SALINE AND BRACKISH GROUNDWATER AT SHALLOW AND INTERMEDIATE DEPTHS: GENESIS AND WORLD-WIDE OCCURRENCE

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ABSTRACT
This paper addresses the genesis and occurrence of saline and brackish groundwater at shallow and intermediate depths. Across the globe, most groundwater at these depths is fresh. This large volume of relatively easily accessible, fresh groundwater makes it worldwide a valuable source of water for various uses. However, at greater depths, groundwater is replenished at much smaller rates. As a result, originally fresh groundwater often has turned brackish or saline because of mineralization processes during the very long residence time underground, and aquifers originally filled with saline or brackish groundwater have not been refreshed because they are beyond reach of active fresh groundwater circulation. In some cases, these processes also occur at shallower depths. The paper looks at various mechanisms of saline groundwater genesis at these depths. It differentiates between marine (connate marine groundwater, seawater flooding, spraying and intrusion), natural terrestrial (evaporation from shallow groundwater tables, dissolution of salt-bearing sediments, membrane effects and hydrothermal igneous activities) and anthropogenic terrestrial mechanisms (irrigation and pollution by numerous types of contaminants). The position and vertical extent of the saline or brackish bodies of water groundwater inside an aquifer depends strongly on their genesis. An inventory of known occurrences of saline groundwater published in papers, reports and maps, combined with the use of proxy indicators related to the above mentioned groundwater salinity genesis, has allowed to produce a provisional global map of saline and brackish groundwater occurrences at shallow and intermediate depths. As the content of dissolved minerals in groundwater limits the suitability for various domestic, agricultural and industrial purposes, brackish and saline groundwater need to be controlled carefully. Despite the fact that it was derived only from information that was easily accessible during the inventory and hence subject to considerable improvement, the map may contribute to developing the necessary understanding of salinity patterns and processes that need to taken into account in order to make the full benefit of the fresh groundwater resources.

1 INTRODUCTION

1.1 Objective and approach

The objective of this study is to improve the understanding of brackish and saline groundwater at shallow and intermediate depths, with an emphasis on their genesis and world-wide occurrence. Shallow and intermediate depths are here used to indicate the zone where the bulk of active groundwater circulation and conventional fresh groundwater abstraction takes place, say down to 200-500 m below ground surface, depending on local conditions. Across the globe, most groundwater at shallow and intermediate depths is fresh. This large volume of relatively easily accessible, fresh groundwater makes it worldwide a valuable source of water for various uses. However, at greater depths, groundwater is replenished at much smaller rates. As a result, originally fresh groundwater often has turned brackish or saline because of mineralization processes during the very long residence time underground, while aquifers originally filled with saline groundwater have not been refreshed because they are beyond reach of active fresh groundwater flows. In some cases, such conditions also are present at shallower depths. It is believed that enhanced knowledge on brackish and saline groundwater improves the effective utilization and sustainable management of groundwater resources.

The approach taken in this study is based on rapid assessment of available information on brackish and saline groundwater. The study produced a provisional global picture of occurrences of brackish and saline groundwater shown in a world map (see figure1). Furthermore, these occurrences are categorized in a number of distinguishable genetic processes of groundwater salinity. Knowing the origin of the groundwater salinity provides groundwater resources managers the opportunity to forecast changes in the salinity characteristics and to develop effective measures to manage these resources sustainably.

1.2 Methodology

The contents of dissolved solids in groundwater vary highly from one location to another on Earth, both in terms of specific constituents (e.g. halite, anhydrite, carbonates, gypsum, fluoride-salts, and sulphate-salts) and regarding the concentration level. The latter, often called salinity level is a convenient macro-parameter for a first general characterization of water quality. It is usually expressed as Total Dissolved Solids (TDS in mg/l) but the use of proxies such as the Chloride Content (mg/l) or the Electrical Conductivity (EC, in μS/cm) is widespread as well.

