Rate	The rate of transfer of fluid, particles, or energy across a given area.
Formation	A body of rock of considerable extent with distinctive characteristics that allow geologists to map, describe, and name it.
Fracture	A separation or discontinuity plane in a geologic formation, such as a joint that divides a rock segment into two or more pieces. Fractures can be caused by stress exceeding the rock strength.
Fracture/Fault Reactivation Pressure	The geologic formation pressure threshold that when achieved will cause re-opening of a sealed fault or fracture.
Geochemical Process	Geochemical processes refer to chemical reactions that may cause alterations in mineral phases.
Geologic Sequestration	The process of injecting captured CO_2 into deep, subsurface rock formations for long-term storage. This term does not apply to its capture or transport.
Geomechanical Processes	Processes that may result in alterations in the structural integrity of geologic material.
GS System	A system that is comprised of the confining system, the CO_2 stream, and the injection zone.
GS Footprint	The areal extent of the CO_2 plume and associated pressure front.
Hypercapnia	A physical condition involving an excessive amount of CO_2 in the blood.
Impact Category	Term for classifying groups that might experience adverse impacts. Impact categories include human health and welfare, atmosphere, ecological receptors, surface and ground water, and the geosphere.
Injection	The subsurface discharge of fluids through a well.
Injection Zone	A geologic formation, group of formations, or part of a formation of sufficient areal extent, thickness, porosity, and permeability to accommodate CO_2 injection volume and injection rate.
Injectivity	Injectivity characterizes the ease with which fluid can be injected into a geological formation.
Lateral Extent	The surface area of the confining system that overlies the GS footprint.
Leakage	The movement of CO_2 (or other fluids and gases) to the surface (for example, to the atmosphere or oceans).
Legislatively Protected Species	Species designated as threatened or endangered by State and federal government authorities.

Measurement, Monitoring, And Verification	Collectively, a comprehensive protocol for providing an accurate accounting of stored CO_2.
Mechanical Integrity	The absence of fluid-conducting openings within the injection tubing, casing, or packer (known as internal mechanical integrity), or outside of the casing (known as external mechanical integrity).
Mechanical Integrity Test	Evaluations used to confirm that a well maintains internal and external mechanical integrity. These tests are a means of measuring the adequacy of the construction of an injection well.
Migration	Subsurface movement of CO_2 (or other fluids) within or out of the injection zone.
Mineral Trapping	When injected CO_2 reacts with the formation waters and/or formation rocks to form carbon-containing minerals such as carbonates, thereby effectively retaining the CO_2 in the formation.
Mineralization	The chemical process involving the reaction of CO_2 with the formation waters and/or formation rocks to form carbon-containing minerals such as carbonates.
Mineralogy	The mineral content of a rock or geologic formation. Evaluating mineralogy can help determine whether metal and metalloid-bearing mineral phases (e.g., metal oxides, sulfides, carbonates) are present.
Molar Volume	The volume occupied by one mole of a substance (chemical element or chemical compound) at a given temperature and pressure.
Monitoring	Employing various technologies for the purposes of measuring quantities of injected CO_2, tracking the location and movement of injected CO_2 and other fluids, ensuring the effectiveness of injection wells, assessing the integrity of abandoned wells.
Open System	A system in which pressure levels associated with injection of CO_2 dissipate to background levels before reaching the physical boundaries of the system.
Other Sensitive Receptors	Ecological receptors that may be sensitive to exposure to CO_2, other stream constituents, brine, or other fluids that may result from GS activities but are not legislatively protected. These receptors may be vulnerable either because of their behavior (e.g., soil-dwelling organisms) or because their physiology makes them unusually sensitive to increased concentrations of released substances.
Packer	A mechanical device set immediately above the injection zone that seals the outside of the tubing to the inside of the long string casing. A packer may be a simple mechanically set rubber device or a complex concentric seal assembly.

