GROUNDWATER GOVERNANCE: A Global Framework for Country Action
GEF ID 3726

Thematic Paper 10: ***GOVERNANCE OF THE SUBSURFACE SPACE AND GROUNDWATER FRONTIERS***

By

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1. Introduction

This thematic paper focuses on the conventional and non conventional use of aquifers, encroachment into the subsurface space and the evolution of groundwater ‘frontiers’ to the extent that they impact aquifers and pose new challenges for groundwater governance. Some uses of the underground space, such as mining, are not new, but the scale and intensity of mining activity and the environmental consequence of groundwater recovery in abandoned mines are such that groundwater legislation is having to ‘catch up’[1]. The same applies to the controversial use of hydrofracturing (or ‘fracking’) to capture shale gas. The technological limits to mankind’s interference with the Earth’s crust are important considerations and Box 2 indicates where the current limits stand.

For reference, the working definition of groundwater governance adopted but the project is given in Box 1.

Box 1: A working definition of groundwater governance

Groundwater governance is the process by which groundwater resources are managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global. (Adapted after Saunier and Meganck. 2007. Dictionary and Introduction to Global Environmental Governance)

Groundwater protection forms the main governance concern when abstracting water, gas and oil resources and when using wells to inject fluids into underground formations. These developments have always been expensive ventures: Expensive, originally in terms of manpower, and latterly, in terms of finance. However, in the past the detrimental environmental impacts were not usually understood both during operation and subsequently after abandonment. As a result there is a growing legacy of environmental problems to be addressed. The 10,000 m3/day Sidoarjo mud flow (Lusi) from a gas exploration well that went wrong in Eastern Java is a classic example: Unstemmed, the Sidoarjo flow is expect to last more than 30 years by which time some 0.11km^3 of mud will be expelled and flood the surrounding heavily populated area.

Since geology is essential for technically assessing groundwater frontiers and the subsurface space, the paper first focuses the geological setting of deeper aquifers and sedimentary formations. The geological history of a formation dictates its water bearing characteristics both in terms of porosity and permeability and whether the groundwater is part of the current or a recent past hydrological cycle, or connate (trapped when the formation was deposited) or juvenile (has a deep seated origin). In some cases the base of deep aquifers is marked by impermeable basement, in others, the vertical limits are not yet proved and have to be inferred from geophysical surveys and interpretations.

While an understanding of the groundwater occurrences cannot be directly translated into governance models, it does provide an essential background to developing workable governance models. Formulating a governance structure to cover the subsurface space and groundwater frontiers needs a deeper geological basis than has been entirely necessary for the management and protection of shallower groundwater occurrences where a hydrogeological terrain or province classification has proved adequate

The approach taken in this report is to consider the range of cases where the underground space is being used; these include water supply, minerals extraction, energy generation and conservation and construction in the underground space. In each case the geographical distribution and geological setting of the resource is established and a brief timeline covering the resource exploitation and the necessary legislation that arose to control the beneficial or detrimental impacts of the developments.

This paper does not address the ownership of deep underground space and mineral rights nor does it address the legal conflicts between the holders of water rights and the developers of the underground space. This is largely because the legislation on these matters is always evolving or private property rights are overridden by state claims to ownership of mineral rights. For these specific legal issues, reference should be made to Thematic Paper 6.

[1] http://www.water.nsw.gov.au/Water-management/Law-and-policy/Legal-reform/Legal-reform#policy

Box 2: The limits to drilling into the earth's crust.

Groundwater, oil and gas are most efficiently abstracted by wells and the first hand-dug wells are dated to 10,000 BP: The deepest hand dug well (385m) for water supply purposes was completed in 1858 at Woodingdean in southern England. The first drilled wells were constructed using percussion techniques to extract natural brines for salt production in Sichuan, China around 2,000 years ago. Between the 3rd and the early 19th Century (1835), the depth drilled increased from 140m to over 1000m. Since then the capacity to mechanically drill deeper boreholes has steadily increased and the current depth record is held by the Kola super-deep, scientific investigation borehole in Russia at 12,262m. The deepest water wells rarely exceed 1,500m and currently the deepest oil wells rarely exceed 7,500m vertically.

Oil and gas wells are the second most wide-scale intrusion into the underground space after water wells.

Since 1950, 2.6 million oil and natural gas exploration and production wells have been drilled in the United States: In 2009 there were 363,107 producing oil and 460,261 producing gas wells[2] in number. According to the American Ground Water Trust, the number of domestic water wells in the United States exceeds 15 million and there are over 250,00 public water supply wells: During 2012 some 6,00 new water wells are drilled each week in the United States..

Extracting groundwater from wells becomes increasingly technically and economically restricted as the pumping head increases. Positive displacement reciprocating pumps can be used to lift groundwater from considerably more than 1,500m, yield performance and efficiency limits their economic application for large scale groundwater abstraction. The head limit for regular commercial 200mm electric submersible water pumps is 600 to 650m but high performance 750 kW multistage submersible pumps used in oil wells can handle heads up to 3,700m.

Part 1 (Baseline) presents an overall description of different types of use of the subsurface (for disposal and storage purposes; and for accommodating technical infrastructural works) and of the two main forms of deep groundwater exploitation: the abstraction of fresh water from deep seated aquifers and the use of groundwater as a carrier of geothermal energy. For each of these subjects, current governance practices are briefly reviewed. This part of the paper is concluded by some observations on the planning process and aquifer use.

Part 2 (Diagnostics) explores the most relevant constraints to, and opportunities for improving governance. In addition, it addresses a few specific issues.

Part 3 (Prospects) looks into the future. In the first place, it explores the future role of technology in managing the underground space, assesses options for joining forces (enhanced public/private sector co-operation) and makes a plea for more active involvement of geologists and hydrogeologists in the debate on, and the planning of the multiple uses of the subsurface and its resources.

The paper then makes a number of conclusions.

[2] United States Energy Information Agency. http://www.eia.gov/pub/oil_gas/petrosystem/us_table.html

Part 1 Baseline: Current status of knowledge, utilization and management

2. Pushing the aquifer frontier

With few exceptions, groundwater abstraction around the world remained at relatively shallow depth until the end of the nineteenth century, or even much later in some countries. Apart from diverting water from springs, groundwater mostly used to be tapped by dug wells (rarely deeper than 50 – 100 m, water lifted by human or animal traction) or by infiltration galleries (e.g. qanats or karez – within tens of meters below surface). Technology for deeper abstraction was not yet available and knowledge on the presence of any aquifers beyond the near-surface was in most cases non-existent. Significant advances in drilling and pump technology, as well as in subsurface exploration techniques (geophysics) and geological knowledge have changed the panorama drastically during the 20th century. Deeper aquifers have been discovered, numerous deep wells have been drilled and wells have been equipped with mechanical pumps, often very powerful ones. Arguably, this has precipitated a 'silent revolution' in groundwater development, resulting in an unprecedented intensity of groundwater abstraction particularly in arid and semi-arid regions. Wells down to several hundreds of metres of depth are common nowadays almost anywhere in the world. However, wells intended for the abstraction of freshwater for consumptive use (domestic, agricultural or industrial water) are rarely deeper than 400 to 500 m. Indeed most economically recoverable groundwater is derived from the shallow groundwater circulation in the Earth's crust at depths between 0-300 metres.

Beyond an arbitrary 500m limit groundwater tends to become progressively saline or mineralized as deeper groundwater circulation mixes with juvenile and connate groundwater. Also reliable assessments of aquifer properties and water quality become more expensive and technically demanding to obtain. Currently, exploitation of such aquifers is restricted to the recovery of geothermal energy, which is a non-consumptive water use since the abstracted water usually is re-injected. However, as demand for water increases and shallow aquifers are depleted or degraded, these deeper resources have become attractive where high value uses, including urban water supply and horticultural crops, have been able to afford technology and energy to pump from depths of up to 600 m. With this advance of the groundwater frontier in the 20th century, questions over the long term economic and technical sustainability of deep pumping have arisen (Custodio, 2002; Llamas & Custodio, 2003) particularly where deep aquifer systems are not linked to contemporary recharge and progressive depletion of pressure and storage within the system is a known consequence (Foster and Loucks. 2006)

2.1. Existing knowledge on deep seated aquifers

Knowledge on deep seated aquifers around the world is still scarce, fragmented and in most cases lacking the detail required to make a reliable judgement on the suitability of individual deep aquifers for fresh water withdrawal. They are most likely to be selectively found under certain tectonic settings (Zektser and Everett, 2004; Margat, 2008). A significant percentage of the deep seated aquifers currently identified are categorised non-renewable resources. (Foster and Loucks, 2006) while the remaining ones are only weakly recharged. This creates significantly different conditions and risks for aquifer development compared with the annually recharged shallow aquifer systems. The risk of encountering saline groundwater occurrences is higher in deep seated aquifers where emplacement of paleo-recharge, mineralization and incursion of juvenile waters has characterised the evolution of the deeper groundwater circulation (Van Weert et al, 2009).

Basin Type	Characteristic sediments	Depositional environments	Model examples
Rift or aulacogen†	Earliest crystalline rocks overlain by thick gravel and sand; younger rocks may include evaporites and limestones. Long lived sediment-filled grabens. Little deformation.	Rivers and lakes changing to shallow-marine	cratons, continental rifts
Back arc – Intra-cratonic	Homogeneous quartz-rich sands and limestones, but may include muds, evaporites, or coal at certain times. Little deformation.	Mostly shallow-marine with some deltaic	platform sediments and basins

Passive margin	Quartz-rich sands and limestones passing seaward to muds. Diapirism (salt domes).	Shallow-marine shelf to deeper-marine geosynclines. Deltaic	platform sediments and basins
Trench	Fine sediments overlying ocean-floor basalts. Extensive. Deformed accretionary wedge.	Deep marine	accretionary prisms
Fore arc (subduction) zone	Varied thick sediments ranging from pelagic through turbidites to alluvial fans, much derived from adjacent orogenic belts. Volcanoclastics common. Deformed accretionary wedge.	Non-marine to deep marine	accretionary prisms, fold and thrust belts
Foreland	Heterogeneous gravels, sands and muds derived from the orogenic belt and shed on to the continental craton; may be coal-bearing. Relatively stable areas.	Mostly river and mountain front outwash deposits	foreland basins

Table 1: Tectonic classification of major sedimentary basins, (modified from IAEG). †Aulacogen = failed rift

The use of tectonic plate settings by the International Association for Engineering Geology and the Environment (IAEG)[3] to define six forms of sedimentary basin is appropriate for considering the potential occurrence of deep aquifers. However, for hydrogeological purposes, the IAEG fore and back arc basins can be considered as a separate depositional environment with the back arc basins being equated with the IAEG intracratonic basin as shown on Table 1: Also the IAEG foreland basin class essentially equates to a late-stage, uplifted continental back arc basin environment.

However, wells intended for the abstraction of freshwater (domestic, agricultural or industrial water) are seldom deeper than 600m. The scarce available information suggests that freshwater aquifers deeper than 600m – the so called 'deep seated aquifers' [4]- remain largely untapped for the water supply uses.

The sparseness of the available information suggests a governance deficit in respect of the data collection, storage and dissemination. The indications are that considerable groundwater data collected during the 1960s and 1970s was not made widely available even within the commissioning organisations and ministries. The current Southern African Development Community (SADC) groundwater grey literature archive[5] is partially addressing this situation the region but the compilers are aware of gaps in the current listings (notably from Portuguese archives from Mozambique and Angola – these were widely available in Zambian Ministry libraries in the 1960s and 1970s).

Most known deep aquifer occurrences are found where the passive continental plate margins are encroached on by back arc basins deposits as a continental plate and an oceanic plate slow drift towards each other. This is best seen in along the northern margin of the African Plate as it closes with the Eurasian Plate. Here the deposition sequence starts with mid Palaeozoic (Ordovician) tillites that are overlain by continental arkoses and red-beds and finishes within the mid-Cretaceous Nubian Sandstone before a marine transgression deposited a sequence of marine shales, dolomites, evaporites and limestones in the Palaeocene and Eocene in thye Sirte Basin. Where this sequence has been deposit close to known Basement highs, fresh groundwater has been encountered in the lower Palaeozoic sediments that merge into the Nubian Sandstone sequence (Mobil oil exploration wells concession 126-A1 and A3 drilled in 1968 for example).

The groundwater occurrences in eastern Yemen, northwest Oman and southern Saudi Arabia are found is a similar sequence of sandstones and limestones with the prolific Cretaceous Mukalla Sandstone aquifer supporting irrigation developments in Wadi Hadhramaut, Yemen. At depths of 200-800m below ground, the Lower and Upper Umm er Radhuma Limestone aquifers together with the Damman Limestone (J. Cramwinckel, 2010) are partially proven targets for deep aquifer development in the area to the South of the Rub al Khali and Umm al Hait (Muqshin oasis).

[3] http://www.iaeg.info/totalgeology

[4] The concept 'deep seated aquifers' as used here does not include deep parts of thick aquifers that extend upwards to shallower depth, less than some 500 m below ground level.

[5] http://www.bgs.ac.uk/sadc/index.cfm

In the semi arid Ogaden Region of Ethiopia, a similar series of shallow late Palaeozoic and Mesozoic shelf deposits with shallow marine limestones followed by a continental sandstone sequence. Here drilling in 1977 near Gombor, 120 km south east of Jijiga encountered semi-confined groundwater in the Adigrat Limestone under approximately 180 m of Jessoma Sandstone. The indications were the groundwater was recharged by influent seepage from spate flows in the seasonal Greer River to the west. The records of this borehole were lost during regional conflicts later in 1977 and 2007 Google Imagery shows a small compound at the well site.

Given the subsequent difficulties with providing water to satisfy the refugee situation in the region during the 1980s and 1990s, development of this resource could have been possible had legislation required this information to be lodged and recorded in a publicly available database. This would have saved expensive water trucking operations.

2.2. Governance issues

There are few specific provisions or regulations for the governance of deep seated aquifers as a source of fresh water. Hence, they may be implicitly included in area-specific water resources or groundwater resources management plans (as far as existing), but usually not explicitly addressed because of their depth and the lack of information. A complication may be formed in several countries by the fact that beyond a certain depth mining laws are applicable and supersede water law, which may have consequences as well for institutional mandates and jurisdiction.

In relation to governance, it is important to note that most deep seated aquifers are virtually isolated from the present-day active hydrological cycle. This makes them an ideal source for emergency water supply in cases where natural disasters (e.g. tsunamis, floods, droughts, earthquakes, etc) have resulted in acute drinking-water shortage and degradation of shallower aquifers and wells. It makes them also insensitive for climatic variations and climate change, thus they may constitute important buffers in that respect. Some deep seated aquifers may be converted from non-renewable to renewable aquifers as a result of exploitation, as this may induce recharge through or from overlying aquitards.

Enhanced governance may have a very significant impact on groundwater data collection, storage and dissemination, including data on deep seated aquifers. Promising initiatives have been taken at several levels, although usually not specifically for deep aquifers. At the regional level, the current Southern African Development Community (SADC) groundwater grey literature archive[6] is partially addressing this situation for this region.

An additional aspect of hidden data concerns the results of the detailed geophysical reflection seismic surveys and drilling records that are collected and compiled by the international oil prospecting and production companies. Although the results of the deeper surveys (1,000 m +) have a high commercial value, the leasing national governments should insist that interpreted the shallow (> 500 m to <1,000 m) information showing major faults, formation tops and bottoms and borehole geophysical logs should be made available to their natural resources and environmental agencies and that this should be included in the terms of the licensing agreement. This topic is covered under the heading “Hidden data sources” in a recent GEF-TWAP International workshop on new technologies for the acquisition of information on transboundary aquifers organised by IGRAC and UNESCO-IHP (2010). While oil exploration reflection geophysical survey results are rarely made available, Figure 1 illustrates the type of detail that was available to supplement a hydrogeological study of the deep coastal aquifers in Lagos State, Nigeria: A city with severe water supply problems that relies on deep boreholes (800 m+) exploiting the drilled the Cretaceous Abeokuta Formation limestone aquifer and the sand horizons in the Ilaro Formation (H.O. Nwankwoala, 2011).