In practice, water often is classified into a number of discrete salinity classes. In this study the simple classification presented by Freeze and Cherry (1979) is used which is based on TDS levels.

Table 1: Water salinity classification

Class name	Class limits (TDS range, in mg/l)		
Fresh water	0	-	1,000
Brackish water	1,000	-	10,000
Saline water	10,000	-	100,000
Brine		>	100,000

(After Freeze and Cherry, 1979)

In this inventory a lower limit criterion of 1,000 mg/l, TDS is used. Thus, when talking in this paper about saline groundwater, this tacitly includes brackish groundwater and brines as well.

For practical reasons and as mentioned before, the inventory has been limited to the subsurface domains currently considered relevant for the exploitation and regular management of groundwater resources. This means that the collected information does not go beyond about 250 to 500 m below ground surface. Some of the saline groundwater bodies found only have a limited thickness. For example, groundwater salinisation due to irrigation practices normally does in vertical direction not go beyond a number of tens of metres. Consequently, only part of the groundwater column up to 500 metres depth is salinized in such a location while the rest remains fresh. In this inventory, this area is still denoted to contain saline groundwater.

No attention has been paid to relatively small bodies of saline groundwater, as they are irrelevant on the global scale and would require excessive time for their inclusion in the inventory. How to interpret "relatively small" depends on local conditions, but single groundwater bodies containing less than one billion m^3 of saline water in storage are not included in the inventory, unless they are considered very significant for one reason or another, and/or form part of a pattern that covers significant area or length. The occurrence of hydrothermal springs is an example of the latter. Despite the fact that the surfacing springs themselves are often only localized with limited geographical extent, they may represent larger hydrothermal groundwater systems at depth.

It is considered unfeasible yet to produce a global map of saline groundwater or even a world-wide inventory on the basis of collecting, interpreting and combining monitoring data. Monitoring groundwater quality like TDS is still non-existent or erratic in many parts in the world. When such data do exist, they may not be easily accessible and they will very likely be non-uniform across administrative borders. It was therefore decided to base this inventory on information and knowledge already documented in scientific papers, reports and hydrogeological maps. This secondary information was then combined with various kinds of proxy information like maps with distributions of geological, geographical, soil, land use, irrigation, aridity, elevation data, and storm and flood frequency data.

In many cases, documentation on measured occurrences of saline groundwater only represents geographical areas of limited spatial extent. Often the size of a case study or project area is much smaller than the minimal size of saline groundwater bodies considered. Therefore, proxy information and expert judgement have been used to extrapolate the documented occurrences into larger areas where a high probability of groundwater salinity is assumed.

2 GROUNDWATER SALINITY GENESIS AND WORLD-WIDE OCCURENCE

In general, fresh groundwater is particularly found in those parts of the subsurface that are most actively involved in the water cycle, the domain of so-called 'meteoric water'. Consequently, fresh groundwater is more likely present in the shallower domains of the sequence of geological layers. Based on this rationale, fresh groundwater is often comparatively young and tends to be actively renewed. In contrast, a large part of all saline groundwater on earth – but certainly not all of it – is present in a more or less stagnant condition at greater depths and may have been there already for many thousands or even millions of years. Continuous dissolution over geological times of constituents of the rock matrix of the reservoirs containing this groundwater may have enriched the mineral content in the groundwater. So groundwater salinity tends to increase with increasing depth. In the next sections, saline groundwater bodies are categorized according to a number of marine, terrestrial, natural and anthropogenic genetic types. For each type of genetic type, a number of illustrative aquifers or geographical areas are described which contain saline groundwater of that particular origin. These occurrences are labelled by numbers in the text for their easy identification on the map.

2.1 Saline groundwater of marine origin

Connate saline groundwater: This is typical for sedimentary formations of marine origin: seawater was deposited together with the rock matrix and still is present in the interstices, unless it has been flushed away afterwards. Under natural conditions, migration of connate saline groundwater tends to be extremely slow.

