Framework for the Assessment of Interaction between CO2 Geological Storage and other Sedimentary Basin Resources

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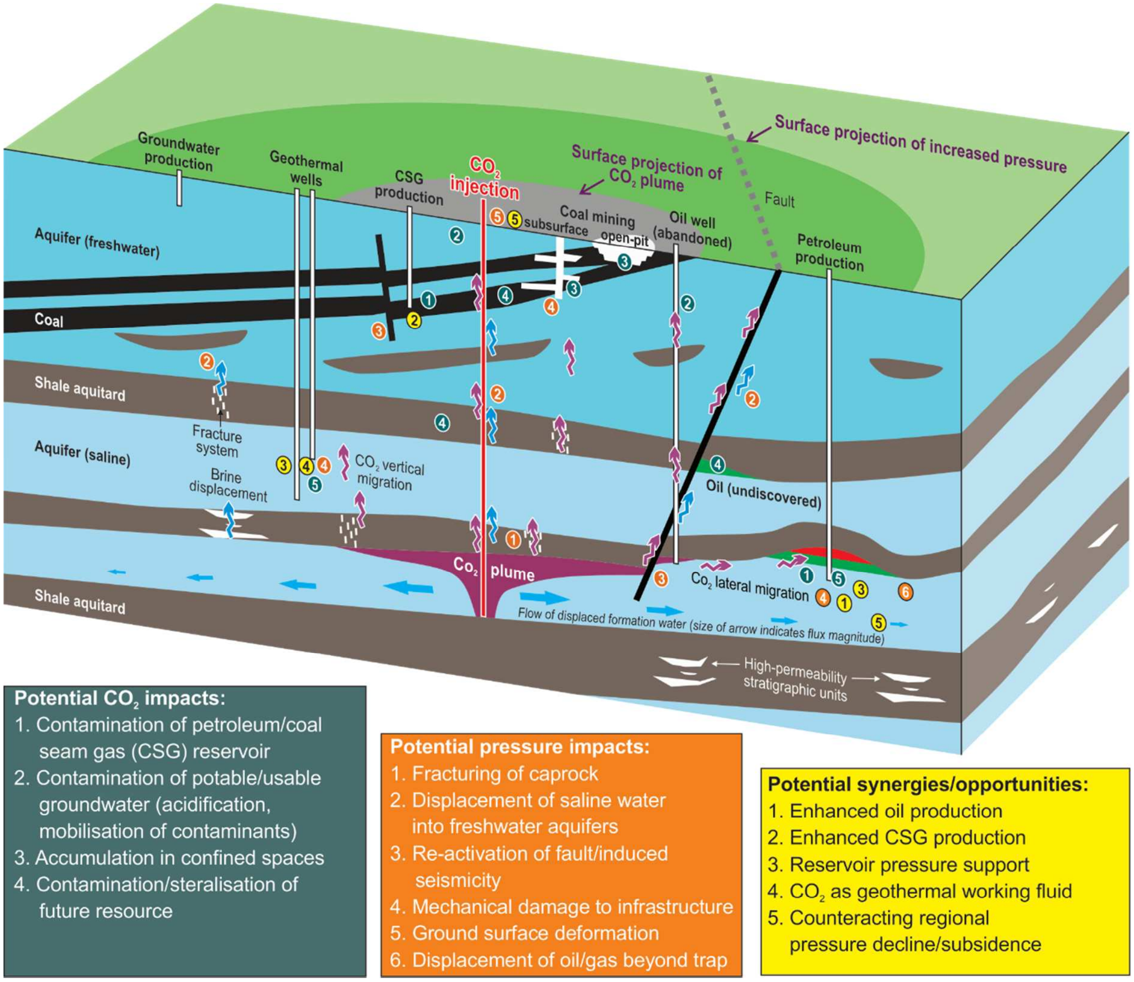

Potential CO_2 impacts:

1. Contamination of petroleum/coal seam gas (CSG) reservoir
2. Contamination of potable/usable groundwater (acidification, mobilisation of contaminants)
3. Accumulation in confined spaces
4. Contamination/sterilisation of future resource

Potential pressure impacts:

1. Fracturing of caprock
2. Displacement of saline water into freshwater aquifers
3. Re-activation of fault/induced seismicity
4. Mechanical damage to infrastructure
5. Ground surface deformation
6. Displacement of oil/gas beyond trap

Potential synergies/opportunities:

1. Enhanced oil production
2. Enhanced CSG production
3. Reservoir pressure support
4. CO_2 as geothermal working fluid
5. Counteracting regional pressure decline/subsidence

Managing the interaction between carbon dioxide storage and other basin resources should focus on preventing potential conflicts and enhancing synergies.

Environmental Impact Statement

Managing the development of multiple natural resources in a sedimentary basin has been becoming an increasing issue the last decade with the emergence of unconventional petroleum resources (e.g. coal bed methane, shale gas) and potentially large-scale sequestration of greenhouse gases. Sedimentary basins around the world considered suitable for carbon storage usually contain other natural resources such as petroleum, coal, geothermal energy and groundwater. Storing carbon dioxide would reduce the emissions of greenhouse gases to the atmosphere but would add to the competition for the use of pore space where other resource-based industries also operate. Managing potential impacts that industrial-scale injection of carbon dioxide may have on other resource development must be focused to avoid conflicts or enhance synergies where possible.

Framework for the Assessment of Interaction between CO_2 Geological Storage and other Sedimentary Basin Resources

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Abstract

Sedimentary basins around the world considered suitable for carbon storage usually contain other natural resources such as petroleum, coal, geothermal energy and groundwater. Storing carbon dioxide in geological formations in the basins adds to the competition for access to the subsurface and the use of pore space where other resource-based industries also operate. Managing potential impacts that industrial-scale injection of carbon dioxide may have on other resource development must be focused to prevent potential conflicts and enhance synergies where possible. Such a sustainable coexistence of various resource developments can be accomplished by implementing a Framework for Basin Resource Management Strategy (FBRM).

The FBRM strategy utilizes the concept of an Area of Review (AOR) for guiding development and regulation of CO_2 geological storage projects and for assessing their potential impact on other resources. The AOR is determined by the expected physical distribution of the CO_2 plume in the subsurface and the modelled extent of reservoir pressure increase resulting from the injection of the CO_2. This information is used to define the region to be charactised and monitored for a CO_2 injection project. The geological characterisation and risk- and performance-based monitoring will be most comprehensive within the region of the reservoir containing the carbon dioxide plume and should consider geological features and wells continuously above the plume through to its surface projection; this region defines where increases in reservoir pressure will be greatest and where potential for unplanned migration of carbon dioxide is highest. Beyond the expanse of the carbon dioxide plume, geological characterisation and monitoring should focus only on identified features that could be a potential migration conduit for either formation water or carbon dioxide.

1. Introduction

Human activities are producing ever-increasing amounts of greenhouse gases, particularly carbon dioxide, which are being released to the atmosphere and which are considered to be one of the most significant factors in causing extreme climatic variability. Geological storage of carbon dioxide is one of the primary greenhouse gas reduction strategies available as identified by the Intergovernmental Panel on Climate Change[1], and is projected to contribute about 17 percent reduction of carbon dioxide emissions to the atmosphere by 2050[2]. Prospective sites for geological storage of carbon dioxide target sedimentary basins as they provide the most suitable geological settings for safe, long-term storage of greenhouse gases.