[6] http://www.bgs.ac.uk/sadc/index.cfm

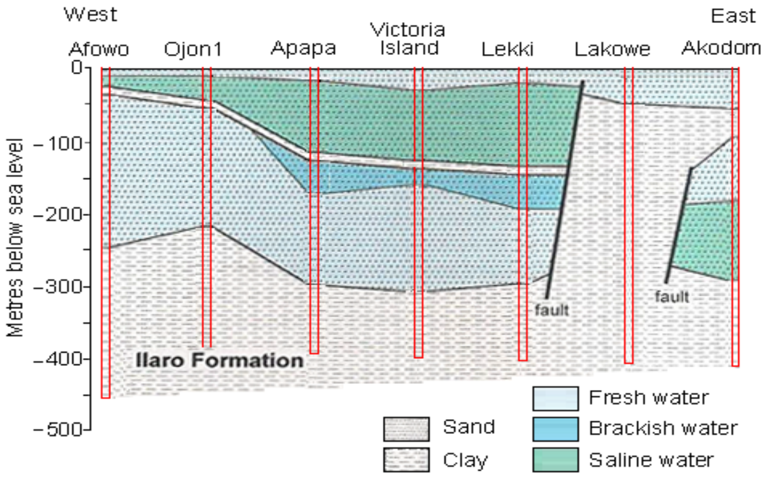


Figure 1: Section along the Lagos coast, Nigeria compiled from reflection seismic survey data and Lagos State Water Corporation borehole records, The section is approximately 20km long (redrawn from S.M.A. Adelana, et al., 2008)

3. The Impact of Mining

Historically, the main ventures into deep underground space have been for the mining of metallic and non-metallic minerals. This led to a steady development of pumps and power sources for mine drainage. Deep mining continues largely un-restrained by little effective governance in many countries. Even where belated governance has been introduced there are legacy issues. This is seen with the Cornish Wheal Jane Mine in SW England where tin was extracted from the mid-18th Century until 1992. Following abandonment, the mine flooded and acid drainage water escaped into the surface drainage. The subsequent remedial works were demanded under environmental legislation at a cost of over US $300M. Additional examples worldwide are highlighted by the fact that four out of the ten most contaminated sites are due to lead mining.

While engineering and geotechnical mining problems demand a closely focused approach on detail, groundwater appraisals require a much wider view of the geological setting of the problem.

3.1. An example - groundwater and mining in the Zambian Copperbelt

Mining in the Central African Copperbelt started around 1903. The Konkola and Kawbe (Box 3) Mines in Zambia are located on the African Erosion Surface close to major water divides. The current 300,000 to 350,00 m3/d of groundwater pumped from >1,500m below ground level to dewater the workings at Konkola considerably augments the flow in the Kafue River (Engineering and Mining Journal, 2011). The dewatering pumping peaked at 425,500 m3/d in 1978 (S. C. Mulenga and B. C. Chileshe, 1994). The copper ore bodies occur on the nose of the Kirilabombwe anticline of the late pre-Cambrian where early Palaeozoic Katanga Series tillites, conglomerates, sandstones and dolomites that are folded against an ancient Basement Complex craton (Mulenga, S. C., et al., 1992). Arguably the wettest underground mine in the World (some 59 tonne of groundwater per tonne of ore is lifted to the surface compared to a local norm of 4 tonnes per tonne of ore), it has been subject to numerous hydrological, hydrogeological and environmental studies.

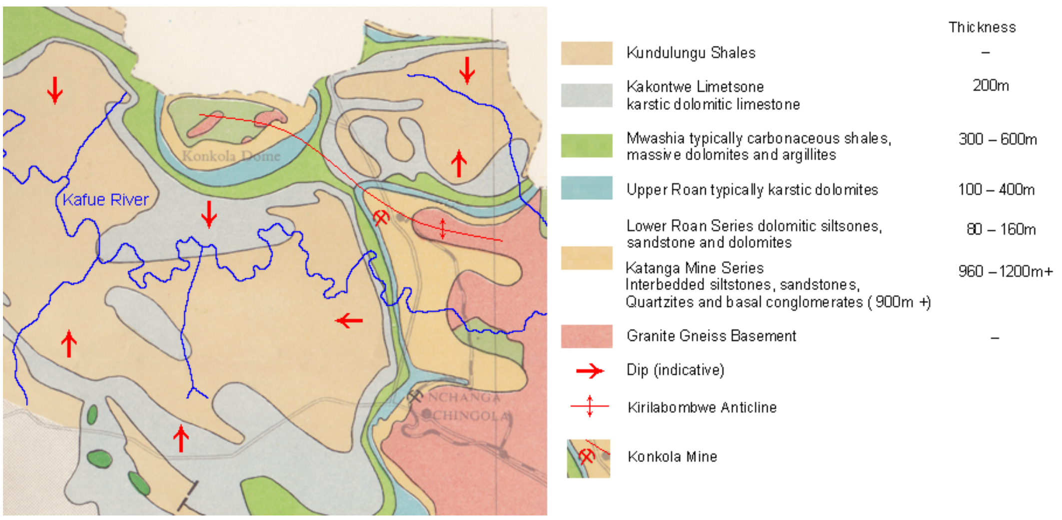


Figure 2: The geological setting of Konkola Mine, Zambia (based on the Geological Survey Map of the Copperbelt, 1961)

Since mining started over 6 km3 of potable groundwater (V. M. Simumba, 1993) has been pumped from the Mine into the Kafue River. The source of this underground water was first suggested to come from the Kafue River. In the mid 1960s tests showed this was not the case and a regional groundwater source was tentatively identified. Subsequently in 1971, the Zambian Department of Water Affairs hydrogeologist who was undertaking a detailed study of the hydrogeology of the Kabwe Lead and Zinc Mine (M. J. Jones and K. D. Töpfer 1972) examined the tectonic setting of Konkola mine and concluded that active flow and recharge over local dolomite outcrops and the 400 km^2 synclinal structure extending to the southwest of the Mine as the most probable sources. However, this has been questioned by Mulenga, S. C., et al., (1992) who presented detailed chemical and isotope analysis and proposed a variety of surface water sources including local streams, tailings dams, and surface water ponds as contributors to some 45% of the dewatering flow. Based on this assumption recommendations were made to line water courses or divert the local streams.

The main water bearing horizon in Konkola Mine is the 100 to 400m thick, strongly-karstic, Upper Roan Dolomite with the equally karstic, Lower Roan Dolomite as a secondary source (Figure 2). Given the high permeability of the strongly karstic dolomites aquifers, the cone of influence is likely to be much more extensive than currently mapped. Less clear is the degree of hydraulic continuity between the Mine and the younger karstic Kakontwe dolomitic limestone above the Mwashia Shale. However given the extensive regional and local faulting, the lithological variations of the Mwashi Shale and under the heads introduced by the Mine dewatering a high degree of hydraulic continuity is very likely to exist. The decline in the dewatering requirement sine the 425,500 m3/day 1978 peak suggests that the extra 100,000m3/day came from the original confined storage in the Kakontwe and Upper Roan aquifers in synclinal basins to the north and south west of the mine. The extension of karstic flow zones under the Kundulungu Shales is plausible given the extremely long karstic flow paths (500km +) observed in Damman and Umm er Radhume Limestones of the Arabia Peninsula that supported the fresh groundwater springs off shore of Bahrain.

A wide ranging appraisal of the Zambian Copperbelt Mining Municipalities' water supplies foresees continuation of the 330,000 m3/day as essential for maintaining the flow in the Kafue River and will have to be sustained at a high cost if mining at Konkola ceases (Norconsult, 2004 and 2005): The Kafue River being the main source of most urban and industrial raw water supplies downstream of the Konkola Mine dewatering discharge.

When compared with the dynamic groundwater regime at the Broken Hill Lead Mine at Kabwe and given the comparative size of the synclinal basins, it is considered that contemporary recharge within the Konkola mine dewatering cone of influence cone has the potential to support all the observed abstraction.

The pattern of increasing recharge to significant karst dolomite aquifers has been established moving north in Zambia from Lusaka to Kabwe to Ndola where the mean annual rainfall varies from 820mm to 930mm and 1182mm and mean recharge has been estimated at 12%, 16% and 20% (P. Hadwen, 1971, M. J. Jones 1971, M. J. Jones and K. D. Töpfer 1972). However, these estimates have since been found to be low and a value of 20-25 % (170 to 215mm) of the revised mean 1963-1993 rainfall of 857mm is now accepted for Lusaka (A. Nick, L. Museteka & R. Kringel, 2010). This would suggest that the earlier estimates for Kabwe and Ndola are less than half of correct recharge value (see Table 1). (D.J. Burdon and N. Papakis (1963) plotted similar relationships between precipitation and infiltration for a number of Mediterranean karst outcrops).

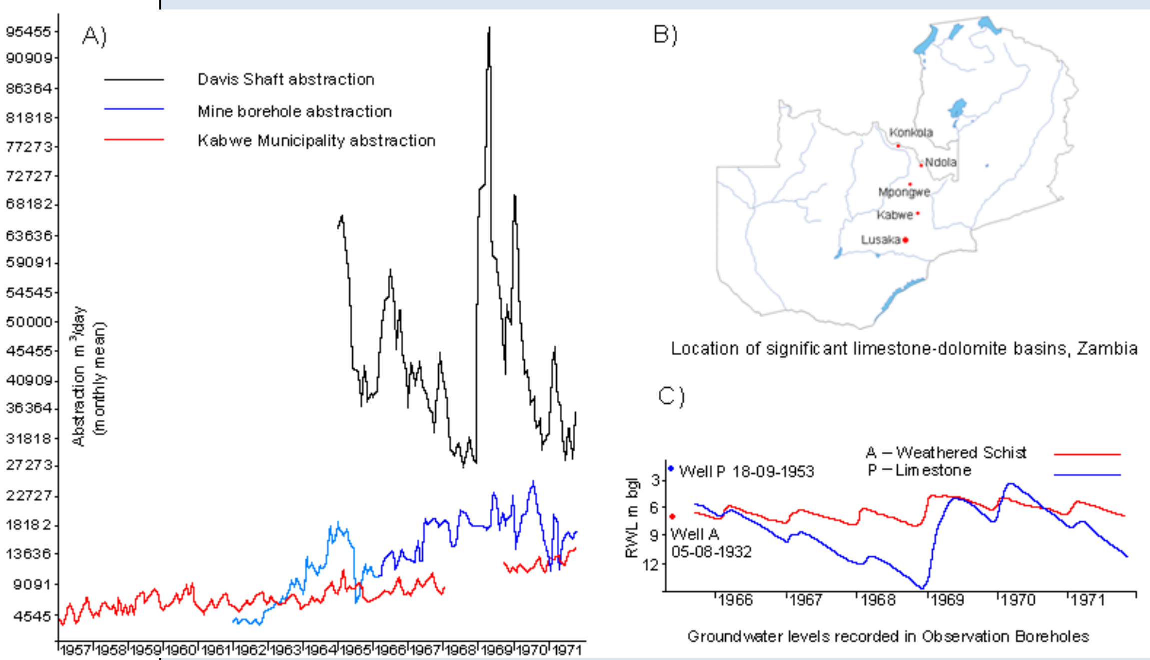
Translating the calculated infiltration based on the analysis of daily data as recharge to the Kakontwe dolomitic limestone at Kabwe shows how the recharge is less dependent on the total wet season rainfall and more dependent on the pattern of the rainfall (M. J. Jones and K. D. Töpfer 1972). This pattern has also been observed by a BGR.team reporting on the Development of a Groundwater Information and Management Program for the Lusaka Groundwater Systems (R. Bäumle and S. Kang'omba, 2009. Reporting on the same project, A. Nick (2011) presents maps showing large areas with mean annual recharge to the Lusaka dolomite aquifer exceeding 40% of the annual rainfall. Additionally as the Lusaka Dolomite outcrop dominates the southern lower lying areas of Lusaka and has been historically legacy of major floods despite the aquifer being extensively pumped for urban, industrial and irrigation purposes: The most recent floods occurred in 2010.

Based on this sound information from similar dolomitic limestone aquifers in Zambia, it is entirely reasonable to expect the underground workings to rapidly fill to the original groundwater levels and the regional hydrological regime will readjust to close to the pre-mining development conditions within a few years of shutting down the dewatering system pumps.

ox 3 Groundwater at Broken Hill Mine, Kabwe, Zambia

Vhen opencast mining commenced in 1906 the water levels stood between 1.2m and 6m below ground depending on the season. Underground mining started in 1938 when the Davis Shaft was completed to 330m and ceased in 1995. The ore body occupied the core of a synclinal basin groundwater catchment to he mine was estimated to cover around 45km^2.

Between 1950 and 1952 the Davis Shaft was deepened to 486m. In response to exceptionally heavy rains n the 1951-52 season (1,283 mm) that caused flooding of the underground workings, the pumping apacity was increased to 118,200 m3/day. During the underground mining, the water level in the Davis Shaft was held at 456m during the rainy season and at 420m during the dry season. Figure B3-1 A shows he abstraction from the Mine from 1961 to 1971. The average volume of water pumped from the Mine per year is 50,000 m^3/day.



igure B3-1: A) Broken Hill Mine – mean monthly Davis Shaft abstraction; B) location of some sinificant arstic limetsone and dolomite aquifers on the African Erosion Surface and on or close to the Kafue-uangwa water divide and C) Groundwater hydrographs for observation wells outside mine cone of nfluence.

he calculated infiltration values shown on Table B3-1 can be equated to recharge and correlate with the lewatering abstraction from the Davis Shaft at the Mine (Figure 12 A). The well hydrographs are from sites emote from the mine and close to the local groundwater divides.

	Precipitation	Rainfall Surplus*		Infiltration	
Year	mm	Mm	%	mm	%
1966-67	807	300	37	127	16
1967-68	737	91	12	145	20
1968-69	1450	1126	71	970	66
1969-70	841	393	46	457	54
1970-71	833	317	38	218	27

* Calculated from daily rainfall, potential evapo-transpiration and soil moisture deficiency

Table B3-1: Water Balance Calculations for the Kalulu Dolomitic Limestone Aquifer – Kabwe, Zambia

Figure 3: Munkumpu and Mpongwe groundwater based irrigation projects, Zambia (Google Earth Image).

Among the recommendations made in 1971 by Department of Water Affairs hydrogeologist was for the development of large scale groundwater based irrigation schemes that would tap the Kakontwe and Upper Roan karstic aquifers around to the west and south of the Mine. The proposed target abstraction was set at 2 to 3 cumecs. Intriguingly at the time this suggestion was made, the mine operators at this time (Nchanga Mines) were planning the Munkumpu irrigation development based on a 1.5cumec karstic spring discharging form a synclinal structure to the west of Mpongwe where the Government of Zambia were to develop a pumped groundwater irrigation development: Currently some 3500 ha is under irrigation at these developments that were merged in 1998 (Figure 3).

While engineering and geotechnical mining problems demand a closely focused approach on detail, groundwater appraisals require a much wider view of the geological setting of the problem. In the case of Konkola Mine, its location on the African Erosion Surface implies sound knowledge of the geomorphological development and hydrological response of this landsurface. Thick soils and low gradients point to low surface water runoff and high evaporation losses across the areas of deeply weathered crystalline Basement. Here the low recharge rates assigned in many past regional studies are appropriate whereas they are certainly not appropriate for the limestone and dolomite blocks where high recharge and perennial springs commonly are the main source for surface water streams. A further observation can be made regarding the prevalence of the high infiltration capacity of the soils (+50mm/hr) supporting the ubiquitous Miombo forested interfluves of the main water course on the African Surface (R. Webster, 1965, F. White, 1983). These interfluves generate very little surface water runoff but retain the infiltrating rainfall in soil profile and local perched aquifer horizons.

3.2. Governance Issues

Preparing guidelines to ensure that future frontier resource assessments are adequately staffed by professionals with the right expertise and who have, or are given access to the appropriate information presents a governance problem in a climate where financial institutions and clients priorities are based on minimum costs. This elusive need is nowhere more clearly seen than when costly and long-term developments are being considered. The mining industry clearly need to be regulated by institutions that do not only look at mining profits, but also take possible externalities into account.

4. The Impact of Oil and Gas Developments

Oil and gas wells are the second most wide-scale intrusion into deep underground space after water wells. For example, just in the United States of America, in 2009 there were 363,107 producing oil and 460,261 producing gas wells[7] in number. There are over 1.5 million injection wells used for oil and gas recovery and the disposal of oil field production brines (by volume, the mean ratio being 7.5 brine to 1 of oil produced)[8].

An overview of the geological setting of the major onshore and certain offshore hydrocarbon provinces shows that many coincide, or are located near significant groundwater occurrences. With the exception of the African rift basins, the tectonic setting of most major hydrocarbon provinces match those identified as suitable for CO_2 storage (Figure 4).

Figure 4: Sedimentary basins showing suitability as sequestration sites (from IPCC, 2005).