The Nubian Sandstone Aquifer System in Libya, Sudan and Egypt contains saline water of connate origin at relatively shallow depth in its Northern confined part near the Mediterranean ([1], Sherif and Singh, 2002). In the Niger basin in Northern Africa, the southern part of the

Tin Sériririne-Irhazer and Iullemeden aquifer system contains brackish to saline fossil water with TDS up to 30 g/l [2]. A very large, more or less continuous zone of brackish groundwater can be observed running from the Paraguayan part of the Gran Chaco all the way South to Eastern Patagonia (USCE, 2008). This water is considered to be predominantly connate saline groundwater originating from the Miocene marine invasion (Mar Enterriano or Mar Paranense) [3]. Connate saline groundwater of marine origin is also found in large parts of the USA's Coastal Plain Region: in the Northern Atlantic Coastal Plain Aquifer System, the South-Eastern Coastal Plain Aquifer System, the Texas Coastal Lowlands Aquifer System, the Texas Coastal Uplands Aquifer System, the Mississippi Embayment Aquifer System, the Coastal Lowlands Aquifer System, as well as in the Floridan Aquifer System (together denoted as [4]).

Saline groundwater originating from marine transgressions: Throughout geological history, the sea level tends to change over time. Consequently, it is common that coastal lowlands became flooded by the sea during marine transgression periods. During the transgression period, seawater percolates downwards because of its higher density compared to fresh water and may turn originally fresh coastal aquifers into saline groundwater reservoirs. This process is relatively fast. Within hundreds of years, aquifers of hundreds of metres of thickness may turn saline due to this process.

Relict saline groundwater of marine origin can be found in a large continuous zone in central Sweden and along the present Baltic Sea coastline in Sweden and Finland. This saline water is not connate, but originates from two postglacial transgressions of the Baltic Sea: the Yoldia Sea at about 7,700 BC and the Litorina Sea at about 5,000 BC ([5], SWIM, 1999). The Caspian Sea with a salinity of about 1/3 of seawater salinity experienced fluctuating water levels of metres in the past few centuries. During the last decades, water level rose 3 metres resulting in flooding and lateral intrusion of the saline lake water in its coastal regions [6].

Saline groundwater originating from incidental flooding by seawater: A similar mechanism of salinisation may occur at a much smaller time basis. When sea levels are exceptionally high, e.g. during a tsunami, or when coastal defence systems fail during high tides, low-lying coastal plains may become temporarily flooded by seawater. Although the period of flooding is much smaller than in the case of a marine transgression, large extents of coastal aquifers nevertheless may become salinized due to the infiltration of seawater ponded on land surface. The effect is mostly limited to the shallow (first metres) domains of these aquifers. Temporal submersion of unprotected wellheads during the flooding may lead to introduction of saline water to greater aquifers depths via the well screens.

The low-lying Chinese coastal areas between Hong Kong and Shanghai, low-lying parts of The Philippines, Taiwan and Japan are in the typhoon susceptible area. About 2 or 3 typhoons and 3 or 4 cyclonic storms reach these countries annually and result in incidental seawater flooding [7]. Parts of the coasts of India (Violette et al., 2009), Sri Lanka, Bangladesh, Thailand, Malaysia and especially NW-Sumatra were hit by the December 2004 tsunami. Extensive parts of the coastal areas (especially in Aceh province) were flooded by seawater during this catastrophe causing groundwater salinisation [8].