Sedimentary basins commonly host various natural resources that may occur in isolated pockets, across widely dispersed regions, in multiple locations, within a single layer of strata or at various depths. The primary basin resources are groundwater, oil and gas, unconventional gas, coal and geothermal energy (Figure 1). Other resources include gas hydrates, mineral and oil sands, salt, potash, uranium, diamonds and other sediment hosted mineral deposits. Understanding the nature of how these resources are distributed in the subsurface is fundamental to managing basin resource development and carbon dioxide storage. Surface infrastructure and land use also impact subsurface resource development and must be considered in any basin resource management strategy. Natural resources can overlap laterally or with depth and have been developed successfully for decades. Geological storage of carbon dioxide is another basin activity that must be considered in developing a basin-scale resource management system to ensure that multiple uses of the subsurface can sustainably and pragmatically co-exist.

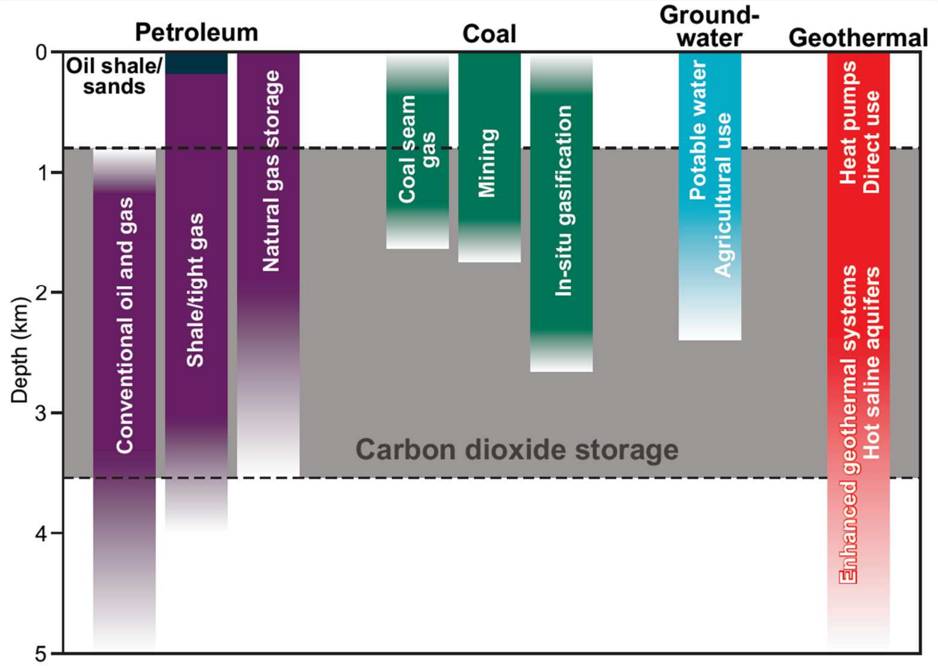


Figure 1. Typical depth ranges for the development of various subsurface resources (modified from Field et al. [3]).

2. Potential Impacts of Carbon Dioxide Injection

Carbon dioxide injection has been employed in the oil and gas industry for enhanced production purposes since the 1970s. Carbon dioxide storage with the specific goal of reducing greenhouse gas emissions commenced in 1996 at Sleipner in the North Sea, where it has been in successful operation for more than 15 years [4]. Carbon dioxide storage sites should be chosen based on geological settings that have highly effective containment characteristics. For example, storage complexes comprise a reservoir into which the carbon dioxide is injected and one or more rock layers that serve as caps or seals to contain the carbon dioxide. So how can injection of carbon dioxide impact another basin resource? Two general processes need to be considered: a) migration of carbon dioxide and b) increase of pressure (Figure 2). Carbon dioxide may migrate laterally or vertically outside the planned storage complex. If migration did occur it is possible that some carbon dioxide may comingle with natural gas or enter a coal seam. Another potential impact is that once a reservoir is used for geologic storage it may limit the use of that formation for future resource development such as for geothermal energy potential or undiscovered resources.

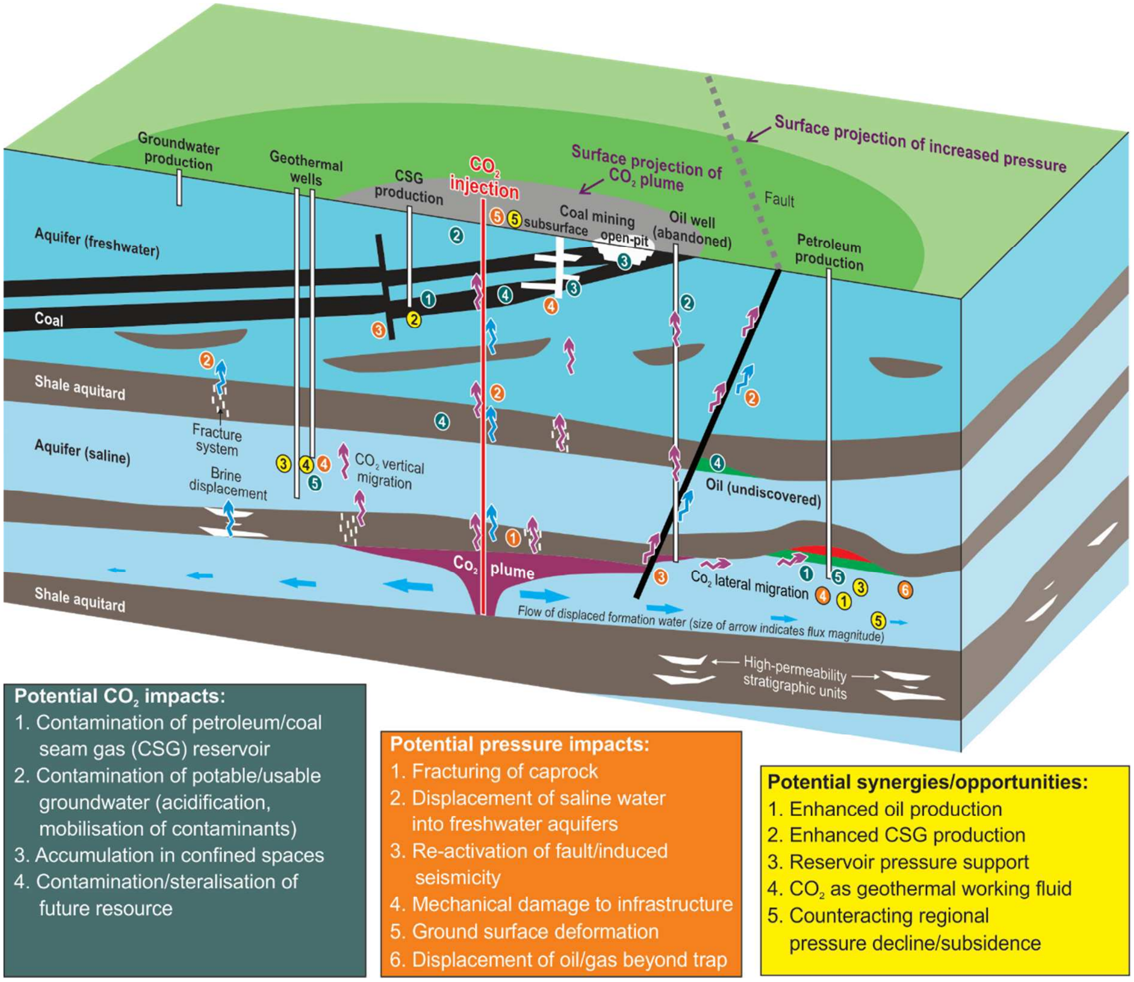


Figure 2. Potential impacts of CO_2 geological storage on other basin resources (Reproduced from K. Michael et al., EAGE Third Sustainable Earth Sciences 2015 Conference, DOI: 10.3997/2214-4609.201414262).