All phases of hydrocarbon exploration, production and abandonment can pose a risk to groundwater resources and are subject to strict environmental controls but unfortunately accidents occur: The majority of these are the result of human error and are avoidable. This would appear to place them beyond the role of governance and in to realm of the insurance sector where the problems can be subject to risk assessments.

While the industry has ample experience in drilling exploration and production wells, there are always a range of problems associated with the loss of control over high pressure zones that can lead to a severe pressure kick or full scale well blowout. Depending on the drilling phase, shutting in a high pressure kick can force the reservoir fluids and gases into overlying permeable geological horizons. In the case of the Iranian Masjid-i-Sulaiman Oilfield, during the 1960s a deep exploration well targeting a Jurassic prospect leaked high pressure gas into the overlying, producing Eocene oil bearing horizons[9]. This disturbed the hydraulic balance in the upper producing zones and the formation brine displaced the oil in the Eocene production zones that had been in production since 1908. Although in this case no groundwater resources were reported impacted, it highlights the potential for the rapid transmission of reservoir brines and hydrocarbons into overlying aquifer horizons.

The consequences of any deficits with the well construction related to the integrity of the casing and/or grouting can lead to problems during the operation of production phase oil and gas wells. Holes in the casing or leakages between the casing and the well wall can allow formation fluids to migrate into overlying aquifer formations.

A substantial area of the Midwestern hydrocarbon province in the United States is overlain by the High Plains – Ogallala - Equus Beds (Kansas) Aquifer (Figure 5). The hydrocarbon bearing rocks were deposited during the

[7] United States Energy Information Agency. http://www.eia.gov/pub/oil_gas/petrosystem/us_table.html
[8] United States Energy Information Agency.
http://www.gwpc.org/e-library/documents/general/Injection%20Wells-%20An%20Introduction%20to%20Their%20Use,%20Operation%20and%20Regulation.pdf
[9] Source7th World Petroleum Congress, April 2 - 9, 1967 - World Petroleum Congress Document ID 12276.

Palaeozoic and Mesozoic along with substantial halite (NaCl), gypsiferous ($CaSO_4 :2H_2O$) and anhydrite ($CaSO_4$) evaporite horizons that are recognised as potentially sources of contamination to the overlying High Plains aquifer.

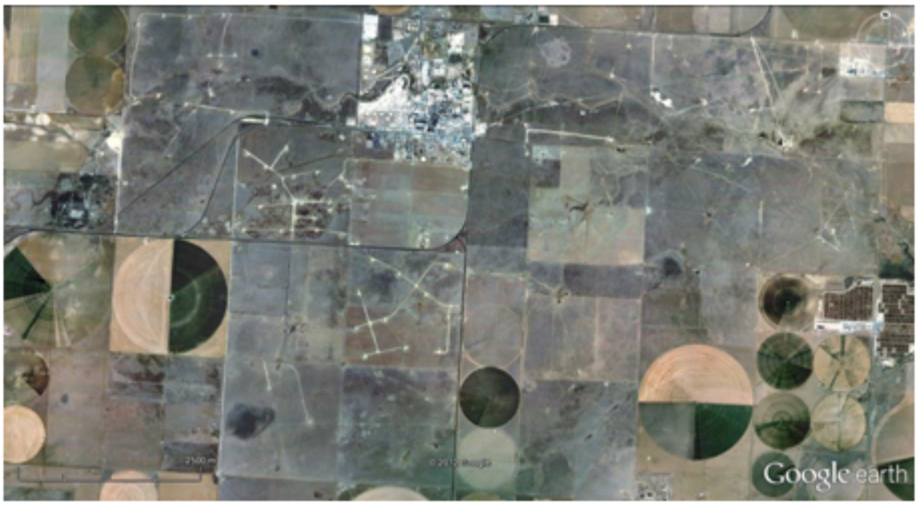


Figure 5: The juxtaposition of groundwater and oil wells on the Ogallala Aquifer in Moore County, NW Texas. (Valero McKee Refinery top cetre of image: Centre pivot irrigation and spider traces link oil well sites). Google Earth Image.

Detailed studies in Kansas (D. O. Whittemore, 1997, 2004 and 2007) identified a range of aquifer contamination sources and problems that have been brought under control by a continuously evolving but largely retroactive governance regime. The solution of halite during early oil well drilling problems caused many localised cases of subsidence (R. F. Walters, 1978) but the main source of the groundwater salinisation identified in the overlying aquifers are oilfield brines. These are chemically differentiated by a bromide signature. Originally, the oilfield brines were disposed of in surface ponds and local drainage systems but since this practice was banned, on-going groundwater contamination is traced to the use of enhanced recovery wells were brine injected below the hydrocarbon trap leaks into the fresh water aquifer occurrences.

4.1. Specific Governance Aspects associated with Hydrocarbon Developments

In general requirements of the United States and Western European environmental agencies have set out strict regulations and guidelines to protect groundwater resources but also accept that accidents are bound to happen and, therefore, have to rely on the development of cleanup measures and imposing punitive fines to attempt to control the industry.

In a widespread review of the impacts of oil and gas exploration and production in Kansas, R. F. Walters (1978) describes how in the early 1930s, attention began to be given to the plugging of abandoned and closed oil and gas wells as these were increasingly being identified as sources of aquifer salinisation. At first regulations were weakly enforced and the techniques employed were insufficient to prevent aquifer contamination. However, when further regulations governing the plugging of abandoned wells were introduced in 1935, they had to be revised as a series of ever-more stringent abandonment regulations by State environment agencies to protect the aquifers and these regulations had to be extended to cover all forms of drilled wells including abandoned water wells, mineral exploration and geotechnical investigation boreholes.

While the oil and gas companies have strong commercial interests in ensuring the industry standard engineering technology is applied to the construction of investigation and production wells, they can also have equally strong commercial reasons for avoiding the additional costs that may be required to meet the requirements of external environmental regulators. By the second half of the 20th Century, major oil companies had built up a very questionable legacy of bad practices in may oil and gas provinces. In addition, these companies are adept at evading any subsequent penalties arising from cavalier practices as seen in the Niger Delta where the environmental damage places it in the World ‘top ten’ of worst contamination events.

In contrast to the mining sector where engineering and financial management dominates, geologists occupy the higher management positions in most oil and gas exploration and exploitation companies. This ensures that the latest and often very expensive techniques and surveys are applied to the resource investigations and developments. The results of this approach have provided much of the material used in to establish the geological principles set out in this paper. However, when it comes to the engineering aspects of oil and gas drilling exploration and production wells and processing installations, the industry becomes engineering and cost conscious and corners are cut despite the best efforts of the industry regulators: The 2010 Deepwater Horizon blowout in the Gulf of Mexico is just one of an on-going series of similar industry failures where the onshore events can impacted on the local groundwater resources.

Countries with weaker legislation or enforcement capabilities are likely to be faced with a growing legacy of resource and environmental problems. It is felt that such countries should review their oil and gas licensing agreements and include ample internationally recognised indemnities to cover all potential resource and environmental degradation. As this will incur additional costs to the operators and ultimately the consumers that the oil and gas companies will resist, it is considered that either the World Trade Organisation or the other relevant United Nation's agency should design and implement such insurance cover possible by using an escrow account on behalf of the oil and gas exporting nations.

5. Geothermal Energy

Groundwater, likewise surface water, may be considered as an energy source. In fact, the layers of rock that make up the Earth's surface grow increasingly hot with depth, from crust to mantle to core, and this heat – held in rocks and groundwater - can be tapped as energy. The heat content of groundwater increases constantly with depth, even in average gradient conditions (30^{o}C/1Km). When thermal anomalies, linked to volumes of magma intruded near to the surface or to deep reaching fractures, are present at shallow crustal levels, groundwater may reach temperatures up to over 400 ^{o}C at economically reachable depths. The heat content of groundwater, either transformed into electricity (high temperature systems) or used directly (e.g.: heating), is known as Geothermal Energy.

Geothermal energy remains today an underdeveloped energy resource compared to the vast amount of thermal energy contained within the Earth's crust. The total heat flux through the Earth's crust has been estimated to be 42 x 106 MW and the total heat energy above 15°C stored within it is on the order of 5.4 x 1021 MJ. Mankind's present total annual primary energy consumption is estimated at 4.2 x 1011 MJ per year (OECD/IEA, 2004), which is negligible compared to the heat stored in the crust: the geothermal energy resource base is thus enormous. There are however serious technical and financial limitations to how large a proportion of the energy can be harnessed as an energy supply for humanity: (i) production wells must be drilled, and technology currently available does not allow to drill deeper than 5–10 km; (ii) there need to be a circulating fluid to extract the heat from the hot rock and bring it to the surface; (iii) the amount of useful heat that can be extracted is very limited; (iv) there are theoretical limitations to the conversion of heat to electricity or other energy carriers and, (v) energy production from geothermal energy has to be accomplished at competitive prices. The main challenge for geothermal development is to overcome these barriers and give the world access to a huge resource that will last thousands of years.

Various levels of technological maturity exist, depending on the specific energy product (electricity or heat) and, in the case of heat, the conversion process, where geothermal energy may be used directly (e.g. district heating) or indirectly (e.g. heat pumps). The technologies used to transform the heat into electricity are mostly linked to the temperature and pressure of the geothermal fluid. Direct steam turbines use natural high-temperature steam resources directly to generate electricity, and result in the lowest power plant cost. For the high temperature mix of brine and steam, a flash steam plant separates the steam from the liquid and then expands it in a turbine. If the resource has lower temperatures (e.g. between 120 and 180ºC), a binary cycle plant is more efficient and has better environmental performance, although it is more expensive. Beyond pure electricity generation, geothermal combined heat and power (CHP) is a natural energy-efficiency option used, for example, in district heating networks.

Box Economic Considerations

Capital costs for conventional geothermal electricity are in the 1 000 – 3 800 €/kW range, resulting in 40 – 80 €/MWh. Enhanced Geothermal Systems (EGS) investment costs are much higher given the experimental nature of the technology (10 000 – 26 000 €/kW) and result in a cost of 170 – 350 €/MWh. Capital cost for heat supply from conventional sites is in the range of 100 – 300 €/kWth, resulting in a cost of 4 – 7 € /MWhth. Heat supply costs from EGS are only speculative at one tenth the EGS electricity costs. The single item that has the highest impact on costs is drilling, typically 30 - 50 % of total development cost for electricity generation. Well costs can vary from a few tens of thousands to several million euro for high-temperature wells for electricity generation. Piping costs vary from 200 to 6 000 €/meter in highly developed urban areas. Drilling two boreholes, known as a doublet, to a depth of 3 000 meters can cost up to 14 million euro. Insurance premiums can cost up to 25 % of the sum insured. Over half of the total production costs over the lifetime of the project are expenses associated with the well field. Up to 50 % or more of the wells might have to be replaced over the course of the project, possibly increasing leveled electricity cost by 15-20 %.

The installed cost of heat pumps vary between 1 000 and 2 500 €/kW for typical domestic facilities of 6 - 11 kW, and between 1 700 and 1 950 €/kW for industrial or commercial installations in the 55 – 300 kW range. Capital costs depend greatly on the ground exchanger layout, whether horizontal or boreholes. Data from Greece suggests capital costs between 1 200 and 1 500 € /kWth, electricity and maintenance costs of 28 €/MWhth, giving total costs of 48 €/MWhth (including capital amortization over 20 years with 5 % cost of borrowing money). This has to be compared with diesel oil: 72 €/MWhth; natural gas between 58 and

65 €/MWhth and air source heat pumps of 60 €/MWhth. Of the estimated EUR 81 billion (USD 120b) invested in renewables worldwide in 2008, around 6 % (4.9 €/m) were directed to geothermal heat and power.

The system availability for a geothermal energy plant can reach 95 %. A modern electricity plant can reach a 92% load factor (8,000 full-load hours), whereas actual national figures vary from 60% to 85%. The mode of operation determines these load factors: whereas most plants are operated as base-load supply, thus reaching high load factors, the depletion of the reservoir may force peak-load operation, reducing the load factor accordingly. Heat pumps have a lower actual factor at around 20 %, whereas other heat uses reach load factors of 20 to 60 %.

Electricity is generated from geothermal energy in 24 countries. In 2002, geothermal energy occupied third place worldwide amongst renewable sources to generate electricity in the world after hydropower and biomass. In 2002, electricity production from geothermal energy in the world totaled 57 TWh, compared to 52 TWh from wind power, 1 TWh from solar power (photovoltaic) and 2610 TWh from hydro- power (OECD/IEA, 2004). The relative growth in wind and solar energy has in recent years outstripped that of geothermal energy, reflecting strong investment for research and development in these sectors compared to geothermal energy. Geothermal power plants are, contrary to wind and solar energy plants, well suited to producing an electrical base load. Total installed geothermal power today is about 10 GW, 92% of it generated in conventional power plants, while 8% is generated in binary plants. The Global Geothermal Power and Heat Pump Market Outlook 2010-2015 estimates an average annual growth of 14% of geothermal electric generation and direct uses together, from 661,200 MW of 2010 to 120,300 MW in 2015. For electricity generation only, the Report indicates an annual growth of the installed capacity of 12.4%, from 10,500 MW in 2009 to 19,200 MW in 2015. Direct uses of geothermal heath[10] will grow 14.9% annually, from the present day 50,500 MW to 101,100 MW at the end of 2015.

5.1. The new geothermal frontiers

The hot wet rock (HWR) and hot dry rock (HDR) systems

The water associated with the hot wet rock geothermal occurrences may be of deep-seated, juvenile origin or recharged by groundwater flow. Hot wet rock occurrences are the main source for current geothermal electricity generation. Geologically the wet rock occurrences are associated with obviously active igneous terrains. The hot dry rock geothermal systems are artificially created by drilling into hot impermeable rock: the necessary permeability is created by high pressure hydro-fracturing. Several attempts were made in early 1970s to produce energy from impermeable hot dry rocks, including experiments to create a sufficiently network of permeable pathways within deep the target heat sources to allow for the circulation of the heat extraction fluids between the injection and extraction wells at Fenton Hill (target at 3km) in New Mexico, USA, Rosemanowes (3km) in UK, Ogachi (1.3) in Japan and in France and Germany where the targets are between 4.5 and 5km below ground level (Massachusetts Institute of Technology, 2006). None of these was entirely successful due the hydraulic fracturing opening the pre-existing anisotropic planes of weakness (fractures and fissures) within the rock, rather than creating new random fissuring and permeability as is the case with oil well hydraulic fracturing. The result of this fracture pattern is the creation of preferential flow paths between the injection and abstraction wells that in effect short circuited the heat abstraction capacity.

[10] Heath pumps account for 67% of direct geothermal uses, with accelerated growth in Germany, Holland, Norway, Sweden and the United States.

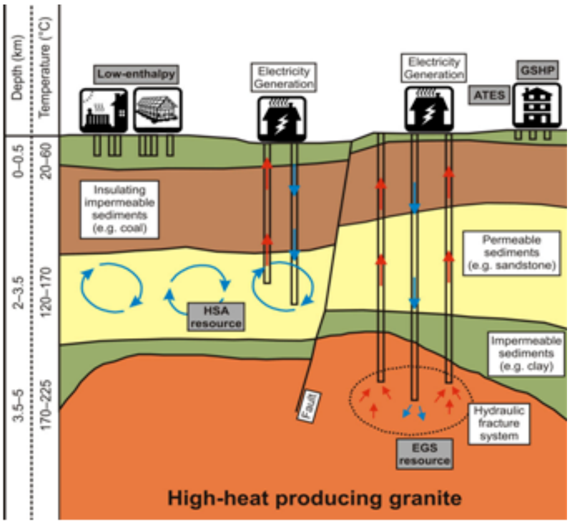


Figure 6: Schematic diagram showing low and high enthalpy geothermal energy systems (from J. P. Driscoll and H. Middlemis, 2011).

Key:

GSHP - Ground Source Heat Pumps

ATES - Aquifer Thermal Energy Storage

Enhanced geothermal systems (EGS)

In recent years, interest has been growing for developing the concept of EGS. Unlike HDR systems, EGS systems are not only high-temperature anomalies in the crust but also have some primary permeability, which needs to be enhanced to make production feasible. Several projects of this type are now ongoing in the world like in Soultz-sous-Forêts in France, Groß Schönebeck in Germany, and the Cooper Basin in Australia. This latter is presently attracting considerable interest, as many companies are now attempting to enhance an over 200°C geothermal reservoir in a huge 4–5 km deep sedimentary basin underlain by a heat source – a large mass of granites. If successful, geothermal energy could rapidly become Australia´s main source of electric power and facilitate similar geothermal projects elsewhere.