Permeability	The ability of a geologic material to allow transmission of fluid through pore spaces.
Permit	An authorization, license, or equivalent control document issued by EPA or a State to operate an injection well. Permits may be individual permits (covering a single well) or area permits (covering multiple wells in one area).
Physical Capacity	The volume within a geologic formation that is available to accept CO_2.
Physical Trapping	When injected CO_2 rises owing to its relative buoyancy or the applied injection pressure, and reaches a physical barrier that inhibits further upward migration.
Plugging	The act or process of stopping the flow of water, oil or gas into or out of a formation through a borehole or well penetrating that formation.
Populations Covered By Executive Orders	A series of executive orders require proposed federal regulations and programs to specifically address potential impacts to environmental justice populations, children, and tribal governments.
Pore Space	Open spaces in rock or soil. In the subsurface, these are typically filled with water, brine (i.e., salty fluid), or other fluids such as oil and methane.
Porosity	A measure of the percentage of a rock that is occupied by pore space.
Precipitate	A solid separated from a solution, especially as the result of a chemical reaction (i.e., the reaction of minerals within the confining system with CO_2 and salt ions).
Preferential Adsorption Trapping	When micropores in certain geologic formations tend to adsorb CO_2 and displace other present gases to which they have a lower affinity.
Pressure Change	A change in force per unit area. Pressure changes are likely to be associated with the injection of CO_2 into the subsurface.
Pressure Equilibration	A state of balance achieved when formation pressure levels reached during injection return to the original formation pressure levels.
Pressure Spatial Area Of Evaluation	The pressure spatial area of evaluation is delineated based on the potential for subsurface pressure changes that are sufficiently significant to cause adverse impacts to overlying receptors (e.g., fluid displacement into an overlying aquifer).
Protected Or Sensitive Drinking Water Supplies	Drinking water supplies that are vulnerable to endangerment or contamination.
Receptor	A surface or underground feature whose presence within the CO_2 and pressure spatial areas of review could affect the vulnerability of adverse impacts in the event of unanticipated migration, leakage, or pressure changes.
Regional Groundwater Flow	The direction and rate of groundwater movement in the subsurface.

Release	Another term for leakage, the movement of CO_2 (or other fluids) to the surface (for example, to the atmosphere or oceans).
Remediation	The process of correcting any source of failure to stop or control undesired CO_2 movement if it occurs.
Residual Water Saturation	Retainment of water in pore space due to capillary forces.
Risk Assessment	An approach to measuring the probability and severity of consequences.
Safe Drinking Water Act	The main federal law that ensures the quality of Americans' drinking water. The Safe Drinking Water Act sets the framework for the Underground Injection Control Program to control the injection of fluids. EPA and states implement the UNDERGROUND INJECTION CONTROL Program, which sets standards for safe injection practices and bans certain types of injection.
Seismic Activity	Seismic activity is defined as the shifting of the Earth's surface due to changes at depth. Increased seismic activity can lead to earthquakes.
Seismic Technology	A monitoring approach that involves measuring the velocity and absorption of energy waves through rock and provide a picture of underground layers of rocks and reservoirs.
Seismicity	The episodic occurrence of natural or human-induced earthquakes.
Stratigraphic Position	The order and relative arrangement of a specific layer of rock that is recognized as a cohesive unit based on lithology, fossil content, age, or other properties.
Strike	The line representing the intersection of a planar feature with the horizontal.
Subsidence	Lowering, or "sinking," of geologic formations due to dissolution of formation minerals. Dissolution of formation materials can result from CO_2 acidification of formation waters.
Supercritical Fluid	A fluid above its critical temperature (31.1 degrees Celsius for CO_2) and critical pressure (73.8 bar for CO_2). Supercritical fluids have physical properties intermediate to those of gases and liquids.
Tectonic Activity	Natural activity involving structural changes to the Earth's geology.
Total Dissolved Solids	The measurement, usually in mg/L for the amount of all inorganic and organic substances suspended in liquid as molecules, ions, or granules. For injection operations, TDS typically refers to the saline (i.e., salt) content of water-saturated underground formations.