Groundwater originating from laterally intruded seawater: This genesis occurs in coastal zones because of interaction between the seas and hydraulically connected coastal aquifers. In a dynamic equilibrium, this results in a natural landward thinning 'saltwater wedge' overlain by fresh groundwater discharging into the sea (Bear et al., 1999). Lateral seawater intrusion in coastal areas may be enhanced by surface water bodies connected to the sea, such as estuaries and rivers (greatly increasing the coastline length) if conditions allow seawater to travel inland through these bodies. When the shallow fresh groundwater resources are abstracted for human productive use and when land use changes decrease groundwater replenishment, the shallow fresh groundwater head decreases. This can cause *up-coning* of deeper often more saline groundwater and an inland movement of the fresh/saline groundwater interface. Also decreased estuarine river discharge because of upstream water allocation may increase seawater intrusion. This anthropogenic induced intrusion can be a relatively fast process, depending on the hydraulic pressures changes and the transmissivity of the coastal aquifers.

Seawater intrusion is a threat almost anywhere along the sea coast, since the coastlines are mostly underlain by high-capacity aquifers hydraulically connected to the sea. The coastal aquifers of Belgium and The Netherlands [9] have been the subject of many seawater intrusion studies, which suggests the local relevance of this phenomenon. The 'seawater intrusion tongues' are dynamic but represent saline groundwater bodies of modest dimensions only, compared to the bodies of connate saline groundwater. Several rivers with extremely low hydraulic gradient bring the seawater intrusion risk to aquifer locations inland.

Drinking water supplies in many of the urbanized coastal areas are heavily depending on groundwater pumping. Groundwater overexploitation in the last few decades has lead to many occurrences of groundwater salinisation due to seawater ingress in such areas. Tokyo, Kawasaki, Yokohama, Taipei city in Taiwan, Cebu city and Manila in the Philippines, Chennai in India, Dar es Salaam in Tanzania, Barcelona in Spain, Miami in the US are all cities known to experience man-induced seawater intrusion [10].

Groundwater enriched in mineral content by seawater sprays: The lower air in coastal zones may be rich in salt particles, originating from the sea. These salt particles will be absorbed by rains and be incorporated in groundwater recharge water, thus contributing to groundwater salinisation. These are often small zones near to the coasts. However, it is assumed that dryland salinisation found in Australia has its origin in aerial salt deposition which took place over long geological times.