Supercritical Geothermal Systems (SGS)

Above 374°C and 221 bar pressure, water achieves supercritical condition. Fluid values are slightly higher if the fluid is saline. It has been calculated that the energy output per volume unit from a well with supercritical fluid can be as much as 5–10 times the energy output from a conventional high temperature system. Geothermal systems where such conditions prevail are called supercritical geothermal systems (SGS). It is already known that very high temperatures can be reached in high-temperature geothermal systems near or within cooling intrusions. For example temperatures up to 340°C degrees have been observed in several high temperature systems, e.g.: in Iceland, Italy, China (Tibet). Conservative extrapolation of temperature depth curves indicate that temperatures above 400°C can be expected at 4–5 km depth, and the pressure there should be high enough to create supercritical conditions if hydrostatical pressure is assumed. In addition, extensional stress field and fracture formation revealed by frequent earthquakes indicate that considerable permeability should exist in recent fracture systems. Based on this information, a consortium of stakeholders called the Iceland Deep Drilling Project (IDDP) has been formed to drill three 4–5 km deep wells into Icelandic high temperature systems to explore for SGS and to develop methods to utilize the fluid for electricity. The first well, IDDP #1 drilled in the Krafla geothermal system in northern Iceland, has produced superheated steam 12 h after opening: T: 410°C, P: 40 bar, H: 3150 KJ/Kg, Power output potentially 30-40 MWe. The well was closed 11 August for modification on the flow line. Pilot tests will begin about mid-September 2011. The main technical challenges include development of proper well design and suitable drilling methods, material selection to withstand highly corrosive fluids and methods to handle the fluid and convert the heat energy to electricity. The timeframe of this experiment will be on the order of ten years and will, if successful, have great replication potential in other high-temperature geothermal systems.

Ocean Floor and Submarine Geothermal Systems

The mid-oceanic ridges comprise a more than 50,000-km-long continuous chain on the ocean floor. These are places where hot mantle material is upwelling from the mantle and is emplaced as intrusions at shallow depths below ridge crests. The extensional tectonic environment causes tensional fractures, and strong hydrothermal circulation is observed forming hot springs on the ocean floor. Hot springs at great depths on the mid-oceanic ridges are known as “black smokers” where temperatures exceeding 370°C have been measured. They are places where water in supercritical state is injected into the cold ocean water exhibiting the huge energy reserves below the mid- oceanic ridges. Technology for exploitation of oil and gas in the deep oceans has developed rapidly in recent years. It is not impossible to envisage that production of geothermal energy at mid-ocean ridges will eventually be technically and economically possible.

Presently, an interesting and innovative project is being implemented in Italy: the Marsili Project, named from the Marsili submarine volcano (Eolian Island Arc), the largest active volcano in Europe. The project – now under way - includes the drilling of offshore exploratory wells into the volcano, and the assessment of its geothermal potential, estimated to be large.

Hot sedimentary Aquifers

The HSA system (Figure 6) are designed to extract and re inject groundwater from hot deep seated aquifer horizons (RPS Aquaterra and Hot Dry Rocks, 2012). These deep aquifers can be saline and precautions are taken to prevent contamination of shallower aquifer horizons. Lower empathy deep sedimentary aquifers with temperatures above 60o C can be developed using the Organic Rankine Cycle for heat extraction and this widens the areas where geothermal electricity generation is feasible: Figure 7 shows the potential for HSA resource potential on the UK mainland. Successful HSA developments rely on conduction and advection, where induced temperature gradients and high vertical permeability exist, convection flow will improve the efficiency of the system.

Unlike HDR systems, HSA systems are not only high-temperature anomalies but also have inherent permeability that can be enhanced to make production feasible. Several HSA projects being implemented including those at Soultz-sous-Forêts in France, Groß Schönebeck in Germany, and the Cooper Basin in Australia where a number of commercial companies are attempting to enhance an over 200°C geothermal reservoir in a huge 4–5 km deep sedimentary basin underlain by a heat source (Figure 6). If successful, geothermal energy could rapidly become Australia ́s main source of electric power and facilitate similar geothermal projects elsewhere.

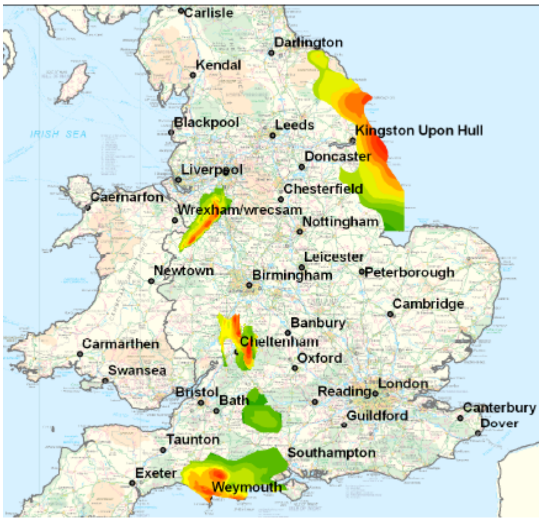


Figure 7: Main HSA basins on the UK mainland (from J. Busby, 2010). Temperatures at 2-5km below ground level range from 50 to 105oC.

Geopressured aquifers

A further advance in the potential HSA energy resources has been the identification in the northern sector of the Gulf of Mexico of deep over-pressured gas zones. These also occur in the Niger Delta (Section 3.5.2). Referred to as geopressured aquifers, they contain significant volumes of dissolved methane trapped in sedimentary formations at a depth of about 3 km to 6 km. The temperature of the water is in the range of 90°C to 200°C. Although theoretically a possible source for thermal energy, hydraulic energy and methane, they have not been systematically evaluated for economic development. Specific Governance Issues for Geothermal Energy and Impacts on Groundwater

The potential impacts of geothermal energy generation on groundwater have been set out under the United Nations University - Geothermal Training Program as shown on Table 2.

Given the scale of geothermal existing and planned development even in the United States (Figure 8), future depletion of the available resource is unlikely to be of immediate concern even though the localised rate of heat extraction from geothermal sources is estimated to be 10 times the natural geothermal replenishment[11].

The Massachusetts Institute of Technology (2006) lists no less than twelve separate legislative controls to geothermal developments in the United States. The International Finance Corporation (IFC 2007) refers to similar lists of international and national guidelines and legislation as providing the necessary governance controls for developments elsewhere in the World.

	Low Enthalpy Systems – HSA	High Enthalpy Systems EGS	
		Vapour dominated	Liquid dominated
Drilling operations			
Contamination of groundwater by drilling fluids	1	2	2
Mass withdrawal			
Depletion of groundwater	0	1	2
Hydrothermal eruptions			
Ground temperature changes	0	1	2
Waste Liquid disposal			
Infiltration of surface disposal	1	1	2
Re-injection contamination of groundwater	1	1	1

Key	0 = no effect	1 = little effect	2 = moderate effect	3 = high effect

Table 2: Potential effects of geothermal developments on groundwater (adapted from T. M. Hunt 2001)

Given the very high costs of investigations and development plus the known environmental risks associated with the hydrothermal fluids, the general governmental view would appear to be that all operators will apply the necessary precautions and risk management plans before undertaking tangible investigations and developments. Also on the side of governance, as with hydrocarbon developments, even with appropriate legislation, governments have to accept accidents are bound to happen and, therefore, they have to rely on the development of cleanup measures and imposing punitive fines to control the geothermal sector.

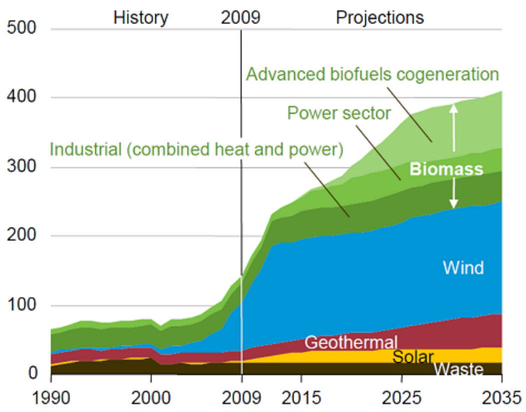


Figure 8: (Original caption) United States non-hydropower renewable electricity generation, 1990 – 2035 (billion kilowatts per year): From U.S. Energy Information Administration, 2011

[11] http://www.teara.govt.nz/en/geothermal-energy/5

6. Disposal and storage of hazardous wastes

Waste may end up in the subsurface unintentionally, e.g. by lack of adequate treatment and sewerage systems, through septic tanks or as a by-product of subsurface activities such as drilling (drilling mud, cuttings, etc.), mining or tunnelling. Not all waste of this category is hazardous, but some of it certainly is, e.g. PPCPs (pharmaceuticals and personal care products), EDCs (endocrine disruptive compounds) and radioactive residues (e.g. from hospitals). In an increasing number of countries, however, parts of the subsurface domain are used or considered to be used for planned storage of waste of different categories, including hazardous waste. Most notorious is the storage of radio-active waste from nuclear power plants. Other categories are the storage of carbon dioxide and the storage of various types of waste through deep-well disposal. Except for the storage of carbon dioxide (Carbon Capture and Sequestration or CCS; it will be addressed in the next chapter) these different categories will be briefly reviewed below. In addition some information is provided on nuclear weapons testing and nuclear accidents, not intended as a form of disposal and storage of hazardous waste, but with some similarities,

6.1. Deep-well waste disposal

Deep-well injection is a technique for the disposal of liquid waste or solid waste that can be reworked to a slurry. In general, permeable formations with good storage capacity – such as sands, sandstones and fractured or karstic limestones - are required to receive the liquid waste, while effective impermeable cap rocks should be present to ensure that the injected waste remains permanently isolated from the biosphere. Injected hazardous waste should be trapped in deep formations for millions of years, like oil and gas. That is why injection sites should be free from seismic hazards. Injection depths are usually of the order of one thousand to a few thousands of metres.

The waste products to be injected originate from different sectors. They include oil field brines, cuttings, drilling mud, sulphides, mercury compounds, arsenic, cadmium and other waste produced in the oil and gas industry; liquid waste from solution mining and other mining operations; all kinds of industrial and municipal liquid waste; and even low-level radioactive waste.

Deep-well injection follows technological protocols and governmental laws and regulations (not clear to what extent countries have these available and implement them carefully). E.g., the USA distinguishes five injection well classes, to which State regulations refer. Oil and gas companies have become more keen during recent years to comply with environmentally sound solutions for their E&P waste products, including deep-well disposal. Careful study of selected sites and detailed monitoring before, during and after injection are prerequisites for safe waste disposal. Although deep-well injection seems to attract the general public's attention less than radioactive waste and CSS activities, environmentalists occasionally oppose to newly proposed deep injection wells if they consider them to be risky.

6.2. Subsurface storage of radioactive waste

Radioactive waste ranks highest within the category of hazardous waste. Its potential subsurface disposal is still controversial and unresolved, although there is wide agreement that storing nuclear waste in a geologically stable and isolated location underground is a far more promising option than dumping it in sealed barrels into the ocean, which has been practiced for some time during the period 1940-1960.The problem of nuclear waste lies not only in the extremely devastating impact of potentially released radiation on the exposed biosphere (including humans), but also in the enormous persistence of its hazardous properties. Radiation half lives of important nuclear waste components are in the order of thousands to millions of years, which means in practice that a safe repository should isolate the waste from the human environment for infinite time.

Sources of nuclear waste include the nuclear fuel cycle (front end and back end), nuclear weapons, medical and industrial waste, as well as fossil fuels. Often a distinction is made between low-level waste (containing small amounts of mostly short-lived radioactivity) and high-level waste (as produced by nuclear reactors). Uranium mill tailings, left over when ore is refined and processed, is the largest by volume of any form of radioactive waste, but their level of radioactivity is low. Spent rods in nuclear power plants contain radioactive fission products and actinides. These isotopes are formed in nuclear reactors and build up gradually to a level where they stop the chain reaction. The fuel in the reactor then has to be replaced by new fuel. The used fuel is either stored (USA) or reprocessed to remove the fission products and re-used (Russia, UK, France Japan and India).

Spent fuel rods are high-level waste and the mentioned reprocessing produces a very concentrated form of high-level waste as well. The annual production of high-level nuclear waste is approximately 12,000 metric tons world-wide.

Currently, various approaches to the disposal or containment of radioactive waste can be observed. Low-level waste is (or should be) disposed on controlled low-level waste sanitary landfills, sometimes after on-site containment for a number of years as to allow decay to a safe level. Cases of illegal dumping, however, are known (sometime is remote countries). Probably most liquid low-level wastes are poured down the drain, whether or not they are still radioactive. Uranium mill tailings have been used as foundation and building materials, until their risk was discovered. Preferred ways of disposal nowadays are to store it in clay pits, far from population centres, or in abandoned mines.

Current practices in managing high-level radioactive waste are a combination of temporary storage and investigating options for permanent storage. Nuclear waste is stored temporarily on-site at the power plant in specially constructed containment pools or transported to temporary containment facilities. Many countries are studying already for decennia options for permanent subsurface storage. A suitable permanent repository should be geologically stable, isolated from the modern hydrological cycle and unlikely to be affected by seismic activity or to be disturbed otherwise for at least tens of thousands of years. Potential sites selected and studied in detail are in volcanic rock high above the water table (Yucca Mountain, USA), in crystalline rock (Finland, Sweden, India), in thick impermeable clay (Boom Clay Formation, Belgium) and in salt domes (Gorleben site, Germany).

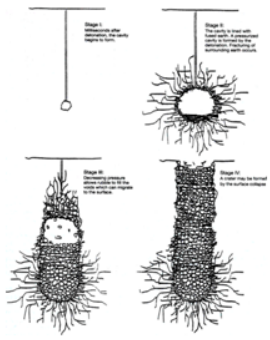
6.3. Nuclear Weapons Testing and Nuclear Power Accidents

Underground nuclear testing probably represents the most aggressive invasion of, and the burial of radioactive waste probably the most heavily investigated aspects of the subsurface space. Atmospheric tests created a tritium peak that has been widely used for groundwater dating purposes.

Around 2,010 underground nuclear tests have been carried out worldwide but apart from the Nevada Death Valley Test Site (NTS) in western United States, only limited data related to groundwater has been made publicly available. Most terrestrial underground test sites are located in arid or semiarid climatic areas with very deep (>200m) groundwater levels (Figure 9).

The French conducted undersea testing in the lagoon of Moruroa Atoll in French Polynesia and despite the extreme military secrecy the heat generated by the tests produced a geothermal convection cell that created a water percolation rate of 10m/year. At this rate highly radioactive material is expect to reach the floor of the lagoon with 50 years instead of the 500 to 1,000 calculated before the tests. The hydraulic circulation of the geothermal cell is considered to have been assisted by the shock fracturing of the underlying basalt seamount. By the late 1980s, radioactive cesium134 that could have only originated from the test was detected during surveys in the lagoon at Moruroa. When limited test data was compared with these surveys, it became clear that in some cases the cesium134 migrated to the lagoon floor within six years. As a result of these findings, plans to use Moruroa as a long term nuclear waste site should be ruled out and essentially the atoll is already a leaking nuclear waste dump.

Figure 9 (above): 1945-1998 Sites of over 2,000 Nuclear Test Sites (from Atomic Archive[12]).



[12] http://www.atomicarchive.com/Almanac/Testing.shtml

Figure 10 (right): Schematic diagram of the formation of a debris chimney associated with an underground test ((US DOE, 1996).

Over 800 underground tests were conducted at the United States NTS (J. M. Fenelon, D. S. Sweetkind, and R. J. Laczniak, 2010) and considerably fewer in the Marshall Islands in the Pacific. A number of tests vented to the surface. Most formed debris chimneys and subsidence craters (Figure 10). Groundwater contamination as a result of the underground tests is acknowledged and has been thoroughly investigated under the direction of the US Department of Energy. The main mechanism for radioactive species to enter the groundwater flow systems include leaching of the more soluble elements[13] that condensed in the rubble chimney after the test: Less radioactive material[14] is leached from the melted and fused rock and bomb debris that formed at the base of the explosion cavity.

Accidents form another mechanism of unintended nuclear pollution of the environment, including the subsurface. Figure 8 shows the distribution of nuclear power plants, the impact of the 11th March 2011 Tōhoku earthquake and tsunami on the Fukushima Dai-ichi nuclear power station has brought the safety of nuclear power plants into public focus with Japan suspending and Germany phasing out all nuclear power generation.

Since the introduction of nuclear power plants in 1952 and there have been 16 incidents rated at 3 or over on the International Atomic Energy Agency's 7-fold scale[15]. The worst incident was the 1986 Chernobyl explosion (rated at 7) cause severe environmental contamination over a wide area.