Injecting carbon dioxide into the subsurface increases pressure in the reservoir that, although very unlikely, could push saline formation water vertically along a wellbore or through existing fractures into groundwater sources [5] or, if uncontrolled, cause fractures in top seals preventing further use of storage. Alternatively, increased pressure may provide support for oil or gas fields that have had their pressure reduced by production, and may even limit the decline of groundwater levels in stressed aquifer systems [6].

2.2 Evaluation of containment risks

Regardless of whether there are other basin resources present in the vicinity of a storage site, for CCS to be an effective mitigation option for greenhouse gas emissions to the atmosphere containment of the injected carbon dioxide needs to be ensured. Vertical containment is usually provided through the presence of geological units that cap the storage reservoir such as shales, anhydrites or salts which can greatly restrict any upward flow of fluids because they typically have extremely low permeability [7]. These types of strata are among the most effective sealing units or cap-rocks and they must be thick enough to provide a barrier to any buoyancy-driven vertical movement of reservoir fluids such as carbon dioxide. These are also the types of rocks that retain oil and gas in reservoirs for millions of years. Lateral containment of the injected carbon dioxide may result from undulations in the sealing unit, lateral decreases of permeability or changes in lithology within the storage formation, or juxtaposition of the storage unit with low-permeability rocks along faults; these containment configurations are all analogous to conventional traps for hydrocarbons. If no lateral barriers are present, the distribution of carbon dioxide would be limited by residual trapping, dissolution into formation water and reactions with the reservoir matrix to form new minerals.

Therefore any undesired incursion of carbon dioxide into areas or levels having other basin resources would only result if migration unexpectedly occurred beyond the limits of the defined storage area. Some of the possible ways this undesired migration may take place are:

- Insufficient fault membrane sealing can result in across-fault flow where permeable reservoirs are self-juxtaposed [8], which can lead to CO_2 lateral migration to adjacent compartments. An assessment of the unit's juxtaposition pattern and a model of the fault zone lithology are required to evaluate across-fault flow.
- Insufficient fault sealing potential can result in up-fault flow and top seal bypass; this can lead to CO_2 leakage and migration to the overburden or to the ground surface. An assessment of the fault zone lithology and the in-situ stress on the fault plane are required to evaluate up-fault flow.
- Low top-seal capacity due to insufficient threshold capillary entry pressure of the caprock can be overcome by the pressure build-up in the CO_2 column due to injection; this can lead to CO_2 leakage and migration to the overburden. An evaluation of top seal mercury injection capillary pressure is usually required to assess the CO_2 column height that can be trapped by a shale-rich caprock.
- Insufficient top-seal mechanical integrity can result in the development of natural hydraulic fractures once the pore pressure variation induced by CO_2 injection exceeds the minimum horizontal stress plus the tensile strength of the rock [9], possibly leading to leakage of CO_2

from reservoirs and migration to the overburden. The definition of the Mohr-Coulomb and Griffith-Coulomb failure criteria, based on the caprock strength data and coefficient of internal friction, are required to evaluate top seal integrity.

- Interaction between injected CO_2 and abandoned wellbores may result in degradation of well cements and casing, potentially creating vertical leakage pathways from the storage horizon to the overburden or to the ground surface [10]. An analysis of well geomechanics and the potential stresses and strains around wellbores can be performed to investigate the mechanical integrity of wellbores. Static and dynamic laboratory experiments may be employed to investigate wellbore cement behaviour as a result of exposure to a CO_2 rich liquid. Downhole geophysical logs (i.e. cement bond logs) can be used to assess the integrity of wells in the vicinity of a CO_2 injection site.
- Unexpected lateral migration of the injected CO_2 due to inadequate geological mapping of the confining top surface, unknown channels, or unpredicted vertical flow barriers in the form of lithological facies changes or sealing faults.

A primary focus of the site assessment process is always the evaluation of top seal or vertical containment characteristics, existence of fault seals and determination of well-bore integrity within the area impacted by CO_2 injection. Any potential points of weakness in the geological containment system identified during the systematic risk management process as part of the general assessment should be prioritised in the monitoring, verification and mitigation program.

2.3 Potential impacts on groundwater resources

Groundwater is an essential resource for much of the world as a source of drinking water and for agricultural use. The term groundwater can sometimes be confusing however, as it may mean different things to different industries, technical disciplines and government departments. To a hydrologist and also general public, groundwater generally connotes shallow aquifers that contain water suitable for drinking or agricultural use. To a geologist and hydrogeologist, groundwater may include all water contained in rocks from near-surface to great depth, and many of these geological formations contain brines or highly saline water (often referred to as saline aquifers or saline formations) unsuitable for drinking, agriculture or even much industrial use. Depending on jurisdiction the salinity of groundwater constrains its possible usage: potable water is usually less than 1000 mg/l of total dissolved solids (TDS), water for irrigation or domestic washing purposes less than 2,000 mg/l, stock watering less than 7000 mg/l, and water having greater than 10,000 mg/l TDS is generally used only for specific industrial purposes. Highly saline waters having greater than 100,000s mg/l TDS are usually found only in deep portions of sedimentary basins and are sometimes used for recovery of mineral content such as potassium for fertilizers.

Sedimentary basins may have multiple groundwater requirements from housing, agriculture, mining, and petroleum operations that place stresses on deep aquifers and shallow groundwater. Carbon dioxide storage programs usually target deep strata, typically saline-water bearing aquifers in limestones or sandstones. It should be noted that having saline formation water is not a requirement for storage, nor is all deep water necessarily highly saline. Groundwater is an integral part of the hydrologic cycle and, although through this cycle it is replenished, the quantity and quality of groundwater requires careful management to ensure its sustainable use for social and environmental needs. Thus the existing knowledge of a basin's usable groundwater distribution, jurisdictions and existing policies must be reviewed for planning and management of potential resource interactions involving geological storage of carbon dioxide.

Lemieux [11] (and references therein) described the current state of knowledge on potential impacts of CO_2 geological storage in deep saline aquifers on shallow groundwater resources and determined that the environmental impacts appear to be low. Possible consequences include the dissolution of carbon dioxide into saline or non-saline formation water, and pressure changes within the aquifer. The effect of dissolution may lower the pH of the aquifer water through the formation of carbonic acid. How much carbon dioxide dissolves into the water relates to the salinity, temperature and pressure – or depth, of the aquifer. A change in pH of the formation water may result in reactions with minerals in the host rock such as dissolution of some minerals or precipitation of other minerals as cements. The extent to which such reactions may occur again depends on temperature, salinity and the rock matrix itself. These water-mineral reactions have the potential to degrade or enhance water quality and flow characteristics within the aquifer, and are highly site specific. One concern is that minerals containing heavy metals may dissolve increasing the heavy metal content of the groundwater, but this again depends on the specific minerals present in a given aquifer. Additionally, pressure may be increased within some reservoirs during injection whereas pressure changes will be minimal in others. In the instance in which pressures do increase this potentially could be sufficient to push brines up old wells and into shallower aquifers. Other less likely, but potential and site specific, impacts could be the incursion of supercritical carbon dioxide into organic-rich rocks that may dissolve and transport organic material into groundwater, or the reduction in ability to extract (abstract) groundwater due to clogging from mineral precipitation.