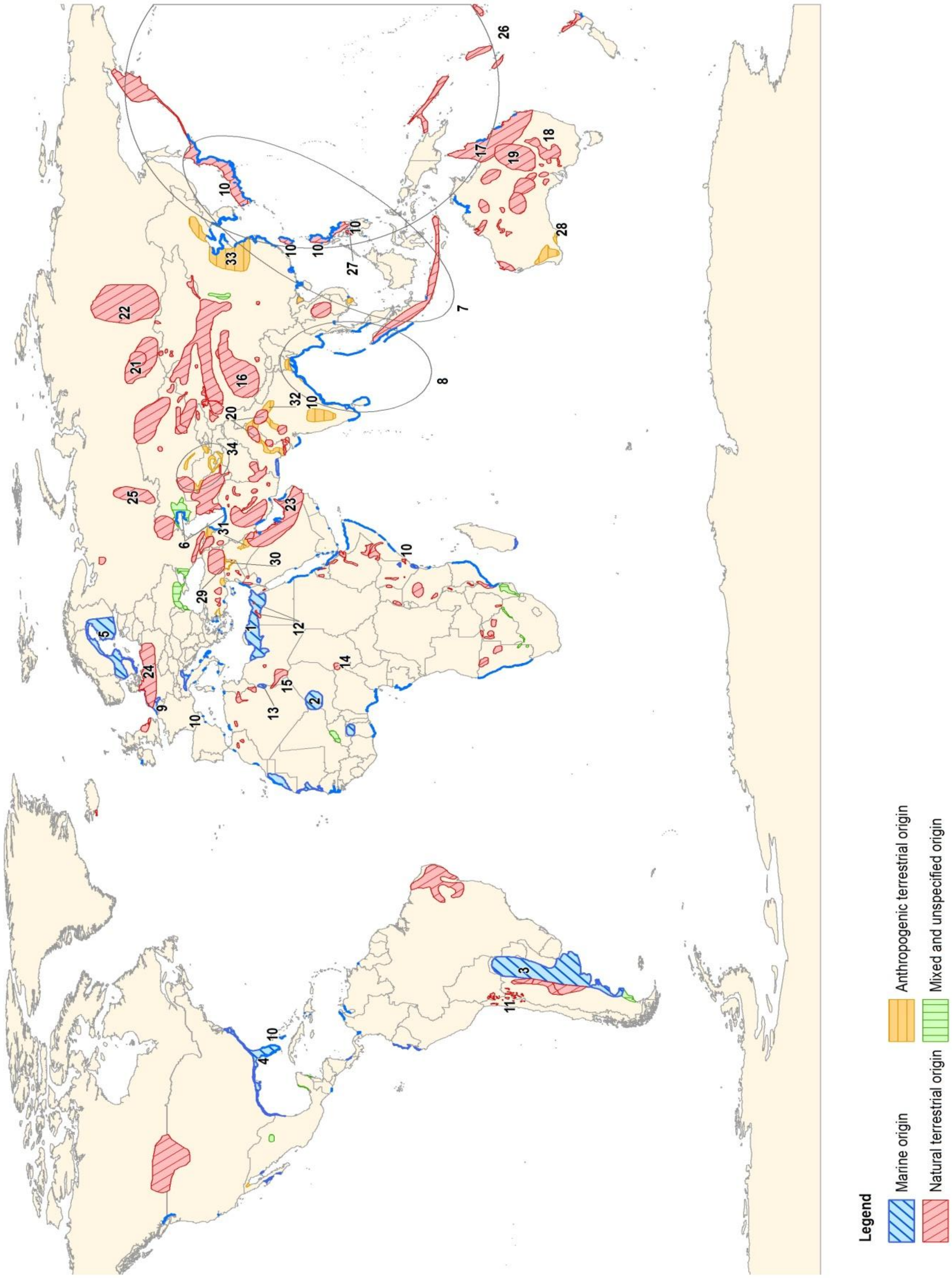

Figure 1. Occurrence of saline and brackish groundwater at shallow and intermediate depths

2.2 Saline groundwater of terrestrial origin – natural

Groundwater enriched in mineral content by evaporation at or near land surface: This origin of saline groundwater is linked to shallow water-table conditions, and develops when climatic conditions favour evaporation (or evapotranspiration through phreatophyts) while flushing of accumulated salts is absent or only weak (Yechieli and Wood, 2002). Such conditions prevail on the so-called chotts, sebkhas, salinas, salars or playas (names of saline lakes in closed basins in various languages and geographical areas in arid and semi-arid regions). It is assumed that the high lake salinity spreads in the underlying groundwater to some depth and distance. Often a salt crust is formed at the lake bottom during dry periods.

Discharge of very shallow groundwater by evaporation is also the main origin of saline and brackish groundwater commonly found in the Southern part of the South American Altiplano. This mechanism is supported by the Altiplano's dry climate and the absence of surface water drainage. From North to South this zone encompasses large salt flats in Bolivia (Salar de Coipasa, Salar de Uyuni), Chile (Salar de Atacama) and Argentina (Salinas Grandes, Salar de Arizaro, Salina de Antofalla) and numerous smaller ones ([11], Rebouças, 1999)

In the El Natrun and Qattara depressions in Egypt, salt is accumulating by evaporation of discharging groundwater [12]. In the Chotts area in Algeria and Tunesia, saline mudflat deposits can be found due to either evaporation of sporadic rainfall or evaporation of artesian groundwater from the NorthWestern Saharan Aquifer System [13]. In the Lake Chad basin, the upper aquifer (0-50 m) has saline water near the lake border due to evaporation (14). Shallow salt deposits are also to be found in the Fezzan area in the South of Libya (paleolake Megafezzan, 130,000 km2, [15]).