6.4. Groundwater governance issues arising from disposal of hazardous waste

From the governance point of view a number comments can be made: Hazards presented by some low-level waste may continue far beyond the formal landfill control period. Information on nuclear weapon production is top-secret, which is an obstacle to ensuring proper handling and storage of the corresponding nuclear waste.

Many countries have their laws, plans, regulations and standards on radioactive waste management. Standards on permissible doses of permitted exposure to radioactivity are in many European countries more stringent than proposed in the USA or suggested by the International Commission on Radiation Protection.

Nuclear energy and the related environmental and health risks are politically sensitive and receive ample attention from citizens. The latter (in particular organized groups of activists) may block options or solutions and thus constitute a factor in the decision-making process. In various cases of transport of nuclear waste activists have tried to prevent this. On the other hand, several countries organize public consultations to get stakeholders involved, so there is a variable picture

Some countries depend on nuclear power (France, Switzerland, Japan, UK, Canada, Russia) but have made very limited progress in selecting and studying permanent repositories for high-level nuclear waste.

International governance is provided by the OECD Nuclear Energy Agency's Radioactive Waste Management Committee (RWWMC) and the International Atomic Energy Agency (IAEA). However, the political and public on-off relationship to nuclear power generation has been largely driven by fear of reactor explosions and melt downs plus health concerns over environmental contamination caused by inadvertent leaks and the ultimate safe storage of potent radioactive waste products. Although readily detectable at very low concentration, radioactive elements and compounds are also a major health hazard at equally low concentrations. This should place all forms of nuclear energy usage under strong international governance. The long half life of the many of the transuranic elements is seen as adding to the risks.

These risks have led democratic governments to adopt a highly hedged approach to the problem. The early nuclear supporters claim that nuclear power would ultimately be so cheap to produce that it could be virtually supplied for free remains attractive. However, past experience has shown the human error and mechanical failures are hard to legislate against and equally hard to rule out.

[13] Dominantly the more volatile alkali metals, uranium, antimony and tellurium.
[14] Dominantly plutonium and the rare earth elements.
[15] http://www-pub.iaea.org/MTCD/publications/PDF/INES-2009_web.pdf

7. Injection and Recovery Applications

7.1. Injection and recovery for Mineral extraction

Developments in drilling and pump technology enable solution mining of salt to become rapidly established in the second half of the 19th Century. J. Whyatt and F. Varley, 2008 for example report of the collapse of a solution mine in 1873 at Varangeville Mine, France. Until the 1950s solution mining was largely limited to the use of water or steam to extra water soluble chloride and bicarbonate salts of sodium, potassium and magnesium.

The use of acid based and other chemical extraction methods started in 10th Century China with the leaching of copper using sulphuric or hydrochloric acid from copper carbonate, oxide and silicate mineral occurrences. The chemical leaching solutions are referred to as lixiviants and all are hazardous to Underground Sources of Drinking Water (USDW) aquifers. Currently 16 copper mines in the United States are using in situ leaching of copper mining. Solution mining of uranium began in the United States and Russia in the 1960s using acid based lixiviants but since the 1970s solution mining in the United States uses a carbonate based lixiviant. Geologically, the uranium ores occur in porous sandstone aquifers. Other uses of solution mining are for the extraction of sulphur and gold.

The US EPA (1999a) undertook a study of injection wells used for solution mining. This report clarifies the situation differentiating various classes of injection wells (Appendix 1. The study reports no groundwater problems associated with the operation of the 2,694 documented Class III injection wells in the United States[16].

The US EPA set out the following requirements for operators of mineral extraction wells to mitigate against contamination to underground sources of drinking water (USDW) aquifers: (US EPA text)

Before commencing injection, operators must obtain an aquifer exemption if they are injecting into a USDW (which is common in ISL uranium mining), or if the overlying aquifer may subside (which may happen in salt mining operations). The wells must be constructed with tubing made of materials that are appropriate for the injected fluids, which are cased and cemented to prevent the migration of fluids into a USDW. They must also provide financial assurance that resources exist to properly plug the wells when injection operations are complete. Operators must pressure test their wells prior to injection.

During operation of the well, the operator must monitor injection pressure and flow rate, and they may not inject fluid between the outer-most casing and the well bore. Operators must also monitor USDWs below and above the mining interval if the well is injecting into a USDW of 3,000 ppm (parts per million) total dissolved solids (TDS) or less. Operators of salt solution mining wells must test the well casing for leaks at least once every 5 years.

When injection operations are complete, Class III operators must properly close (plug and abandon) the wells.

7.2. Residual Geothermal Fluids

Reinjection of geothermal residual fluids started purely as a disposal method, but has more recently been recognized as an essential and important part of reservoir management. Reinjection serves not only to maintain reservoir pressure, but also increases energy extraction efficiency over the life of the resource. Only a small part of the thermal energy in place in geothermal reservoirs can be recovered if reinjection is not applied. Thermal breakthrough has been observed in few geothermal reservoirs but has in all cases been found to be a manageable part of field operation. Silica scaling in surface equipment and injection wells is a delicate aspect of the reinjection process in most high-temperature geothermal fields, but silica scaling in the reservoir has not been considered a problem. Reinjection of low-enthalpy geothermal fluid into sandstone has not been successful, for reasons that are poorly understood. The location of injection wells in relation to production wells influences the ratio of injected fluid recovered in production wells. For peripheral injection, about one third of the injected fluid is commonly recovered, whereas injection within the production area results in a higher ratio of recovered fluid. Subsidence is in general of small concern in geothermal operations and micro-gravity has proved a valuable tool to estimate the recharge to geothermal reservoirs.

[16] http://water.epa.gov/type/groundwater/uic/class5/upload/study_uic-class5_classvstudy_fs_min_wells.pdf

7.3. Hydrocarbons and fluids associated with oil and natural gas production

Injection wells are generally used for the underground storage of crude oil and liquid hydrocarbons in underground caverns, natural or man-made, and in reservoirs/aquifers. The wells are designed for both injection and removal of the stored hydrocarbons. The hydrocarbons are injected into the formation for storage and later pumped back out for processing and use. The underground reinjection of produced liquid hydrocarbons and natural gas can have different purposes: (i) provide industry with short-term deliverability during peak demand, and/or set aside long term strategic reserves; (ii) increase production and prolong the life of oil-producing fields.

The use of underground caverns for the storage of petroleum and low boiling hydrocarbons such as ethylene, propane and butane has become a widespread practice in the petroleum industry. For this purpose caverns formed by washing out salt from a thick rock salt bed have been particularly satisfactory, since the salt bed is substantially impervious to hydrocarbons and leakage from the cavern through the adjacent formation does not occur. The use of washed out salt caverns is obviously limited, however, to areas in which suitable salt beds happen to occur. More recently, storage caverns have been prepared by mining out underground rock formations such as granite. While storage zones of this type are considerably cheaper than above ground storage tanks for storing low boiling hydrocarbons under pressure, they have not proved to be consistently successful due to leakage from the cavern through the adjacent rock. Rock beds often contain small channels through which the hydrocarbon can flow toward a zone of lower pressure. This not only causes loss of hydrocarbons but also may present a dangerous condition due to seepage of the hydrocarbon to the ground level.

Enhanced Oil Recovery (EOR) injection wells are used to increase production and prolong the life of oil-producing fields. Secondary recovery is an EOR process commonly referred to as water–flooding. In this process, salt water that was co–produced with oil and gas[17] is injected into the oil-producing formation to drive oil into pumping wells, resulting in the recovery of additional oil. Tertiary recovery is an EOR process that is used after secondary recovery methods become inefficient or uneconomical. Tertiary recovery methods include the injection of gas, water with special additives, and steam to maintain and extend oil production. These methods allow the maximum amount of the oil to be retrieved out of the subsurface[18].

Salt Caverns - Solution-mined caverns in salt formations are used for storing large volumes of liquid hydrocarbons and compressed natural gas. Salt properties, while usually advantageous for successful hydrocarbon storage cavern operations, can vary considerably both between dome and bedded salts and amongst bedded and dome formations. Salt property variations, inherent differences in caverns developed in bedded and dome formations, and the range in site-specific geological conditions strongly suggest effective regulatory attention. Solution-mined excavations in salt have been developed for temporary storage of a variety of hydrocarbons including crude oil, refined liquid hydrocarbons, and more recently for compressed natural gas. The United States Strategic Petroleum Reserve, developed in the 1970s and 1980s, utilizes more than 50 underground caverns in salt to store nearly 600 million barrels of crude oil for emergency use. Solution-mined caverns in salt are also used by the private sector for temporary storage of crude oil. Solution-mined caverns in salt have been used on a limited basis for compressed natural gas since the early 1970s. However, the number of caverns planned or developed for compressed natural gas storage has risen rapidly in the last few years.

7.4. Hydraulic Fracturing

The geological evaluation of shale gas prospects identifies substantial volumes remaining within the original major source shale formations as shown on Figure 11. Most of the shale gas formations are of mid Palaeozoic (Late Devonian) and Mesozoic geological age (ca < 375 to 69 Ma).

[17] When oil and gas are extracted, large amounts of brine are typically brought to the surface. Often saltier than seawater, this brine can also contain toxic metals and radioactive substances. It can be very damaging to the environment and public health if it is discharged to surface water or the land surface. By injecting the brine deep underground, surface contamination of soil and water is prevented. In the US, when states began to implement rules preventing disposal of brine to surface water bodies and soils, injection became the preferred way to dispose of this waste fluid. All oil and gas producing states require the injection of brine into the originating formation or into formations that are similar to those from which it was extracted.

[18] Approximately 60% of the salt water produced with oil and gas onshore in the United States is injected into EOR wells.

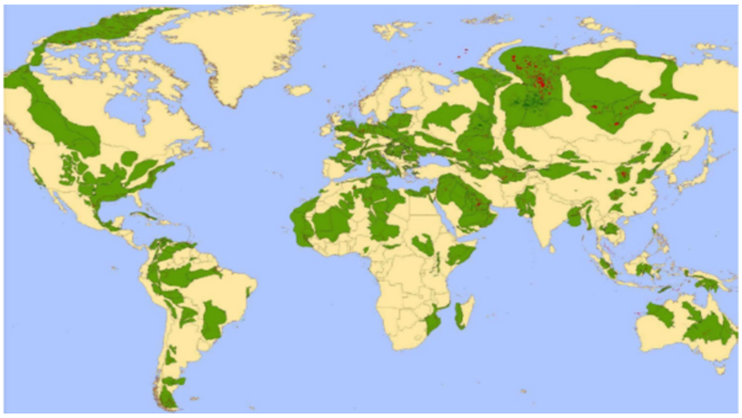


Figure 11: Major Worldwide shale gas prospects (from Canada Free Press quote source as 'No Hot Air, 2011')

The technique of hydraulic fracturing is used to increase or restore the rate at which fluids, such as oil or water, or natural gas can be produced from subterranean natural reservoirs, including unconventional reservoirs such as shale rock or coal beds. Hydraulic fracturing enables the production of natural gas and oil from rock formations deep below the earth's surface (generally 1,500-6,100 m). At such depth, there may not be sufficient porosity and permeability to allow natural gas and oil to flow from the rock into the wellbore at economic rates. Thus, creating conductive fractures in the rock is essential to extract gas from shale reservoirs because of the extremely low natural permeability of shale, which is measured in the microdarcy to nanodarcy range. Fractures provides a conductive path connecting a larger area of the reservoir to the well, thereby increasing the area from which natural gas and liquids can be recovered from the targeted formation.

While the main industrial use of hydraulic fracturing is in stimulating production from oil and gas wells, hydraulic fracturing is also applied to stimulating groundwater wells, preconditioning rock for caving or inducing rock to cave in mining, as a means of enhancing waste remediation processes (usually hydrocarbon waste or spills) or spills, dispose of waste by injection into suitable deep rock formations.

A hydraulic fracture is formed by pumping the fracturing fluid into the wellbore at a rate sufficient to increase the pressure downhole to a value in excess of the fracture gradient of the formation rock. The pressure causes the formation to crack, allowing the fracturing fluid to enter and extend the crack farther into the formation. To keep this fracture open after the injection stops, a solid "proppant", commonly sieved round sand, is added to the fracture fluid. The propped hydraulic fracture then becomes a high permeability conduit through which the formation fluids can flow to the well.

The fluid injected into the rock is typically a slurry of water, proppants, and chemical additives. Additionally, gels, foams, and compressed gases, including nitrogen, carbon dioxide and air can be injected. Various types of "proppant" (sized particles mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment) include silica sand, resin-coated sand, and man-made ceramics. These vary depending on the type of permeability or grain strength needed. Sand containing naturally radioactive minerals is sometimes used so that the fracture trace along the wellbore can be measured. Chemical additives are applied to tailor the injected material to the specific geological situation, protect the well, and improve its operation, though the injected fluid is approximately 99 percent water and 1 percent proppant, varying slightly based on the type of well.

The second stream of "unconventional natural gas resources" developments is the extraction of gas from coal beds (US EPA, 2002). Two methods of methane abstraction from coal beds are in use, the first extracts the gas from existing coal mine workings: This method is in use in Canada, China, Australia, and in the United States where it forms some 10% of the total gas supply. The second method is termed underground coal gasification (UCG) and has been in study since the 1940s in Europe and the United States and recently in Australia. The method hydraulic fracturing of the coal beds in a similar manner to that used for gas shales extraction. The only commercial operation is in Uzbekistan. The method and potential impact on fresh water aquifers is set out by the US EPA (2004).

7.5. Carbon dioxide Capture and Storage - (CCS)

Carbon capture and sequestration (CCS) is the process of storing carbon underground to curb accumulation of carbon dioxide in the atmosphere. It is undertaken because natural sinks of carbon (forests, oceans and soils) are considered unable to accommodate the increasing amounts of carbon dioxide emitted by humans, with consequences in terms of climate change.

The general public is less informed about CCS than about nuclear waste, but when concrete projects are considered there is often public opposition against it (NIMBY effect). This opposition is based on perceived health risks for the population in the neighbourhood if stored carbon dioxide would leak to from the repository (e.g. empty oil or gas reservoirs) to the surface. Although CO_2 is a standard compound of the air (0.04% by volume), it becomes poisonous at large concentrations. That such concentrations are not illusory in the case of leaks (because of its relatively high density) is demonstrated by the famous example of suffocating CO_2 concentrations (in this case of a natural origin) observed in the Grotta de Cani near Naples, mentioned already by Plinius and described in detail in Athanasius Kircher's Mundus Subterraneus (1664). More recent examples of such hazards are the death of 1700 people in 1986 resulting from release of CO_2 from the Nyos lake in Cameroun and the incident in 2008 in Mönchengladbach (Germany) where CO_2 escaped from a defective fire extinction installation, causing illness of 107 people.

Major Geological Storage of CO_2 is ongoing in three industrial-scale projects (projects in the order of 1 MtCO_2 yr or more): the Sleipner project in the North Sea, the Weyburn project in Canada and the In Salah project in Algeria. About 3–4 MtCO_2 that would otherwise be released to the atmosphere is captured and stored annually in geological formations.

Many storage sites are far from large emission sources. Coupled with the fact that long-range intercontinental transportation of CO_2 would incur significant additional cost, this means that the economic storage potential is country and region specific and smaller than the total geologic storage potential. However, in most world regions storage capacities do not pose a constraint for widespread CCS use for decades to come. At this stage, the total cost of CCS could range from 50 to 100 USD per ton of CO_2. This could drop significantly in future. In most cases, using CCS would cost 25-50 USD per ton of CO_2 by 2030, compared to the same process without. Certain early opportunities exist with substantially lower cost, but their potential is limited. The cost of CO_2 storage depends on the site, its location and method of injection chosen. In general, at around 1-2 USD per ton of CO_2, storage costs are marginal compared to capture and transportation costs. Revenues from using CO_2 to enhance oil production could be substantial (up to 55 USD/t CO_2), and enable the cost of CCS to be offset. However, such potential is highly site specific and would not apply to most CCS projects. Longer-term costs for monitoring and verification of storage sites are of secondary importance. Using CCS with new coal- and gas-fired power plants would increase electricity production costs by 2-3 US cents/kWh. By 2030, CCS cost could fall to 1-2 US cents per kWh (including capture, transportation and storage).