Methods for the detection and remediation of impacts on groundwater quality are well-established in the groundwater industry. Carbon dioxide, however, occurs naturally in shallow groundwater and has relatively large natural fluctuations in concentration making the early detection of small leaks challenging. Direct detection through water sampling (for pH or salinity changes) or pressure monitoring is limited by the location and density of the well monitoring network. Alternatively, most remote monitoring techniques including near-surface geophysical methods have broader coverage, but are relatively coarse so that small leaks are unlikely to be observed. A critical review of the state of art in monitoring and verification of CO_2 storage projects is provided by Jenkins et al.[12].

It should be noted that while the majority of onshore sedimentary basins contain potable groundwater, this is not the case for most offshore areas. In the case of offshore storage potential impacts on the marine environment and resources would need to be considered.

2.4 Potential impacts on petroleum resources

Estimates of conventional hydrocarbon resource potential are available for many hydrocarbon-prone basins thereby minimizing the need for extensive analysis of petroleum data and exploration models. Hydrocarbon resources are classified according to the Society of Petroleum Engineers' Petroleum Resources Management System [13] as reserves (commercially recoverable), contingent resources (potentially recoverable but not yet commercial) and prospective resources (estimated but undiscovered). This classification scheme provides a useful framework for carbon storage projects to review the hydrocarbon potential of a basin during site screening and selection process.

It gives insight into reserves and contingent resources that reflect the proven commercial potential of the basin. The undiscovered, or future, potential of the basin is presented as prospective resources. It is not uncommon, however, that a new play emerges in a mature hydrocarbon basin that changes the assessment of hydrocarbon potential. A recent example of this is the emergence of unconventional resources such as shale gas and tight oil reservoirs. Therefore, it is important for carbon dioxide projects to consider emerging resources in the assessment of potential impacts on hydrocarbon resources of a basin. For example, regional shales are considered important seals for carbon dioxide storage, but could also be a prospective unconventional gas resource in the future. Production of shale gas and associated hydraulic fracturing procedures are not compatible with maintaining effective sealing capacity for a carbon dioxide storage site [14].

Depleted or depleting hydrocarbon reservoirs make excellent injection targets for geological carbon dioxide storage due to suitable reservoir properties, proven containment security and abundance of relevant subsurface data sets[15]. In considering this storage option, basin resource management may be used to identify potential carbon dioxide storage sites based on timing around declining production of individual oil or gas fields and their ensuing availability for storage. Carbon dioxide can also be injected into certain maturing oil fields to rejuvenate declining production as has been performed since the 1970’s and in now over 130 fields globally, 90 per cent of these being in North America [16].

Liquid-like, or supercritical, carbon dioxide is a highly effective solvent for organic compounds, and injecting supercritical carbon dioxide into existing oil fields has been proven to dramatically increase oil production. Thus, screening oil fields within a basin for suitability for carbon dioxide – enhanced oil production (CO_2 EOR) can reveal opportunities for the synergistic co-existence of resources. An initial CO_2 EOR operation within a basin may also serve as an “anchor” to lower the cost of entry for smaller sites through its existing investment in transport and capture infrastructure. Not all declining oil fields are candidates for CO_2 EOR, however, and many individual hydrocarbon fields will not provide the capacity or volume necessary for a long-term commercial storage operation. Although the injection of carbon dioxide to enhance gas recovery (EGR) and enhance coal seam gas (ECSG) production may also provide opportunities for joint resource exploitation and storage, these processes have only had limited application and marginal economic and operational successes to date.

Developing and operating large-scale carbon dioxide storage sites with ongoing hydrocarbon production and exploration within a basin can be managed through planning, modeling and monitoring, although prospective future resources do present additional uncertainty. In general, any potential interaction between carbon dioxide storage and hydrocarbon reserves should be avoided. Potentially unfavorable impacts resulting from carbon dioxide incursion into hydrocarbon resources would include carbon dioxide contamination of the reservoir, disturbance of reservoir equilibrium, and impacts on the facilities and operations. These impacts will have commercial consequences requiring new investments, increasing operation costs and compromising profits due to decreased production, degraded hydrocarbon quality or increased production costs. Remedial measures are generally limited once the interaction occurs but some viable options include termination or reconfiguration of injection, drilling of pressure relief wells, installing hydraulic barriers, and separation of carbon dioxide at a surface facility and reinjection at a different location.

2.5 Potential impacts on coal and coal seam gas resources

Both coal and coal seam gas (CSG) are expected to be significant resource extraction industries for the foreseeable future. Thus basin management to avoid conflict between carbon dioxide storage sites and coal-based resource extraction is of paramount importance. To identify whether an economic resource of coal or CSG exists close to a planned carbon dioxide storage project, coal and gas quality and quantity may be determined from drill-hole, logging, laboratory assay and modelling data. Even today, knowledge about the distribution of this important resource may be limited in some basins where data are sparse; alternatively there may be extensive data available in others and each case reflects the level of resource exploitation. Knowledge of the current situation should not presume that other deep or sparse coal or gas may be of future value as technologies improve; thus a full technical and spatial assessment of potential carbon dioxide interaction with coal based resources is important. Coal is currently extracted from open cut mines to about 300 m and from underground mines to depths of almost 1000 m. CSG gas may be extracted with current technology from depths up to 1200 m. Therefore, both of these resources overlap with depths greater than 800 m which are typically suitable for carbon dioxide storage sites so that basin management strategies are needed to avoid potential conflict with resource development.

During site characterisation for carbon dioxide storage consideration of the location and geological setting of onshore coal deposits and mines within the AOR should minimize any potential interaction between these activities. The impact of injected carbon dioxide encroaching into a coal deposit or seam will not reduce the value or quality of the coal itself; however, the carbon dioxide could displace methane from coal which would reduce or negate the value of the coal for CSG exploitation. Other hydrocarbons that could be mobilised from coal by supercritical CO_2 include poly-aromatic hydrocarbons (PAHs) which have the potential to adversely affect groundwater quality even at relatively low concentrations [17].

Carbon dioxide, has a higher affinity to be adsorbed onto coal than does methane which is the basis behind enhanced coal seam gas (ECSG) production. ECSG to date, however, has had limited technical or economic success in part because injection of carbon dioxide is difficult and causes swelling and plugging of the coal cleats. This would suggest that unplanned migration of carbon dioxide into coal seams would have limited extent or likelihood. Leakage of carbon dioxide into an underground mine provides more serious concerns as it could act as an asphixiant. Although the likelihood of this occurring is extremely low, the consequences are potentially severe. Further, if the migrating carbon dioxide displaces methane in the coals this could represent an explosion hazard. Any such leakage or migration of carbon dioxide into a coal mine, however, would probably be slow and ventilation and air-quality testing in modern mines should identify and mitigate potential issues. By providing a mine or CSG facility with ongoing monitoring and modelling data safety procedures can be dedicated toward monitoring any potential carbon dioxide influx.