Tracer	A chemical compound or isotope added in small quantities to trace flow patterns.
Trapping Mechanism	A physical or geochemical feature in the geologic system that retains injected CO_2, immobilizing it under thick, low-permeability seals or by converting it to solid minerals.
Travel Time	The interval of time that is required for a fluid (e.g., CO_2 or brine) to migrate across the thickness of the confining system.
Tubing	A small-diameter pipe installed inside the casing of a well. Tubing conducts injected fluids from the wellhead at the surface to the injection zone and protects the long-string casing of a well from corrosion or damage by the injected fluids.
Underground Source Of Drinking Water	An aquifer or portion of an aquifer that supplies any public water system or that contains a sufficient quantity of ground water to supply a public water system, and currently supplies drinking water for human consumption, or that contains fewer than 10,000 mg/l total dissolved solids and is not an exempted aquifer.
Uplift	Rising of geologic formations due to increased pore pressure from injection.
Vulnerability Assessment	An approach to examining conditions that lead to increased or decreased susceptibility to consequences.
Water Quality	The characteristics of a source of water that determine its usefulness for a specific purpose.
Well	A bored, drilled, or driven shaft or a dug hole whose depth is greater than the largest surface dimension. Wells can be used for production, injection, or monitoring purposes.
Wellbore	See borehole.

APPENDIX A

Properties of Carbon Dioxide (CO_2)

This appendix provides a brief overview of the physical and chemical properties of CO_2 and a description of the supercritical phase in which CO_2 will be injected for GS. The properties discussed in this section are important considerations addressed in the VEF.

Physical Properties of CO_2

Carbon dioxide typically exists as a gas at normal pressure and temperature (i.e., at the earth's surface). It can be processed into a solid (i.e., dry ice) at temperatures below -55°C (-67°F). At very high pressure, CO_2 may exist as a solid, liquid, or a supercritical fluid. A substance may be a supercritical fluid at high pressure and temperature when the gaseous and liquid phases have the same density and cannot be further compressed with additional pressure. Carbon dioxide exists as a supercritical fluid at temperatures greater than 31.3°C and pressures greater than 73.9 bar (IPCC, 2005).

Chemical Properties of CO_2

Carbon dioxide is soluble in water, forming carbonate ions and acidity [CO_2 (g) +H_2O => H_2CO_3 (aqueous) => HCO_3^- + H^+ => CO_3^{2-} + $2H^+$] (IPCC, 2005, Chapter 6). The solubility decreases with increasing temperature and salinity and increases with increasing pressure. Solid hydrates may form in aqueous solutions of CO_2 at high pressure and temperatures below 11°C (IPCC, 2005).

Characteristics of Supercritical CO_2

Supercritical CO_2 is approximately one order of magnitude less viscous than water and oil and is highly mobile (Oldenburg et al., 2002a; GEO-SEQ Project Team, 2004; Wilson, 2004). Supercritical CO_2 is less dense and more buoyant than oil and 30% to 50% more buoyant than saltwater (Benson et al., 2002; GEO-SEQ Project Team, 2004; Wilson, 2004). As a result, injected supercritical CO_2 will rise to the top of depleted oil or deep saline