The Tibetan and Shan plateaus in China [16] are dotted with many lakes which have a tectonic (intra-montane basins, strike-slip basins) and/or glacio-fluvial origin (Pleistocene glaciations). 40% of these lakes (in total 21,400 km^2) are closed basins and produce brackish and saline waters and playas due to evaporation. The Qarhan playa in the Qaidam basin on the Northern part of the Shan plateau has an extent of 6,000 km^2 and is considered the largest playa in the world. The shallow groundwater adjacent to these lakes is often brackish or saline (Mianping, 1997).

Large areas in Australia are prone to so-called dryland salinisation. Over the past 100,000 years, salts have been accumulating in the top soil (about 30 kg of salts per hectare) over large areas in Australia. This salt accumulation was created by the process of tropic seawater evaporation, windborne transportation and subsequent precipitation. After immigration of Europeans, a few hundreds of years ago, the natural vegetation of trees in Australia was often removed and the land converted into agricultural land. Groundwater replenishment increased due to this land use change. Consequently, groundwater tables rose in many parts of the country dissolving the accumulated salts. Dryland salinity in East Australia is found at the North-eastern coast of Queensland [17] and especially in the Murray Darling basin in New South Wales ([18], Rengasamy, 2006).

Groundwater enriched in mineral content by dissolution of naturally occurring soluble minerals underground: Groundwater may become saline by dissolving salts from evaporate formations (halites) or carbonates layers, when flowing through or along such subsurface bodies. Even when flowing through 'ordinary' aquifers (of which only a limited fraction consists of easily dissolvable materials) groundwater may become brackish to saline in downward direction, if time and other conditions favour dissolution of salts from the aquifer matrix (not uncommon in arid regions).

Evaporates and other salt-bearing formations are found in the Adavale basins [19] in Australia. In some areas of the Indus and Ganges basins, the deeper sediments contain salt-bearing strata of probably Cambrian origin [20]. Groundwater from these deeper aquifers in Sind, Punjab in Pakistan and Haryana, Punjab and Uttar Pradesh in India is often to be found brackish and/or saline due to dissolution of these salt-bearing strata (Misra and Mishra, 2007).

In the Khakasia area in Russia [21] Devonian evaporates are present resulting in increased salinity of the groundwater and lake water in this area. In the Lena-Vilyuy basin in Southern Siberia [22] Cambrian and Ordovician evaporates are found. Rock salt exploration is existent Northwest of Irkutsk and West of Bratsk. It is assumed that groundwater in the area North-West from Lake Baikal has high salinity levels due to dissolution of these evaporates.

In the Eastern part of the Arabian Peninsula and in the Euphrates-Tigris basin area, many Cambrian and Permian evaporates are situated ([23], ACSAD 1984). These evaporates are correlated with those found in Iran. Groundwater flowing from the hinterland towards the discharge zones in the Gulf area becomes enriched in dissolved salts. Besides evaporates, Palaeogene carbonate sediments are abundant in this region. Groundwater with long residence times across the region has managed to dissolve parts of these sediments and is currently brackish and or even saline in nature.

In the North-European zone of salt tectonics related to the former Permian Zechstein Sea, extending from Eastern England to Northern Poland, pockets of shallow highly saline groundwater can be found ([24], Börner, 2004). Especially in the North-Eastern part of The Netherlands and Northern Germany, diapirs of Permian salts penetrate overlaying younger geological formations and by dissolution they locally have turned originally fresh aquifer zones into saline ones. A second important zone of highly mineralized groundwater due to dissolution is found in West Russia, where Permian salt domes the city of Perm [25].

Saline groundwater produced as a result of membrane effects: Layers of clay or shale may be compacted that much in deep sedimentary basins that they become effective salt filtering membranes. Groundwater is percolating through such layers but the dissolved larger ions are not permitted to pass, which leads to building up high groundwater salinity (even brines) near the inflow side of the membrane. This fractionation process often causes brines constituting of calcium and chlorides (Hem, 1970). The process is called salt filtering, ultra-filtration or hyper-filtration. In the literature sources reviewed so far, no saline groundwater occurrences were found that are assumed to be caused by these membrane effects.