A recent study by Busch et al. [18] proposes some unconventional storage options such as CO_2 storage in abandoned coal mines, through CO_2 sorption either to the residual coal, organic matter and bedrock, or sorption to mining waste before its disposal. Another concept would be using fly ash with high CaO content to bind CO_2 through mineral carbonation [19].

2.6 Potential impacts on geothermal resources

Possible interactions between carbon dioxide storage and resources for geothermal energy production are currently less well-defined than for other resources. Many nations want to increase the geothermal resource component of their “energy supply mix”, and the potential for large-scale geothermal energy projects using heat from sedimentary basins is well documented. Thus there are three main short-term considerations for impacts of carbon dioxide storage programs on potential geothermal resources:

1. Competition for tenure based on future potential for geothermal resources,
2. Potential conflict between CCS and small-scale heat exchange projects, and
3. Potential advantages of co-location and joint development of geothermal and CCS projects.

CO_2 geological storage and geothermal energy production both result in a) decreasing subsurface temperatures and b) change in pressure; hence cumulative impacts need to be considered when assessing temperature and pressure effects on production efficiency, injectivity, as well as reservoir and seal integrity. Examples where co-location or some form of synergy between geothermal, carbon storage and other basin resource developments may exist are listed below.

- Pressure management wells may be needed for CCS projects (e.g. the Gorgon project in Western Australia)[20] to control reservoir pressures. Heat could be extracted from the produced water before re-injection. Alternatively, the water could be processed further (i.e. desalinated) and used in agriculture or industry, as a cooling agent or for water supply.

- Injection of CO_2 will pressurise a reservoir. This could benefit a co-located geothermal project (i.e. low depressurization required in the abstraction wells). That is, a mutual benefit may be derived from an integrated CCS and geothermal precinct. The benefit may also be realized by a reduction in risk by coordinated distribution of pressure within subsurface reservoirs (e.g. reduce environmental risk).

- Using CO_2 as a working fluid for geothermal projects was proposed by Pruess[21, 22], and coupling of geothermal energy extraction with CO_2 geological storage were investigated by Elliot et al. [23].

- At least some of the infrastructure and site characteristics required for CO_2 sequestration and geothermal well field development are common (e.g. pumping stations, pipe lines and wells, permeable sediments etc). A large integrated CCS and Geothermal project may have economies of scale compared to separate projects. The longer term economics of such joint operations must be carefully considered.

Even if the current potential for development of both resources is low, the possibility for large scale development of geothermal resources must be considered and documented in the planning stage of any CCS project and then reviewed periodically throughout the life of the project.

Many of the activities that will help mitigate risk or identify possible benefits for geothermal resource development and CO_2 sequestration are already identified as parts of any best practice characterisation, monitoring and risk assessment process for CCS projects. Additional activities that may be necessary would include: (i) background research for characterisation of existing geothermal resources/activities, (ii) adequate temperature measurements in new CCS wells, (iii) the addition of a hydrothermal component to numerical modelling of CO_2 injection, (vi) thermal property measurement on core samples and (v) include time lapse temperature logging/measurements for new and or existing CCS wells. Again, it is likely that a hydrothermal component may be a requirement for any multiphase hydraulic, mechanical and chemical numerical modelling that would typically be completed for a CCS project. In this case the model could be run to identify possible impacts or benefits for nearby existing or potential geothermal developments. Ultimately each CCS project is unique and should independently carry out a risk-benefit analysis in relation to geothermal resources.

3. Framework for Basin Resource Management Strategy

Existing regulations for carbon storage, for example in Europe[24] and Australia[25], are largely concerned with storage safety and environmental protection by requiring appropriate monitoring systems and mitigation options. The potential interaction between carbon storage and other resource developments is rarely addressed in detail. A generalised workflow shown in Figure 3 can be used for evaluating resource - storage usage and potential interactions and forms the basis for a Framework for Basin Resource Management Strategy (FBRMS). The FBRMS was designed around a complementary Vulnerability Evaluation Framework (VEF) for Geologic Sequestration of Carbon Dioxide developed for the United States by the USEPA [26].

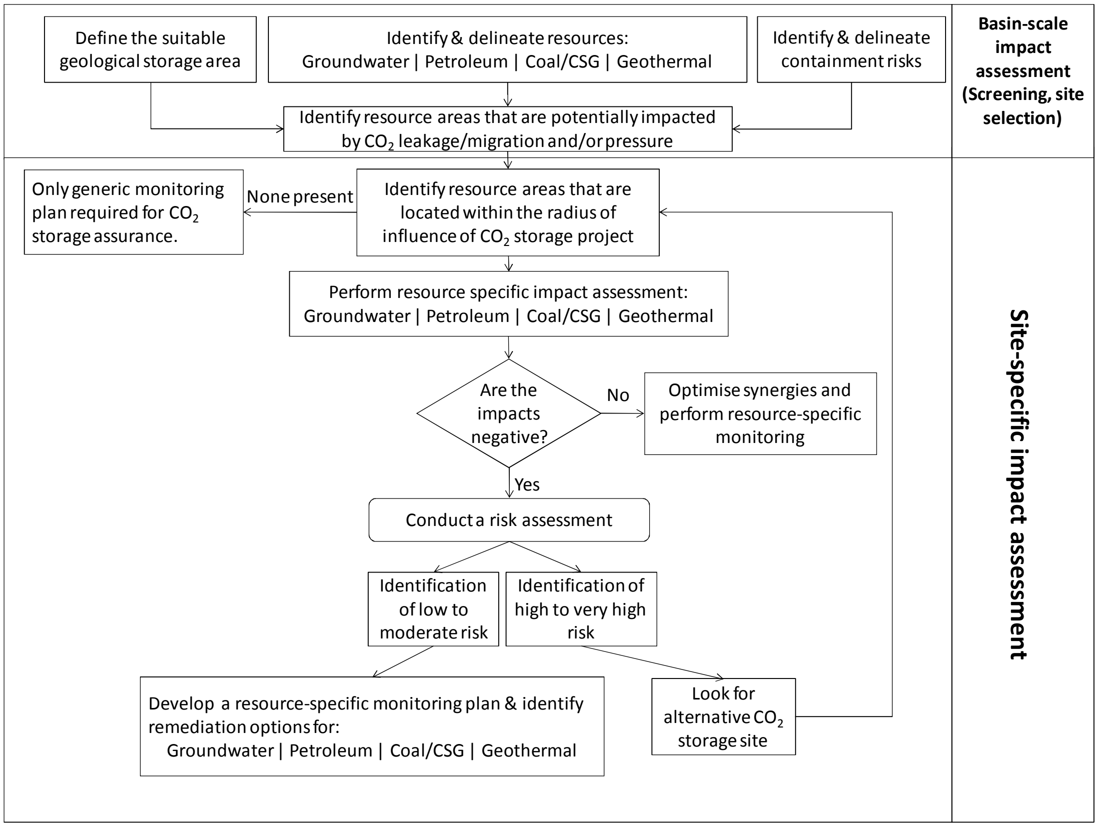


Figure 3. High-level workflow for the assessment of potential interaction of CO_2 geological storage with other basin resources (modified from K. Michael et al., EAGE Third Sustainable Earth Sciences 2015 Conference, DOI: 10.3997/2214-4609.201414262).