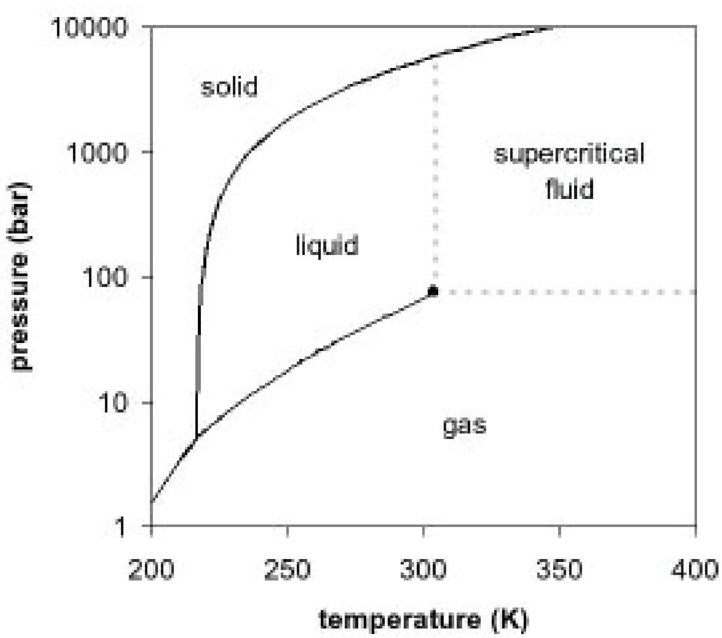

Figure A.1. Phase Diagram for CO_2

formations. In contrast, supercritical CO_2 is denser than natural gas, and will sink when injected in depleted gas reservoirs. As temperature increases, the density of supercritical CO_2 decreases at a given pressure, but increases with increasing pressure at a given temperature. Similarly, the viscosity of supercritical CO_2 decreases with increasing temperature at a given pressure, but increases with increasing pressure at a given temperature. As temperature and pressure increase with subsurface depth, the density and viscosity of supercritical CO_2 injected will be determined by the specific pressure and temperature conditions (Haszeldine, 2006). Finally, when CO_2 dissolves, it shares the physical properties of the substrate (e.g., saltwater) and no longer behaves independently (IPCC, 2005).

APPENDIX B

Comparison of Attributes: VEF, IPIECA, and IPCC

The VEF geologic attributes are similar to characteristics identified in GS summaries by IPCC (2006) and IPIECA (2007) as shown in the table below. However, there are two discrepancies between the IPCC and IPIECA summaries and the VEF. First, in the VEF, the seismic and volcanic risks in a proposed project area must be explicitly identified and considered. This potential pathway is not explicitly addressed in the IPCC and IPIECA guidelines, although their recommended consideration of faults and fractures would presumably include consideration of seismically active areas. Second, the IPCC recommendations explicitly request consideration of potential methane displacement from GS projects. In the VEF this is not explicitly addressed by a specific attribute. Rather, the VEF addresses this potential release as part of the CO_2 and Pressure Areas of Evaluation processes consideration of substances that could be released.

Table B.1. Comparison of Attributes/Pathways Identified as Being Likely to Affect Unanticipated Migration or Leakage from GS Projects

VEF geologic attributes	IPIECA storage site attributes[a]	IPCC potential emissions pathways and sources[b]
Lateral extent (of the confining system)	Effective seal provided by overlying caprock.	Local absence of cap rock.
Capillary entry pressure		Through the pore system in low permeability cap rocks if the capillary entry pressure is exceeded or if the CO_2 is in a solution.
Permeability	Permeable distribution is suitable for both injection and post-injection CO_2 migration.	Through the pore system in low permeability cap rocks if the capillary entry pressure is exceeded or if the CO_2 is in a solution.
Artificial penetrations (i.e., wells, mines)	New and existing wells will not compromise the integrity of the (caprock) seal.	Operational or abandoned wells or future mining of CO_2 reservoir.
Geomechanical processes or properties	Trapping mechanisms (capillary, solubility, and mineralization) are effective.	CO_2/water/rock reactions degrade cap rock.
Faults/fracture zones	Likelihood of contacted faults reactivating and potential for existing fractures to re-open.	Natural or induced faults and/or fractures.
Earthquakes, volcanoes, hot spots		
Physical capacity (of the injection zone)	Sufficient storage capacity.	Reservoir overfilling results in release from a spill point.

a. Source: Bulleted list in on page 23 of IPIECA (2007).

b. Source: Table 5.3 in IPCC (2006).