Saline groundwater of geothermal origin: In addition to the meteoric and connate waters that form the point of departure of the previous genetic types of saline water, one may encounter highly mineralized water that is produced as a side product of igneous activity. Since it has not been part of the hydrological cycle yet, it is called 'juvenile water'. This process is rare but may be observed in regions of prominent igneous activity. Highly pressurized and high temperature groundwater that is present (mostly at greater depths) within areas with high igneous activity has a high dissolving capacity. This groundwater may be enriched in dissolved salts resulting in so-called thermo-mineral waters. In addition, cases of seawater flowing into these volcanic and igneous systems are known. Hydrothermal groundwater systems may transport this highly salinized groundwater to shallower depths and even create localized hot and salty springs at the surface.

The North-western Pacific area is part of the so-called Ring of Fire, an area with intensive tectonic and volcanic activity. Many occurrences of hydrothermal systems are found stretching from Kamchatka, the Kuril Islands, Japan and Taiwan to the Philippines, Indonesia, New Zealand and the Pacific Islands. Groundwater associated with these hydrothermal systems often has a TDS content ranging from brackish to hypersaline [26]. Some hydrothermal systems located relatively close to the coast appear to be hydraulically connected to seawater (like the Taal volcano system on the Luzón island, Philippines) [27]. Part of their groundwater salinity can be explained by seawater mixing (Delmelle et al., 1998).

2.3 Saline groundwater of terrestrial origin – anthropogenic

Groundwater enriched in mineral content by irrigation: Irrigation is augmenting water required for optimal crop evapotranspiration. Water vapour leaving the crops during this process is almost without dissolved solids, thus much less mineralized than the irrigation water supplied. Large-scale irrigation may also lead to shallow groundwater tables (water-logging) and non-beneficial evaporation directly from that water table. Consequently, a residue of relatively mineralized water is left in the soil. This residue may be absorbed by the soil matrix (soil salinity), drain to the surface water system or percolate to below the root zone. It then may reach an aquifer and contribute to a progressive increase in the salinity of its groundwater. In addition, irrigation using brackish water from some source (for example waste water) evidently may create salinisation of the underlying soil and groundwater system. It is assumed that the groundwater salinisation due to of irrigation is restricted to a zone of a few metres to tens of metres below the groundwater table.

Intensive irrigation in the Avon wheat belt and Eastern Mallee in Australia [28] caused water logging and input of brackish groundwater at various locations resulting in shallow groundwater salinisation (Connacher, 1990). Large-scale intensive irrigation found in Turkey (e.g. Çukurova plain and Harran plain, [29]), along the Euphrates between Al Hakkah and Abu Kamal in Syria [30], in Israel and South and East of Baghdad in Iraq [31] has lead to high levels of total dissolved solids in the shallow groundwater in many of these areas (ESCWA, 1999).

Intensive irrigation in the Ganges and Indus River plain has caused severe salinisation of soils and shallow groundwater (especially in areas of the Pakistani Sind province and the Indian Punjab State) as a result of water logging and application of water with high TDS content ([32], Qureshi et al., 2008). Similar processes have lead to salinisation of shallow groundwater over large areas in the Huang-Huai-Hai Plain and Manchurian river plains ([33], Foster and Garduño, 2004, Zhang et al., 2001).

In the former Soviet Union era, large-scale food production (especially cereals) was established and is still continuing in the Central Asian area [34]. This area has a high aridity index and hence most of the agriculture production takes place under irrigated conditions. This large-scale and intensive irrigation caused various environmental degradation effects in the area of which the Aral Sea water level decline and the associated ecological and socio-economic impacts are well known. In many of these irrigation areas groundwater salinity is high due to water logging effects, application of irrigation water with high initial TDS contents and intensive use of fertilizer and pest-control inputs.