CO_2 Injection Technology - The injection of CO_2 in deep geological formations involves many of the same technologies that have been developed in the oil and gas exploration and production industry. Well-drilling technology, injection technology, computer simulation of storage reservoir dynamics and monitoring methods from existing applications are being developed further for design and operation of geological storage. CO_2 storage in hydrocarbon reservoirs or deep saline formations is generally expected to take place at depths below 800 m, where the ambient pressures and temperatures will usually result in CO_2 being in a liquid or supercritical state. Under these conditions, the density of CO_2 will range from 50 to 80% of the density of water. This is close to the density of some crude oils, resulting in buoyant forces that tend to drive CO_2 upwards. Consequently, a well-sealed cap rock over the selected storage reservoir is important to ensure that CO_2 remains trapped underground. When injected underground, the CO_2 compresses and fills the pore space by partially displacing the fluids that are already present (the 'in situ fluids'). In oil and gas reservoirs, the displacement of in situ fluids by injected CO_2 can result in most of the pore volume being available for CO_2 storage. In saline formations, estimates of potential storage volume are lower, ranging from as low as a few percent to over 30% of the total rock volume.

The initial perceived risks associated with CO_2 sequestration are shown on Table 3. Some historic incidents linked to the escape of injected CO_2 used for enhanced oil recovery have occurred and frequent parallels of the dangers are drawn with the CO_2 cloud released from Lake Nyos in NW Cameroon in 1986 as the result of a local tremor and landslip. For similar reasons, CO_2 sequestration sites should not be located in tectonically active or volcanic areas were caprock damage and rapid pressure and temperature changes could disrupt the equilibrium of the CO_2 density and solubility: This will create the risk of uncontrolled, rapid migration and escape of stored CO_2. Periodic measurements for CO2 in the soil gas profile, included in the monitoring programme may identify leakage.

Risk of Geological Storage of CO_2

Local Risks

Global Risk

CO_2 in atmosphere	Deep sequestrated dissolved CO_2	Physical and Chemical Risks	Release of CO_2 into the atmosphere
Human illness of suffocation	Mobilisation of metals and contamination	Ground disturbance	
CO_2 in soils above watertable	Contamination of USDW aquifers	Contamination of displaced USDWs	
Damage of destruction of vegetation and fauna.	Interference of deep ecosystems	Damage to hydrocarbon and other resources	

Table 3: Generalised risks associated with geological sequestration of CO_2 (redrawn and adapted from Chadwick, et, al., 2008)

7.6. Governance Issues

Hydraulic fracturing has become a contentious environmental and health issue with France banning the practice and a moratorium in place in New South Wales (Australia), Quebec (Canada), and some of the states of the US. Concerns about environmental and human health effects associated with hydraulic fracturing include the contamination of groundwater, risks to air quality, the migration of gases and hydraulic fracturing chemicals to the surface, and the potential mishandling of waste. The potential costs associated with possible environmental cleanup processes, loss of land value and human and animal health concerns are as yet undetermined.

Given the intensity of many shale gas wells (Figure 12), the reason it is hard to dismiss public concern over the chemical composition and fate of the hydraulic fluids after the fracturing is completed (US Secretary of Energy Advisory Board, 2011). A comprehensive and well reasoned industry effort to educate the population (G. E. King, 2012) recognises and addresses much of the furore over hydraulic fracturing.

Building on this concern the United States Environmental Protection Agency is drafting regulations covering water use, chemical disclosures, wastewater discharges and injection wells to effectively sidestep the terms of the 2005 Energy Policy Act and bring in appropriate guidance and rules. However, given the dichotomy between State and Federal legislative primacy, the introduction of a new governance regime in the United States is under discussion and remains to be settled (J. A. Pardo, 2012).

In Europe, a group of environmental and health NGOs set out a list of very similar doubts and questions that are largely based on the claimed problem areas cited in the United States (EEB, 2012): The group call for a moratorium on all developments until their questions are answered.

Figure 12: Dense concentration of well sites; shale gas development in Pervis County, Mississippi, USA (Google Earth Image).

Two reports commissioned by the European Parliament (EU 2011 and Philippe & Partners, 2011) present slightly contradictory views on shale gas developments. The first (EU, 2011) notes the lack of a European Mining Law and the absence of an analysis of the available European regulatory framework covering shale gas developments: While it notes that there are probably gaps in the regulatory framework, when compared with other industrial developments, it concludes the current environmental impact assessment thresholds are probably higher than strictly necessary. The report concludes that the assessments should concentrate on a life cycle assessment (LCA) of the developments as when examined in detail each aspect of the life cycle is adequately understood and covered by appropriate existing legislation, if the rules are properly enforced. In particular they quote the EU Groundwater, Water Framework and EIA Directives and recommend that an EU extractive industries directive is developed that specifically includes shale gas developments. The second EU Commission report published in 2012 (Philippe & Partners, 2011) although limited to studies in Poland, France, Germany and Sweden, it recognises that shale gas developments employ some relatively new technology but considers it does not immediately need specific new legislation and concludes that no further EU or National regulation of shale gas development are necessary. The report contends that the existing water framework, groundwater and mining waste directives cover any associated environmental risks while the EU REACH Directive[19] covers the use of hydraulic fracturing fluid additives. However, the report further concludes that this situation should be kept under review as the scale of shale gas development grows. In May 2012 the UK approved shale gas investigations in NW England but stipulated the development must include carbon sequestration.

Finally, the 2012 draft New South Wales Aquifer Interference Policy (NSW Government, 2012) adopts a risk management approach that requires investigations of sufficient level to fully assess the risks associated with a development.

[19] Registration, Evaluation, Authorisation and Restriction of Chemicals EU Directive http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:136:0003:0280:en:PDF

8. Construction into the underground space

Traditional underground constructions such as foundations of buildings, cellars, wells and infiltration galleries are practiced already for many centuries. Cave dwellings have been in use in history in some areas of the world (e.g. in the French Alps, Pindus mountains in Greece, Cappadocia region in Turkey), but nowadays only on the Chinese loess plateau (Xinjiang) a very significant number of people still lives in caves (40 million people). From the late 19th century onwards, however, construction into the subsurface space has become much more intensive than ever before, in particular for purposes of storage and logistics. The motivation behind constructing underground is to a large extent the lack of space at land surface and the desire to protect environmental quality above the ground. In addition, underground space often offers a number of advantages in regard of the envisaged functions, such as a rather constant temperature and protection against certain external interferences and risks.

8.1. Categories of Construction

Pipelines, sewerage systems and cables

Pipelines are commonly used for transport and/or distribution of fluids, in particular water, gas and oil. In densely populated areas they are usually buried, at shallow depth and above the groundwater table. Leaks constitute potential pollution risks for groundwater, although distributed drinking water generally will be harmless. Leaking sewerage systems, mostly buried as well at shallow depth, present a much greater pollution risk (leaks are frequent and sewage contains pollutants). Cables for electricity and communication (telephone, Internet, TV, etc.) can be found at similar depths, but these do not constitute significant pollution risks to groundwater.

Traffic (tunnels and underground railways)

Tunnels allow traffic to pass an obstacle (mountain, river, canal, build-up area) or to cross a railway or road safely. Particularly dense tunnel systems are formed by urban underground rail networks. Since the middle of the 19th century, underground railways (known as: Underground, Métro, U-Bahn, Subway, etc.) have been constructed in urban agglomerations. The oldest ones are in London (1863), Istanbul (1889), Budapest (1896), Glasgow (1896), Boston (1897), Chicago (1897), Paris (1900), Wuppertal (1901), Berlin (1902), New York (1904), Hamburg (1912), Buenos Aires (1913), Philadelphia (1914) and Madrid (1919). At present (2011), there are 146 urban underground railway networks in the world, scattered over 54 countries.

If tunnels – as stand-alone constructions or as components of underground railway networks - are constructed below the water table, then the groundwater regime may be significantly disturbed during construction (e.g. by artificial well-point drainage) and land subsidence may occur by compaction of compressible layers. A recent example is provided by the North-South Metro Line construction project in Amsterdam, where leaking sheet pile walls caused groundwater to enter the tunnel under construction, resulting in damage to monumental historical buildings built in a zone of compressible formations (period 2004-2008). A rather similar groundwater-related problem during U-Bahn construction caused in 2009 the collapse of the famous Historical Archive of the city of Cologne (sand under the building removed by drained groundwater), with loss of human lives and many irreplaceable historical documents. After finalizing tunnel projects, the tunnels may have a permanent influence on shallow groundwater regimes, due to the presence of cofferdams, pile dams, immersed tubes, grouting, slurry walls or other obstructions to groundwater flow. In addition, some tunnels may form preferential locations for the entry of pollutants into groundwater systems.

Underground car parks and other underground constructions

There is a tendency to locate new car parks underground, in order to save space above the ground in urban areas. During construction, conditions and potential problems are similar to those of tunnel construction. After completion, car parks constructed under the water table may need permanent artificial drainage, in order to ensure the car park's stability. The same applies to subsurface urban areas with shopping centres, offices and storage facilities that gradually are developing in various metropolitan areas (e.g. in Montréal since 1962; nowadays also in Washington DC, Kansas, Seoul, Tokyo and Paris).

In several countries ideas are being developed for a more systematic and intensive approach to using the underground space for buildings with commercial or public functions. Impressive open spaces in the shallow subsurface do exist already in some cities – such as Paris, Jerusalem and Naples –, because this is where for centuries building materials have been extracted for local construction. These spaces are ready for getting a function.

8.2. Governance aspects

Probably in most countries regulations do exist regarding different categories of underground constructions. However, poor enforcement, budgetary problems and unexpected problems sometimes may lead to poor compliance with these regulations, such as happened in the Amsterdam North-South Metro Line project, where local politicians ignored technical advice and negative test results in order to keep their prestigious project going.

Several classes of underground constructions will require permanent monitoring to ensure that interactions with subsurface formations and groundwater remain within safety limits. This particularly applies to the construction of sewerage systems at depth.

Although underground constructing may affect groundwater systems, it seems that the subject is rarely included in groundwater management plans and that groundwater resources managers are rarely involved in regulations and decision-making on underground construction.

9. The planning process and aquifer use

Planning processes related to the underground can take many forms, depending on the chosen scope, focus, approach and other factors. In the most concrete form, planning processes are related to a single technical project activity, e.g. the construction of a well for an individual farmer, the development of an underground waste disposal site, the exploitation of a mine, the construction of a tunnel or the installation of a sewerage system. Although the degree of complexity may vary enormously, the planning activity in all these cases focuses on successful completion of a technical project and includes a breakdown and description of single project activity, allocation of tasks and responsibilities, cost estimates, time schedule, etc. The presence and properties of the subsurface are taken for granted; investigating the subsurface usually receives no more attention than needed for a proper design of the envisaged technical works and for complying with formal obligations (e.g. an environmental impact assessment). This is the oldest and most easily understood type of planning: Straightforward and focused on tangible outcomes, according to a clear time-path. At the other side of the spectrum we may observe forms of comprehensive integrated planning. They do not focus on single technical activities, but either on a certain sector (e.g. water supply or waste management) or even on a certain natural resource (integrated water resources management, land use management, subsurface management). Integrated planning takes a broader perspective and especially the latter category – natural resources management – focuses on high-level objectives (e.g. sustainability, macro-economic impact, equitable distribution of benefits, environmental protection) rather than on short-term technical outputs. Single technical activities may be included as means to achieve these objectives, together with non-technical measures that intend to influence people's behaviour.

9.1. Current practices

Single-project planning always emerges when subsurface works have to be carried out. In most low-income countries this is still the predominant form of planning, not or only weakly linked to any form of more integrated planning. Absence of significant integrated planning is in the first place explained by scarcity of means (budgets, expertise, institutional infrastructure), but also because its potential benefits are not yet widely understood and/or because countries cannot afford (financially or politically) to adopt the precautionary principle[20]. In other countries, mostly post-industrial ones, over time a tendency can be observed towards integrated planning, to which single-project planning is made subordinate. In a first phase often a sector-oriented integrated planning was adopted (e.g. public water supply of a town or region), which allowed to select an optimal mix of components to achieve the operational objectives of the entire sector. After having experienced the interdependency between sectors and the degradation of certain functions of the underground (e.g. groundwater depletion or groundwater pollution), area-specific resources planning (e.g. a water resources management plan) came into vogue in certain countries or states. They constitute a general framework specifying measures to be implemented and criteria for judging whether proposed technical activities should be allowed or not, based on the precautionary principle.

9.2. Looking towards the future

Human activities related to the underground – be it for abstraction of natural resources, land use, storage of waste or energy, underground construction or other purposes – will steadily become more intensive in the future. Hence, the interferences between the different activities are intensifying accordingly, externalities will become more pronounced and irreversible degradation of the natural resources is likely to occur. Not only do these trends legitimize government interventions on the basis of a natural resources management plan, they strongly motivate them as well, because without such interventions societal opportunities may be lost and natural resources irreversibly damaged. Here lies an enormous challenge for countries where integrated natural resources management (in particular IWRM) is not yet common practice. Even where integrated management is practiced, it is at present usually still separate for different policy fields: water resources management, mining, land use planning, waste disposal, use of shallow underground space, etc. Further development of the integrated management approach to some of these fields (e.g. use of shallow

[20] The precautionary principle states that if an action or policy has a suspected risk of causing harm to the public or the environment, the burden of proof that it is *not* harmful falls on those taking the action.

underground space) and making the management plans in different policy fields fully consistent are the next challenges.

Part 2 Diagnostic– including constraints/barriers, potentials, and safety issues

10. Constraints and Opportunities

Many developments outlined in the proceeding sections are in the energy sector or minerals production and processing sectors and given the high energy usage in mining and processing they are basically high cost integrated projects. The preceding sections have also included considerable diagnostic analysis and examples of how concerns over groundwater availability and quality lead to the introduction of controlling legislation.

In Europe and North America, the public campaigns are generally strong enough to exert pressure on politicians to implement environmental legislation. Elsewhere this may not be the case and many subsurface developments have been undertaken by commercial enterprises under an initially weak or non-existent regulatory regime. For instance, China's current production of rare earth elements has a high environmental impact. In Europe and North America such mining practices would require implementing environmental measures that would result in a high production cost.

Under centralised planned economies, the state has controlled and developed both the energy and mining sectors.

Although common to all scientific and governance fields, the need to develop an internationally accepted dictionary of definitions and a standardised system of units of measurement will contribute to the transfer of knowledge. It may also reduce or eliminate dangerous or costly of embarrassing mistakes as seen with the crash of the Mars Lander Mission (North Carolina EPA, 2010).

10.1. Barriers and constraints in adopting an orderly path

Lack of data/information and insufficient knowledge of relevant processes

An orderly governance process regarding the exploitation of groundwater and other uses of the underground requires in the first place sufficient information on the subsurface down to relevant depths. Knowledge of the underground is in practice usually based on very limited data, based on which an image is interpreted that is subject to rather large uncertainties. Due to these uncertainties there is significant risk in all subsurface activities (especially the very deep ones), but reducing risk by collecting additional field data is very expensive and often considered not affordable. Since human interest and human behaviour are part and parcel of using and governing the subsurface and its resources, it is necessary to have sufficient information on the socio-economic and political settings as well. Although more visible than the underground, these aspects are often overlooked.

Apart from data and information, it is also necessary to have good knowledge on the relevant processes. Only then it is possible to make reasonable predictions of the impact of any set of measures considered. In particular the assumptions on human behaviour are often overly simplistic. In many cases, the content of governance strategies and the required overall vision are limited by insufficient data, information and knowledge.

Insufficient institutional capacity and mandate to organize an orderly path

Good governance is not spontaneously emerging. It needs continuously initiatives to be taken and activities to be carried out by key partners in the process. Sufficiently strong specialized institutions, with proper mandate and recognized by stakeholders, are indispensable to take the lead in planning and management. Often they are missing, not strong enough or not sufficiently dedicated.

Lack of funds

Sufficient funds are needed to enable the activities required to ensure good governance. Often such funds are not there, or not available at the appropriate moment.

Inadequate legislation and regulatory frameworks

Most countries probably have a law on mining activities, and water laws have become rather common as well. For some underground activities, however, specialized laws and regulations may be missing, which may create a vacuum between government agencies and private parties, with the risk of conflicts or issues not properly addressed. In addition, existing legislation related to different aspects of the underground may be partly conflicting or confusing.

Insufficient political support or vision

The benefits of governing underground natural resources are often not properly understood by politicians or the subject may not fit into their agendas. Rather than being involved in activities of restrictive nature politicians may have preference for supporting activities that give them more positive visibility on the short term. Nevertheless, political support is essential to create conditions for the development governance processes (funding, legislation, institutions, positive message to stakeholders).

Insufficient government power

If governments have very limited power in the area concerned, then they are incapable to play an adequate role in governing the underground resources. In most cases, this will shut the door to the development of good governance of subsurface resources.