The principal theme for the FBRMS is to assess what basin resource – storage interactions are likely and to evaluate how they may be best managed. The earliest steps in the workflow are around the identification of areas of potential interaction and assessment of whether any potential interaction between CO_2 geological storage and other resources may be adverse, beneficial or benign. As regional basin assessments progress into more spatially focused evaluations, correspondingly more detailed characterisation on potential resource overlap will be required. For regions having potential for resource conflicts a basin resource management plan may be required, and the appropriate regulator would need to decide on the priority of each resource and, if parallel development is not feasible, the order in which resources should be exploited.

Ensuring the long term feasibility of a geological site for carbon dioxide storage and minimising unintended impact on other resources underpins most of the associated site-specific planning and development activities of any storage project. Proponents will employ systematic risk evaluation throughout the project life that includes ongoing monitoring of the storage complex and verification that the greenhouse gases are contained and storage is progressing as predicted. The FBRMS is not intended to represent a quantitative risk assessment of impacts from carbon dioxide injection, nor does it prescribe any site-specific assessment methodologies. Rather, the FBRMS represents a step toward integrated resource management that may be considered by regulators, CCS operators and other technical experts, at varying stages of project development. It is expected, however, that the workflow will be instructive for developing site-specific assessment programs to identify aspects that require in-depth evaluation for project design, risk characterisation, data acquisition, monitoring and management. The FBRMS may also serve as a reference document for regulators responsible for approving geological storage sites and proponents appraising storage operations. Detailed technical information and the regulatory requirements within a respective jurisdiction would be needed to apply the FBRMS to a specific storage situation.

3.1 Basin-scale interactions between geological storage of carbon dioxide and other resources

Fundamentally a basin-wide resource impact assessment is based mainly on the geographic overlap between the various resources identified with a basin. The way in which resources are defined and delineated is unique for each resource, and standard methods and classifications typically exist either nationally or internationally for the assessment and mapping of resources. A global example would be the regularly updated World Petroleum Assessment by the United States Geological Survey, which frequently publishes petroleum resource assessment reports for different regions of the world [27]. Generally, federal, state or provincial agencies, often geological surveys, perform the assessments for various resources in their respective countries.

In the context of geological storage of carbon dioxide a regional resource assessment would first map areas within a sedimentary basin considered suitable for storage. Examples for such assessments can be found for North America[28], Brazil[29], Australia[30], Europe[31], South Africa[32], and China[33]. Generic basin characteristics that impact the suitability for carbon dioxide storage were defined by Bachu [34] as a suite of fifteen criteria that include technical and non-technical parameters such as the tectonic nature and geothermal and hydrogeological regimes of the basin, but also the level of infrastructure, political stability and public attitude. Another significant consideration regarding suitability is the presence of other basin resources, of which some may become more, or less, significant with new discoveries, advances in technologies or changes in economic outlook. From the perspective of resource interaction it is interesting to note that large hydrocarbon potential, shallow coal systems and low geothermal gradients correspond to high suitability with respect to potential geological storage sites.

Technical requirements for storage suitability of carbon dioxide are that:

- the basin has enough capacity to store the planned volume of carbon dioxide to be captured;
- the storage reservoir has characteristics (porosity and permeability) that will allow the carbon dioxide to be injected at the required rate; and
- the injected carbon dioxide will be securely retained within the storage container for 100s to 1000s of years.

In addition, with increasing pressure deeper in the Earth’s crust the carbon dioxide becomes denser and transitions from a gas to liquid-like supercritical fluid deeper than about 800 meters. By targeted storage depths deeper than 800 m the carbon dioxide will remain in this dense state which maximises storage capacity and minimizes the buoyancy-drive to rise. The carbon dioxide will be retained in the storage reservoir by a cap rock that has low permeability (such as a shale or anhydrite) or within a large volume of rock sufficient to residually trap the injected greenhouse gas. As part of the storage site selection process, the suitable regions would be compared with the occurrence of other resources and the potential for resource overlap would be assessed as high, medium or low. This provides a first-order identification of potentially vulnerable areas in which the impact of a storage site on other resources would need to be considered. At this early stage of characterisation an area deemed to have high potential for resource interaction would not automatically imply that this is a ‘no-go area’ for geological storage of carbon dioxide. Further work would be needed to specify what operational and monitoring strategies may be needed to avoid resource interaction when selecting a particular carbon dioxide storage site.

Subsequent steps involved in basin-resource assessment include the identification and mapping of areas having present or future resource development potential. For each type of resource the assessment is unique and must provide an estimate of resource quantity and quality, describe the key rock and fluid properties, provide an economic value of the resource and identify the various regulatory controls that apply to the extraction of the resource.

Initially the assessment is a 2-D exercise identifying geographical overlap without consideration of the vertical separation of resource and potential storage locations. In other words, the basin-scale assessment of potential resource impacts does not differentiate between lateral interactions such as migration of carbon dioxide into other resources within the same stratigraphic horizon, or vertical communication in which brine or carbon dioxide migrates into underlying or overlying resources. Additional studies to characterise geological structures, map the types and distribution of strata, perform static and dynamic modelling, monitoring and risk evaluation are used in assessing the long-term containment security of a carbon dioxide storage site. These activities are also essential to understanding and managing potential impacts of storage activities on other basin resources and vice versa.

Injected carbon dioxide may impact other resources by migrating laterally or vertically outside the area of the planned storage complex. Such migration may potentially contaminate another resource, such as comingling with natural gas or entering a coal seam, or may effectively sterilize a region from further development such as in an area having prospective geothermal energy resources. Whereas these particular impacts would occur at depth within the basin, vertical migration into near-surface groundwater or coal mines may pose environmental or even health concerns. Carbon dioxide injection into the subsurface would generally increase pressure in the reservoir which, if uncontrolled, could result in fracturing of top seals or possibly displace brine upward along permeable pathways into shallower, usable groundwater sources. Alternatively, increased pressure may provide support for producing oil or gas fields, and may limit the decline of groundwater levels in hydraulically-stressed aquifer systems.

By overlapping the storage suitability map with resource distribution maps, areas of low, intermediate and high potential for resource interaction may be identified. Alternatively, these areas could be characterised as having low, intermediate or high vulnerability to the impacts of carbon dioxide injection.

Although one of the most critical selection criteria for a CO_2 injection site in a saline aquifer is the presence of a lateral confinement mechanism, it is important to assess the injection zone within the context of the entire basin hydrostratigraphic framework. Assessing the potential for communication with over- and underlying hydrostratigraphic units is particularly important. If there is geographic overlap of subsurface CO_2 storage operations and current or future resource developments (e.g. groundwater, petroleum, geothermal, waste disposal), the risk of interaction between these operations needs to be predicted and addressed by an appropriate monitoring plan. Even if the potential for leakage from a CO_2 storage horizon is negligible, competition for land access may nevertheless preclude co-operations. On the other hand, as many other subsurface resource developments involve aquifer depressurisation by formation fluid production, there could be cases of mutual benefit leading to a synergy between these and CO_2 injection operations. Evaluation of CO_2 storage opportunities in aquifer systems may need to take into consideration the following additional basin features (Figure 4):

1. No resource conflicts (at present/in the future),
2. Development of other resources in the same aquifer at some lateral distance from the CO_2 storage site (at current/in the future), or
3. Development of other resources in over- or underlying stratigraphic units (at current/in the future.

Development of other basin resources in the vicinity of a CO_2 storage site may require complicated numerical simulations or analytical models capable of accounting for multiple pressure sources and/or sinks.

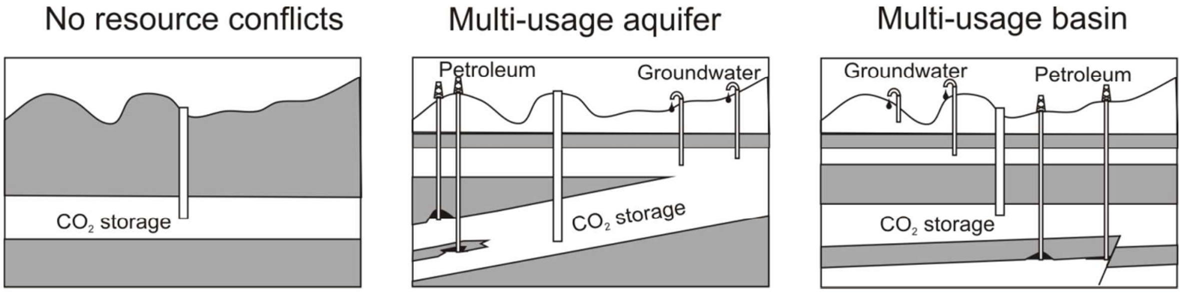
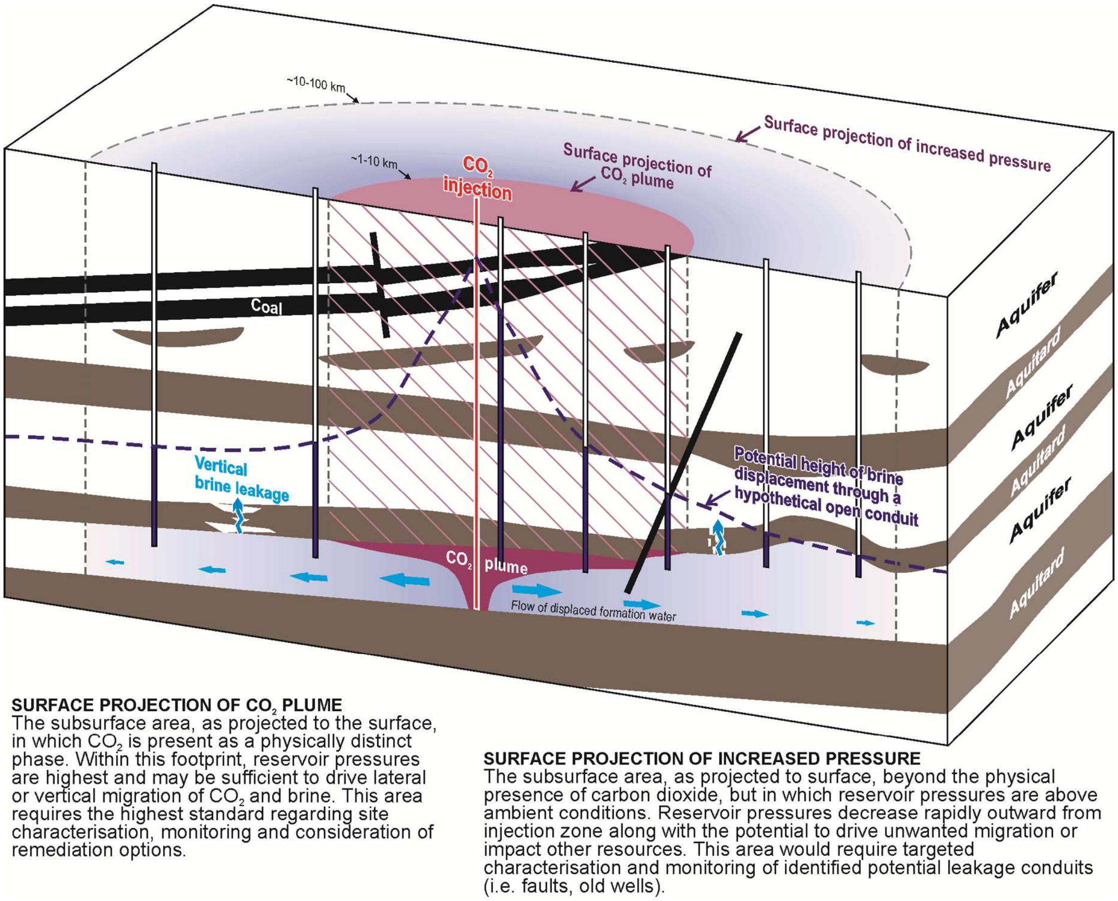


Figure 4. Illustration of different storage scenarios related to potential resource conflicts.

3.2 Site-specific impact assessment

The Area of Review (AOR), also known as Spatial Area of Evaluation [26] or Area of Potential Impact [35], is an important regulatory concept that defines the monitored area for carbon dioxide storage. The AOR includes the surface projections of the carbon dioxide plume, that is the physical presence of carbon dioxide in the subsurface, and the volume in the reservoir subjected to pressure increase beyond the plume itself (Figure 5). The focus of a resource management strategy should be within the defined AOR and, as suggested by Birkholzer et al. [36] follow a tiered approach based on the likelihood of impact occurrence.



SURFACE PROJECTION OF CO_2 PLUME
The subsurface area, as projected to the surface, in which CO_2 is present as a physically distinct phase. Within this footprint, reservoir pressures are highest and may be sufficient to drive lateral or vertical migration of CO_2 and brine. This area requires the highest standard regarding site characterisation, monitoring and consideration of remediation options.

SURFACE PROJECTION OF INCREASED PRESSURE
The subsurface area, as projected to surface, beyond the physical presence of carbon dioxide, but in which reservoir pressures are above ambient conditions. Reservoir pressures decrease rapidly outward from injection zone along with the potential to drive unwanted migration or impact other resources. This area would require targeted characterisation and monitoring of identified potential leakage conduits (i.e. faults, old wells).

Figure 5. Schematic representation of the potential extent of impacts related to CO_2 injection (modified from Michael et al., 2014[37]). The subsurface volumes possibly impacted by CO_2 leakage or pressure increase have approximately cylindric shape. The Area of Review (AOR) at the surface follows the surface projection of increased pressure, whereby the degree of monitoring and characterisation requirements would depend on the radial distance from the injection centre.

Pressure changes within the storage reservoir that result from injection of carbon dioxide (or any fluid) may be distributed across an area several orders of magnitude larger than that of the actual plume. The greatest pressure increase is near the injection well but this drops rapidly outward as the area of flow expands. The geology of the reservoir, its thickness, hydraulic properties and the presence of any restrictions are major factors in how pressure is distributed. The extent of the AOR for basin resource management purposes should not be defined by the absolute increase in pressure, but should be constrained by the degree of pressure increase that potentially results in measurable geomechanical impacts or changes to water quality. For example, the United States Environmental Protection Agency [26] has proposed to limit the extent of the AOR by the minimum pressure increase at which a sustained flow of brine upward through a hypothetical conduit into an overlying drinking water aquifer occurs. Other consideration should be the pressure required to re-activate faults, to induce fractures in the seal, or to drive fluids from the injection reservoir into other natural resources.