Lack of transparency and communication on planning, decision-making and implementation

Once initiatives are taken for resources management, the population of the area concerned as well as organisations involved in certain related activities should be co-operative and comply with regulations. Often insufficient attention is paid to informing the public on the planning, decision-making and implementation processes, with the result that anticipated co-operation and compliance are not forthcoming.

Insufficient involvement of relevant stakeholders

This is related to the previous constraint. Under given circumstances, certain groups of stakeholders expect to play a certain role in the government process. If they are ignored by dominant parties (e.g. a government agency) then their views and preferences are not incorporated and they may become frustrated, non-cooperative or even inclined to sabotage.

Lack of mutual confidence between key actors (including lack of balance of power)

Parties involved have often a negative image of other parties, e.g. by considering governmental agencies arrogant or corrupt, technical-scientists as not having contact with the ‘real world’ and local people as not clever enough to decide about their own future. As long as such negative perceptions remain, smooth and successful cooperation is impossible.

No consensus on facts and on predictions

Given the usual scarcity of information, interpretations and uncertainty play a role. Hence, differences of opinion on the factual situation and on predicted futures may easily arise. Sometimes such differences of opinions are influenced by the different stakes of the parties involved. If consensus is completely lacking, then any actions to move forward may come to a standstill.

No consensus on preferences or on allowable risks (conflicts of interest)

Conflicts of interests are always present in complex situations where ‘common pool’ resources are being used and externalities are created. Under favourable conditions, ways will be found for conflict resolution and for negotiating a compromise. If this is not possible along formal lines, then groups of activists may organize pressure in order to call attention and support for their point of view, or groups may boycott the governance process or decisions taken.

Rapidly changing boundary conditions

Governance processes have their own pace, but because of so many parties involved they proceed usually rather slowly. Consequently, before plans have been implemented fully, they may be outdated already because of rapid changes of boundary conditions (demography, climate change, economic situation, etc.) departing from the assumptions made during plan development. This is to some extent the fate of each planning activity.

It should be taken into account by incorporating sufficient flexibility for making adjustments to measures when required.

The list of barriers, constraints and other complicating factors presented above is not exhaustive, but includes a number of important items. Roughly, they can be subdivided into two groups: the first one related to enabling conditions for developing government, the second one to how to play the game. As can be observed, there are clusters of mutually dependent items. A perfect world where all these constraints and barriers are absent does not exist. People have to be creative to adopt approaches where existing barriers and constraints are not paralyzing the process or even can be reduced. One of the key conditions that has to be addressed is creating sufficient political and public support for governing the underground resources. This will be the key to reducing all other constraints and pave the road towards acquiring the means needed and to forging cooperation between the main actors.

10.2. Scope for securing social and environmental benefits through smarter regulation of the underground space

“Geosciences are hard sciences, valid at any time and place. Law sciences are soft ones, varying from country to country, from time to time. They must adapt to a sustainable use of underground space.” (P.Duffaut)

The world’s subsurface space is already used in a variety of ways, ranging from occupancy to disposal and the bulk storage of materials and fuels. In the future it is likely that it will be put to further use in response to trends in technology, resource supply and demand, socioeconomics and geopolitics. Future uses are likely to be in the area of increasing occupancy (both commercial and residential), the secure storage of documents and data, the storage of carbon dioxide for carbon abatement, natural gas, compressed air stores of energy from traditional and renewable sources, the use of underground heat in buildings and the deep geological disposal of wastes, including radioactive ones.

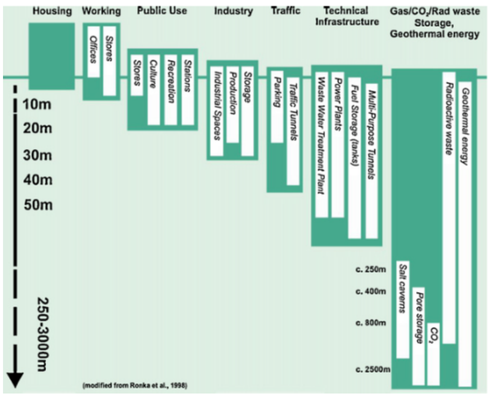


Figure 13: Feasible depth ranges for underground activities (based upon Ronka et al., 1998)

Increasingly underground space is seen as playing a more significant role in the cities of the future, given the huge social and environmental costs of surface development.

Worldwide, the last two decades have seen rapid development in the utilization of underground space and it appears that more use will be made for storage purposes, particularly for energy, and more of our lives are likely to be spent underground as shopping, recreation and even accommodation will be found in the subsurface. Because of its multiple uses and of the interdependencies of those uses, the subsurface will be more crowded, which will necessitate more integrated and comprehensive planning, regulation and monitoring. This will require more geological research to inform policy and regulation and to gain public engagement and acceptance. The risk involved in the various uses of underground space will have to be assessed. For example, a survey at the European Union member state level indicates that regulation and research on the potential impacts of Underground Thermal Energy Storage (UTES) on groundwater resources and the subsurface environment often lag behind the technological development of, and ever-growing demand for this renewable energy source. The lack of a clear and scientifically underpinned risk management strategy implies that potentially unwanted risks might be taken at vulnerable locations such as near well fields used for drinking water production, whereas at other sites, the application of UTES is avoided without proper reasons

The lateral expansion and increase in population that have characterized urban growth and development patterns of the last few decades have produced cities that are often inconsistent with the principles of sustainable development. Due to the high rate of global urbanization, problems such as greater traffic congestion, higher levels of air pollution, lack of green space, and insufficient water supplies not only affect the cities in which they occur, but extend around the world. Cities that optimize the use of the third dimension are seen as a possible path to sustainable urban form. The urban underground possesses a large untapped potential that, if properly managed and exploited, would contribute significantly to the sustainable development of cities[21]. Traditionally, planning of underground works is done on a single-project basis with little consideration of other potential uses. This approach often produces interference between uses (e.g. road tunnels interfering with geothermal structures), causes negative environmental impacts (e.g. groundwater contamination), and restricts innovative opportunities for sustainable development (e.g. using waste heat from metro lines for heating buildings).

Regulating the utilization of underground space and resources

The challenge ahead will be the definition of policies and science based methodologies to regulate the multiple uses of the subsurface space taking into account all the underground space and resources simultaneously and, for projects of national importance including storage, legislation to lessen the effect of local opposition relative to the 'national need'.

Subsurface use is restrained by sets of laws and regulations firstly devised for constructions over the surface. The extension of private property to the centre of the Earth for example, is today counterproductive and might be replaced by a better scheme. The subsurface of a city might be a Public Private Partnership like the common parts in a condominium. Town planning must install all utilities inside common galleries. Transportation needs should make a better use of underground roads and railways. Up to now, transportation of freight and goods inside cities appears a severely underrated problem.

10.3. Reconciling the role of the private sector and the public interest

In common with the regulation of most modern developments, establishing appropriate legislative controls usually only follows after noticeable adverse impacts have already occurred.

The current arguments over the classification of hydraulic fracturing of wells during shale gas developments show how lobbying by vested interests is designed to sway legislation in their favour. However, this can be against the public interest when the result is a blanket approval for totally uncontrolled developments: The history of international mineral exploration and development corporations rightly leaves them open to the public view that the companies have generally behaved in a cavalier way when not held to account by strong local regulation. In the past, the disregard of international corporations can be considered to have challenged the primacy of host country. Recent examples of this are the dumping of toxic crude oil waste in the Ivory Coast by Trafigura and similar dumping of radioactive material in Somalia. In the United States, lead contamination caused by the flooding of the underground workings around the Picher Mines in Oklahoma was found to be so toxic that the US EPA deemed clean up was impractical: A Federal buy-out scheme was put in place and the town and surrounding mining area was completely evacuated in 2009. All these incidents posed an immediate threat to the local and regional groundwater sources.

Establishing robust legislation to protect public interest in the poorer countries where enforcement and regulations lag behind those of the more economically advanced nations calls the setting and policing of internationally recognised laws. The EU industrial directives provide are examples of appropriate regulation.

[21] The use of the four principal resources of urban underground (space, groundwater, geothermal energy and geomaterials) can be optimized to help create environmentally, socially and economically desirable urban settings. For instance: space can be used for concentrating urban infrastructure and facilities, as well as housing, parking facilities and transportation tunnels; energy from geothermal sources and thermal energy stored in the underground can be used for heating and cooling buildings, thereby reducing CO_2 emissions; groundwater can be used for drinking water supply; and geomaterials from urban excavation can be used within the city to minimise long-distance conveyance.

10.4. Conditions for 'acceptable' development of deep groundwater and planned depletion

The dominant abstraction from deep aquifers is by large scale irrigation projects in areas with a low population density. In many cases the developed aquifers receive very little modern recharge and the abstraction takes groundwater from storage. In most cases the decision to continue withdrawing groundwater from storage is based on political judgement that in turn relies on a reasoned technical assessment of the scale of the resource. In the case of the High Plains aquifer in the United States an arbitrary limit has been set in Texas and in other states based on retaining 50% of the existing groundwater in storage at a certain date in the future (usually 2050). However, a huge depth of scientific study is needed to judge if this large-scale High Plains aquifer abstraction is acceptable and ultimately the verification of the success of these management plans, or otherwise, will depend on a well funded, assiduous long-term monitoring programme.

10.5. Conditions for regulated use of deep aquifer stores and repositories

The four main applications of deep drilling that impact on groundwater are water supply, shale gas, CO_2 sequestration and geothermal development. In many cases the hunt for new sources of freshwater will affect the stored groundwater volume and introduce dynamics.

As with the large regional aquifer developments, the shale gas and CO_2 sequestration projects target formations are located in the deep sedimentary basins. However, looking at Figure 12 must pose the question of what happens when such a shale gas development is depleted and scheduled for abandonment given the cited US $ 0.5M (at 2012 prices) for the plugging of each well to which must be added the clean up and disposal of the storage ponds and foundation works. It is highly unlikely that the system operators will be willing or be in a financial position to meet these costs unless some form of escrow account is set up during the operational life of the scheme. (The same goes for all underground and open cast extractive mineral developments).

As also previously indicated, recommendations have been made for the European Union to develop an extractive industry directive to control such developments in the 23 EU States. Developing controls for deep wells for such a directive will undoubted draw heavily on the United States Environmental Agency injection well classification (Appendix 1): In doing this the EU directive will be in a position to tidy-up the apparent discrepancies with this classification of the hydraulic fracturing wells and distinguish between the deep and shallow non-toxic waste disposal wells currently included in the same class under the US EPA Underground Injection Controls.

It is felt that the UNEP and a new EU extractive industry directive could prompt the development of a set of internationally accepted regulations.

Part 3 Prospects

11. Future role of technology in managing the underground space

Consideration of the range of foreseeable activities set out in Figure 13 shows that the majority of developments lie within the capabilities of current technology and certainly more efficient ways will be found to undertake underground developments.

Apart from the very high cost, the hyper cautious approach to implementing secure permanent high level radioactive waste storage is largely driven by a lack of confidence in the known technology as set out by B. Comby (2005). From the tunnelling aspects, technology has enabled several undersea crossings to be constructed and accepted for everyday use: Notably the 53.8km Seikan Tunnel between the Japanese islands of Honshu and Hkkaido. This tunnel reaches a maximum of 140m below the seabed and was constructed through very difficult geological ground conditions. There are many other land tunnels with the longest being the 57,1km Gotthard Base East Tunnel that is scheduled to open in 2016 and cuts through the complex geology of the Alps. The principal technical concern with radioactive waste disposal sites is leakage to surface and groundwater systems either through corrosion of the storage capsules or damage caused by seismic activity. Both these risks have been addressed and accommodated in the construction of these tunnels.

With the 2012 linkage established in the United Kingdom between shale gas abstraction and CO_2 sequestration, the future of these two developments can be expected to accelerate as the demand for energy and gas continues to grow.

However, this growth can be expected to bring further developments in managing the underground space. The first developments are likely be the expanded use of injection wells to create saline intrusion barriers and the possible use for large-scale subsidence control. The creation of saline barriers is already in place for the protection of concrete foundations from salt corrosion and J. F. Poland (and Working Group, 1999) reports on the large-scale, long-term use of treated fresh water injection wells to create a hydraulic barrier (pressure ridge) to prevent saline intrusion in southern California.

The small scale use of injection wells for subsidence control to compensate for settlement caused by the construction of tunnels and highways in Oregon is recorded in the US-EPA (1999) paper on Class V UIC wells. However, the main cause of wide spread land subsidence is formation compaction due to the abstraction of groundwater form confined aquifers: Figure 14 shows the extent of this form of subsidence recorded in the United States.

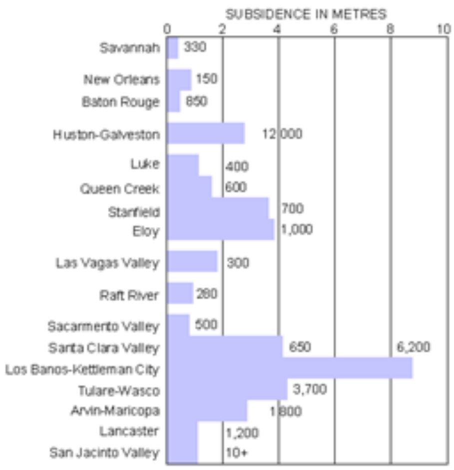


Figure 14: Land subsidence due to groundwater abstraction in the United States: Numbers refer to area of basin in km2 (Redrawn from Unesco, 2000).

Outside the United States, F. Poland (and Working Group, 1999) describe various schemes, test and pilot schemes to re-pressurise the confined aquifer responsible for the subsidence in Shanghai, China, Venice, Italy and Niigata, Japan. The increasing frequency of flooding in Bangkok, Thailand has brought the subject of subsidence control and reversal into focus. The nature of the poorly consolidated sedimentary formations in the Lower Chao Phraya Basin and the sheer number of existing water wells into all aquifer horizons suggests that achieving sufficient hydraulic sealing of the aquifers may not be possible.

In other areas there could be a possibility of pressurising the shale horizons using the same technology used for shale gas abstraction and CO_2 sequestration. Given a 5% shale porosity, the volumes of injected water to achieve over-pressurisation and hence land uplift will be less than that required to achieve the same effect in a more porous aquifer. It is likely that such sites exist in the Mississippi Delta. Precision GPS level measurements are now available to test the effectiveness of subsidence control pilot schemes.

A major constraint to the use of injection wells for any purpose is the role of bacteria and biofouling in reducing the permeability of the formations around the injection well wall. While the use of biocides is accepted for the development shale gas wells, specific studies will be needed to establish appropriate sterilisation processes where drinking water aquifers are involve. Indeed the whole subject of underground bacteriological action above and below the water table probably represents a major area for future investigation and research beyond its common use for bioremediation of contamination plumes. The contribution of bacteria to the rock weathering process is becoming increasingly recognised and the prospect of identifying biological/viral activity and zoning in aquifers is beginning to be investigated for both the mineral recovery and groundwater quality studies (H. S. C. Eydal, 2009). Current research[22] shows the long-term presence (at least 25Ma) of viral and bacterial lifeforms similar to those found around the mid-oceanic rift "black-smoker" volcanic plumes in groundwater contained in granites 3km below ground with radioactive decay and sulphur providing the energy sources (H. S. C. Eydal, 2009).

In the near term, rare earth elements will provide the major impetus for new mining and processing projects and these developments will create further demands for groundwater supplies, energy and pose additional environmental threats in the geographical areas as shown on Figure 15.

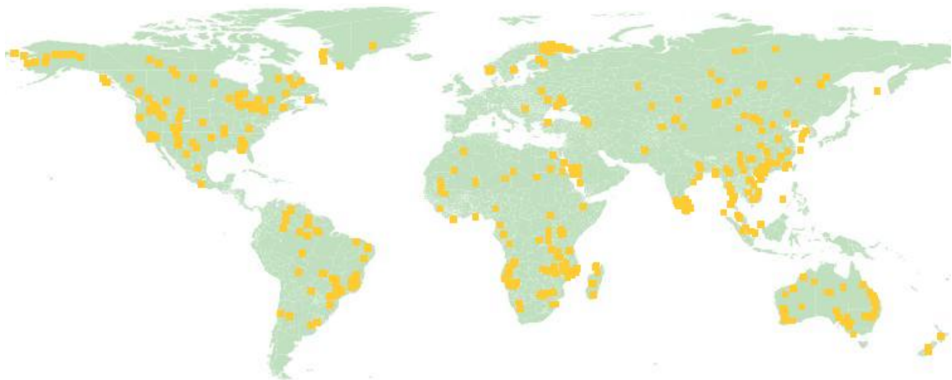


Figure 15: Distribution of rare earth mineral occurrences (from G. J. Orris and R. I. Grauch, 2002).