Site characterisation and monitoring of a carbon dioxide storage operation should identify site specific risks, and rank their severity and likelihood associated with injection. As a general guide, however, geological characterisation and monitoring should be most comprehensive within the footprint area of the carbon dioxide plume, as this is where pressure increases will be greatest and where potential for unplanned migration of carbon dioxide is highest [36]. Beyond the footprint of the carbon dioxide plume, geological characterisation and monitoring should focus only on features that could be a potential migration conduit for either formation brines or carbon dioxide.

If the location of a CO$_2$ injection operation is known, its AOR can be used to further focus the assessment of potential resource interactions to a specific area. In this case, a more detailed characterisation of each resource is required. Depending on the level of interaction potential (or degree of vulnerability), different site characterisation requirements, M&V and mitigation strategies would be recommended in the last step of the assessment workflow. An example of the process for evaluating a CO$_2$ storage project is shown in Figure 6. Many of the decision points in the example workflow as well as the parameters that constrain the vulnerability ranges may require substantial data collection, interpretation and expert risk assessment, which will be different for each basin and the current study can only provide the necessary background information and suggested methodologies. In the end, it will be the regulator's responsibility to define specific workflows, monitoring requirements and key performance indicators.

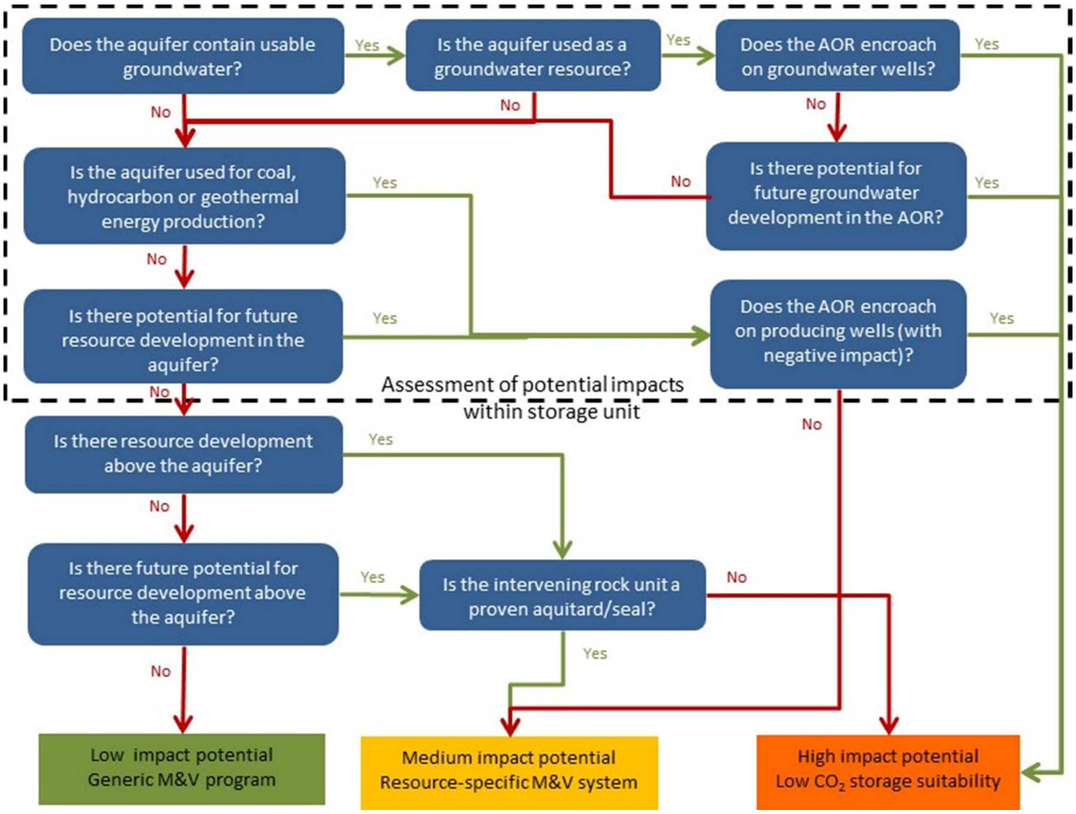


Figure 6. Quick assessment workflow for evaluating a CO$_2$ aquifer storage site with respect to potential resource interactions within its Area of Review.

4. Summary

This paper presents basin resource management strategies associated with large-scale CO_2 storage with a focus on potential interactions involving groundwater, petroleum (conventional and unconventional), coal and geothermal resources. CO_2 geological storage considerations, monitoring strategies, and remediation strategies were assessed to develop a generalised workflow for the evaluation of resource interactions following the methodology proposed by the USEPA [26]. The initial stage in assessing potential resource interactions would require the basin-scale identification of various resources and their geographic overlap with areas suitable for CO_2 geological storage. As basin assessments progress into more project specific assessments, correspondingly more detailed characterisation will be required as well as the identification of potential interactions, either adverse or beneficial, between CO_2 geological storage and other resources. For areas having potential for resource conflicts a basin management plan may be required, and the regulator may need to decide on the priority of each resource and, if parallel development is not feasible, the order in which resources should be exploited.

Sub-surface (geological) characterisation, static and dynamic modelling, monitoring and risk evaluation are essential activities used to determine long-term containment security of a specific CO_2 storage site within an Area of Review. These activities are also key to understanding and managing potential impacts of storage activities on other basin resources. Injected carbon dioxide may impact other resources by migrating laterally or vertically outside the area of the planned storage complex. Such migration may potentially contaminate another resource, such as comingling with natural gas or entering a coal seam, or effectively sterilize a region from further development such as in an area of prospective geothermal energy resources. Whereas these particular impacts would only occur at some depth within the basin, vertical migration into near-surface groundwater may pose environmental or even health concerns. Increased pressure in the subsurface resulting from CO_2 injection could result in brine displacement into usable groundwater sources and if unmonitored may result in fracturing of top seals preventing further development. Alternatively, increased pressure may provide support for producing oil or gas fields, and may limit the decline of groundwater levels in stressed aquifer systems.

Although the above discussion may suggest that resource overlap is an unavoidable scenario, there are some systematic methods to assess this potential. In many basins, the largest potential for resource and storage overlap is among petroleum resources and geothermal energy sources because these generally occur at similar depths as targeted for carbon dioxide storage. Conversely, resources such as coal, coal seam gas, and groundwater suitable for drinking and agricultural use, usually only occur (or can be economically exploited with current technologies) at depths shallower than that targeted for carbon dioxide storage. While this vertical separation can be resolved during early characterisation, impingement of carbon dioxide on these shallower resources may still occur if either continuous or stepwise vertical leakage pathways exist. While storage sites are usually capped by geological units that restrict and prevent any leakage, possible pathways could include some faults (most do not transmit fluids), existing and inadequately completed wells, and connected or adjacent high-permeability rocks within the seal. The identification of possible conduits is a significant aim of the site characterisation exercise and that leads to developing site-specific monitoring schemes to target surveillance on these features as part of overall project risk management.

The framework and principles presented in this paper are of a highly generic nature and would need to be tailored to specific regulatory environments and actual storage operations in the future. Various countries already have existing regulations that cover aspects of overlapping resource development. To date, however, there is little experience of carbon storage interacting with other basin resources as there are few such storage sites in operation[38] and, as they are generally spatially restricted, they have avoided overlap with other resource developments.

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