[22] Princetown Univestity news release 2006, Two miles underground, strange bacteria are found thriving http://www.princeton.edu/main/news/archive/S16/13/72E53/index.xml?section=newsreleases

12. Options for enhancing the private sector's contribution to groundwater governance – an initial assessment.

The shallow crust of our planet, from near surface to depths of several kilometres (i.e.: the maximum commercially reachable depths with present drilling technologies) contains resources which are essential for human development and well being: water, energy, geologic materials (minerals, construction materials), and space. While this is apparent and widely recognized, efforts to improve our knowledge and understanding of the geological conditions and active geophysical and thermodynamic processes at depth have been generally conducted in a fragmented way, sector by sector, with little interchanges of knowledge and experience, thus hindering the achievement of the level of integrated reconstruction of the subsurface which would be needed for introducing sustainable governance principles. Due to the high costs and technological sophistication of subsurface information gathering, this is particularly true for developing regions of the world, where countries often lack the capacity and the knowledge necessary for the sustainable long term management of their own underground resources.

Groundwater is no exception. What lies below the first unconfined aquifers is often scarcely known by those with administrative responsibilities in natural resources planning. Notwithstanding the fact that groundwater research and regional aquifer studies are critical elements of the future health of the economy and the environment, the current level of funding for regional groundwater resource work is inadequate to deal with future needs, even in the developed world.

Over the decades the energy and mining industry has developed an unique wealth of organized information on the subsurface, and has consequently acquired the ability to minimize the mining risks involved in searching for hydrocarbons, geothermal heath, mineral ores. Huge investments have been, and continue to be made in order to improve the understanding of subsurface geological conditions in prospective regions globally, on land and beneath the ocean's floors. The results of these tremendous exploratory efforts have largely and understandably remained property of the investors and of service and consulting firms. Competition has prevented in most cases the broad circulation of this unique patrimony of expertise and knowledge. In some cases however, as a for example in the Saharan region and the Arabian Peninsula, oil exploration has led to the discovery of huge, albeit non renewable, high quality deep seated groundwater resources, which are now being successfully exploited. Without the investments of the oil industry this would have never happened.

There are few if any industrial processes that do not need a constant supply of high quality water, and some industrial sectors are major water users. For example, one of the most significant variables for the entire mining industry, in terms of current operations as well as the materialization of future projects, is the availability of water. Mineral processing requires water, whether it be flotation, leaching or any other kind used. Water and energy issues are also interconnected; for example, the delivery of water depends on energy for pumping, and many forms of energy production require a dependable water supply. Other private stakeholders that in various ways interact with groundwater are the soft drinks and beer industries[23], obvious major water users, as well as bottled water producers, water utilities, the construction sector, the agro-industry.

All groundwater users, from the large private multi-national enterprises, to the farmers and the urban planners, recognize the need for improved knowledge on, and governance of groundwater, key foundations of the sustainable long term use of this precious resource. The challenge however exceeds the mission or capabilities of any one intergovernmental, governmental, university, public or private sector entity. As a consequence, each of these entities has a supporting role to play in protecting human health and the environment by contributing sound technical guidance on groundwater issues.

International organizations, governmental bodies, academia, geological surveys and professional and users associations are keen to join forces and spearhead this endeavour. However, the private energy and mining industries, the water companies, the service and consulting firms, and other private stakeholders, until recently, have not had any platform to discuss groundwater governance in particular. But new initiatives are developing.. For example, the World Business Council for Sustainable Development (WBCSD) provides an opportunity to discuss water governance in general (http://www.wbcsd.org/work-program/sector-projects/water.aspx). Beyond this, there are still huge challenges for making the wealth of information and

[23] More than 90% of beer is water and an efficient brewery will typically use between 4 and 6 litres of water to produce one litre of beer

knowledge the private sector has on the underground available to all parties in the groundwater governance debate. In the case of groundwater and development of the underground space, without private sector commitment, expertise, knowledge, and financial resources, the governance of groundwater and the management of the subsurface might prove impossible or simply lead to more overly-bureaucratic regulation. This may inhibit innovation in the management of the underground space rather than encourage good practice. Opportunities for cooperation will have to be explored based on an assessment of the multiple, sector specific benefits that the private sector may derive by investing its expertise and human and financial resources within the context of an international effort to promote groundwater governance and contribute to expand the knowledge of the groundwater resource.

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13. The future role of hydrogeologists in regulating the underground space

In 1999, the British Geological Survey in its official magazine Earthwise published the following statement:

“The last decade has seen the rapid development in the utilization of underground space and this development seems to be only the beginning of the race for space”.

Encouraged by technological advances, the race is now on, particularly in urban areas and mega-cities, where demand for subsurface space is rapidly growing, and in response to our crowded world’s ever increasing needs of storage space, groundwater resources, and energy. As urbanization and infrastructure are more and more interacting with groundwater resources and underground geological materials, the need grows for geological expertise in the multi purpose planning of subsurface use. In parallel, if geologists want to meet the new challenge, they will have to adapt to this new role, and acquire the broad and multidisciplinary vision necessary to become key advisors in defining and implementing policies for the sustainable utilization of subsurface space and resources. Hopeful opportunities do exist, especially if hydrogeologists follow this call to action to strive for progress in both the science issues as well as the societal/political debates involved.

The Deep City Project presented in 2006 by the University of Lausanne shows an interesting approach to subsurface regulations (Figure 15). The project, motivated by the critical congestion of many cities around the world leading to environmental and public health problems, shows a full understanding of the potential role of geology: “Defining the rules for multi-uses of the resources must take into consideration the various geological formations present below the city and their properties. As underground conditions are very variable from a city to another and even variable at the scale of a city, geological knowledge and 3D modeling is the first step in the process of planning the long term multi-uses of underground space.” This planning must consider the resource of space for underground construction, but also other underground resources such as geomaterials, groundwater and geothermal resources. The management of the urban underground must not be sectorial but must integrate the potential of all these resources.

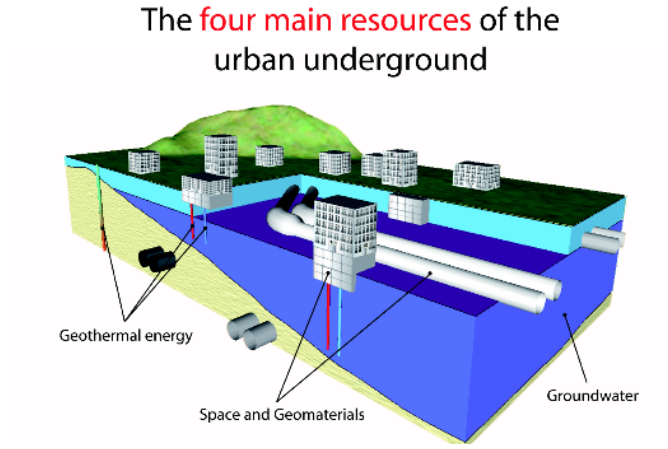

Figure 15: From “DEEP CITY project “ (NRP 54) by Parriaux Aurèle*, Tacher Laurent*, Blunier Pascal*, Maire Pierrick** 2006

14. Conclusions

The subsurface and its resources are used for many purposes: abstracting groundwater; extracting minerals, oil and gas; developing geothermal energy; waste disposal; storage and recovery of substances and heat; and accommodating technical infrastructure. There is a general trend towards more intensive use of the subsurface and its resources.

Although these different categories of use are currently or potentially interfering, management and governance is fragmented over the individual categories of use. The degree of control to prevent environmental impacts and other externalities varies geographically and according to type of use from virtually absent to satisfactory.

Deep aquifers so far are only sparsely tapped around the world for abstracting fresh water. They certainly offer opportunities for more intensive exploitation, in particular as an emergency resource and as a buffer for mitigating climate change impacts. Nevertheless, most deep seated aquifers are no or only little recharge and thus offer mainly non-renewable resources. Depending on depth, deep seated aquifers may come under different legislation and institutional mandates than aquifers at more shallow depth (mining versus water resources).

Mining and hydrocarbon activities traditionally follow an approach much more focused on detail rather than broad groundwater management. They pose considerable risks to groundwater resources and the environment and therefore need to be strictly regulated to prevent damage. Countries with weak legislation and enforcement capabilities are likely to be faced with a growing legacy of resource and environmental problems.

Although its use is annually growing at a rate of 14%, geothermal energy remains today an underdeveloped energy resource, compared to the vast amount of thermal energy offered within the Earth's crust. Access to a huge resource that will last thousands of years is theoretically possible, but requires a number of serious technical and financial constraints to be overcome.

The subsurface is progressively being used for storage of hazardous waste such as nuclear waste and other liquid or solid wastes. Related activities (often using similar techniques such as injection wells) are the injection of fluids for soluble mineral extraction, the storage and recovery of heat and hydrocarbons, carbon capture and sequestration (CCS), hydraulic fracturing ('fracking') and the injection of residual geothermal fluids. All these activities lead to pollution of the subsurface with exotic substances, many of which may be harmful or even dangerous. Strict adherence to adequate regulations therefore are necessary to protect the subsurface environment and related resources. Such regulations exist and are imposed in some countries, while in other countries they are absent, insufficient or not enforced. Against some types of hazardous waste disposal strong public opposition is observed (action groups), especially related to nuclear waste disposal and to CCS, usually because the government is not transparent or there is no confidence in the government's risk assessment and/or the quality of the intended protecting measures.

Nuclear weapons testing is not intended as a method to bring substances into the subsurface, but it does result in nuclear contamination of the subsoil which is a sensitive issue. Therefore, strict protocols and careful investigations are needed to avoid serious degradation of the subsurface.

Use of the subsurface space for underground pipelines, cables, car parks, buildings and other technical infrastructure is increasing. Regulations on such underground construction activities probably do exist in most countries, but compliance may be weak in many cases. The subject is rarely included in regular groundwater management plans. Problems that arise tend primarily to affect the underground constructions themselves rather than that they produce externalities.

Planning the different categories activities related to the subsurface is in most countries extremely fragmented and uncoordinated. Tendencies towards integrated management of the use of the subsurface and its resources can be observed in some countries. Integrated management certainly has the potential to reduce problems and thus to bear fruit.

In the endeavours to establish adequate governance, several barriers and constraints are encountered. They include lack of data and information; insufficient institutional capacity and mandate; lack of funds; inadequate legislation and regulatory frameworks; and many deficiencies in the government's capability to understand/analyse the problems, develop a vision and adequate plans, communicate transparently, gain confidence of the population and implement the required measures.

Smarter regulation of the utilization of underground space and resources will secure social and environmental benefits. This may help reconcile the role of the private sector and public interest with the potential to reduce public-private conflicts of interests. However, world-wide there is still little vision on how to exploit non-renewable fresh groundwater resources for optimal societal benefit.

Promising elements to achieve improved governance of the subsurface and its resources in the near future are technological progress; a closer co-operation between the public and private sector; and a stronger involvement of geologists and hydrogeologists in the debate on the subsurface and its resources, and in the development of strategies and plans for their management.

Therefore, while almost all deep groundwater developments and subsurface activities are expensive, they can be technically engineered to be safe and sustainable. However a mix of demographic, political and development pressures have lead to the implementation of projects without necessarily a full understanding of their probable long term hydrogeological and environmental impacts. When environmental damage has occurred this has often resulted in long term disputes between the public, politicians and private enterprises over liabilities and responsibilities for remediation. While governments will respond in time to address the problems with appropriate legislation, the legacy of damage to aquifers tends to remain and incite public action. Given The default position of public and private enterprises is generally that of denial or shifting blame and in aquifer systems the identification of who has been responsible for particular pollution damage can impose a large burden of proof on the plaintiffs. In many cases, the public have developed an entrenched distrust of the big corporations and their development plans. While this position is being brought under strong governance in the wealthier nations, many other states with politicians driven by the wish for rapid growth and poverty reduction often feel compelled to accept international funded developments that in the long term will prove to continue the legacy of environmental damage.

Finally there is much need for coordinating or even integrating legislation and institutions aiming for the proper management and control of the different uses of the subsurface and its resources. Changing this current experience with project operators and developers who failed to exercise the proper control of their activities suggests that international policies are required to force them to do so by imposing selective trading and/or financial and legal penalties.

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18. Appendix 1: United States Environmental Protection Agency – 2012 Classification of Injection Wells (UIC Regulations)

19.

In the United States Injection wells first came in to use in the 1930's to dispose of oil field brines. When the practice became common in the 1960s and 1970s, groundwater contamination problems were frequent due to well integrity failures. These were addressed by the US 1974 Safe Drinking Water Act and the 1980 US EPA Underground Injection Control (UIC) Regulations (US EPA, 2001). In the US each State has primacy over the adapting and applying the Federal EPA guidelines and regulations providing the met they meet the minimum United States Environmental Protection Agency (US EPA) requirements or the state regulations achieve the same of higher degree of protection of the Underground Source of Drinking Water (USDW[24]) aquifers.

US Environment Protection Agency Classification	Injection Well Description	Number*
Class I	Wells used for disposal of industrial & municipal waste inject far below the lowermost USDW	4841*
Class II	Wells used to inject fluids associated with oil and natural gas production	1,500,000*
Class III	Wells used to inject fluids for the extraction of minerals	19,9253*
Class IV	Wells used to dispose of hazardous or radioactive wastes into or above a USDW	540*
Class V	Wells are used to inject non-hazardous fluids underground	650,000
Class VI	Wells used for injection of carbon dioxide (CO_2) into underground subsurface rock formations for long-term storage, or geologic sequestration.	

Table A5.1: Injection Well Classification based on US EPA 2012[25]
* number taken from the Ground Water Protection Council, 2007

The US EPA UIC Programme is designed to regulate the construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal. The 2012 US EPA classification for injection wells is shown in Table A5.1. Comprehensive US EPA reviews of each injection well class are available.

The 2012 US EPA Class II includes three categories of Wells used to inject fluids associated with oil and natural gas production wells (Abridged USA EPA Text): i) Enhanced Recovery Wells inject brine, water, steam, polymers, or carbon dioxide into oil-bearing formations to recover residual oil and—in some limited applications—natural gas: ii) Disposal Wells inject brines and other fluids associated with the production of oil and natural gas or natural gas storage operations. Class II disposal wells can only be used to dispose of fluids associated with oil and gas production. The 2012 US EPA records show approximately 144,000 Class II operational wells injecting over 7.57Mm^3 of oilfield brine per day. Disposal wells represent about 20 percent of Class II wells: iii) Hydrocarbon Storage Wells inject liquid hydrocarbons in underground formations (such as salt caverns)

Broadly the use of Class V non-hazardous fluid injection wells falls in to three categories: for the disposal of treated and untreated domestic, business, agricultural and industrial waste and surface water drainage into or above USDW aquifers; for returning water extracted for thermal heating and cooling or geothermal power generation, and; for aquifer recharge, aquifer storage and recovery, aquifer remediation, creation of saline intrusion barriers, subsidence control and for wells used to test new technologies. The US EPA[26] sets out the permitting requirements and applications for 22 Class V specific well applications. Aquifer recharge wells and ASR wells (storage and recovery) are included in Class V[27].

[24] A USDW is defined as an aquifer or a portion of an aquifer that: Supplies any public water system; or 2. Contains sufficient quantity of groundwater to supply a public water system; and i) currently supplies drinking water for human consumption; or ii. contains fewer than 10,000 milligrams per liter (mg/L) total dissolved solids (TDS); and **NOTE**: Although aquifers with greater than 500 mg/L TDS are rarely used for drinking water supplies without treatment, the Agency believes that protecting waters with less than 10,000 mg/L TDS will ensure an adequate supply for present and future generations.
[25] http://water.epa.gov/type/groundwater/uic/ (updated of - Thursday, March 15, 2012)
[26] http://water.epa.gov/type/groundwater/uic/class5/classv_study.cfm#two
[27] Full EPA review at: http://water.epa.gov/type/groundwater/uic/class5/upload/2007_12_12_uic_class5_study_uic-class5_classvstudy_volume21-aquiferrecharge.pdf

However, the EPA classification of wells appears to have been revised since the 1999-2001 reviews with some Class V wells for example used for In-Situ Fossil Fuel Recovery Wells now reassigned to Class III.

While current United States federal and state EPA regulations have severely restricted new USDW aquifer contamination, the effects of legacy waste disposal contamination and agricultural practices was widely detected in many public water supply wells in the late 1990s (US EPA, 1999b).

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