Groundwater enriched in mineral content by anthropogenic pollution: Anthropogenic pollutants may enter the groundwater system and contribute to increased salinity of groundwater. Typical examples of such anthropogenic pollutants are road salt (applied in winter), fertilizers, domestic, industrial and agricultural effluents, spilled oil and gas field brines and brines from desalinisation plants. Groundwater salinisation effects of these processes will be rather localized.

Seepage (pollution) of brackish water from shrimp culture in countries like South India, Vietnam, Bangladesh and the Philippines has caused local salinisation of adjacent land and shallow groundwater.

3 COMPLEXITY DUE TO THE FACTOR TIME AND THE SPATIAL OVERLAP OF PROCESSES

Given the characteristic large residence times of groundwater, the time dimension should not be overlooked when defining the origin of saline groundwater. E.g., saline groundwater may have originated in past geological periods when prevailing climatic or water-table conditions were different from what they are nowadays. The genetic categories are associated mainly with geological processes, often at great depth. However, groundwater flow systems may be such that deep groundwater and the related salts are transported to shallower depths as a result of land subsidence, polder drainage and groundwater exploitation as is the case as is the case with a hypersaline groundwater body west of the Dead Sea ([34], Stanislavsky and Gvirtzman, 1999).

In some regions, zones with saline groundwater of different origins overlap. In low-lying coastal zones and delta areas, groundwater salinity is often caused by past marine transgressions and recent incidental flooding. In some cases, also connate saline groundwater adds up to the total observed groundwater salinity. Evaporation induced salinisation is significantly exacerbated when the evaporating groundwater is enriched in dissolved salts picked up along the flow line in the aquifers.

4 DISCUSSION OF WORLD-WIDE OCCURRENCE

According to this inventory, the world-wide aggregated area with occurrences of saline and brackish groundwater at shallow or intermediate depths approximates 24 million km^2. This is about 16% of the total land area on Earth. The genetic types of evaporation from shallow groundwater, dissolution or a combination of these two contribute most to this saline groundwater area, with contributions of 20, 26 and 13%, respectively. The next most important contributor to groundwater salinity – in terms of area - is connate water, with a contribution of 14%. No significant groundwater salinity occurrences caused by membrane effects are found in this study. In addition, the effect of anthropogenic pollution on the TDS-content of groundwater is not significant on this scale.

The largest areas with saline groundwater at shallow and intermediate depths are assumed to be present in the basins of West and Central Asia. They contribute by 14% to the total global area of brackish or saline groundwater at shallow and intermediate depths, as far as can be deduced from the consulted information sources. The Lowlands of South America, the Lowlands of Europe, the Mountain belt of Central and Eastern Asia, and Eastern Australia all contribute individually for about 6-7 % to this total area.

Note that based on this inventory is not possible to estimate the volume of saline groundwater. First, it only looks at saline groundwater to a maximal depth of 500 metres below surface. Secondly, as is mentioned before, in this inventory a certain location is defined to have saline groundwater even when only a minor part of the column of 500 metres is containing saline groundwater. The depths and thicknesses of saline groundwater bodies at particular locations have not been delineated in this study, and their lateral extent is often rather uncertain.

According to this inventory, about 1.1 billion people live in areas with some level of significant groundwater salinity at shallow and intermediate depths. The genetic types contributing most to the amount of groundwater salinity ‘affected’ people are irrigation (25%), lateral seawater intrusion (17%), dissolution (17%) and igneous activities (15%).

Whether people, living in the groundwater salinity affected areas, are really being affected by the salinity is very much dependent on their groundwater use. First, when people are hardly using any groundwater, their vulnerability to groundwater salinity hazards is obviously low. This is for example the case for most people living in the igneous active area of East Asia (the Ring of Fire in Japan, Philippines, and Indonesia). The population density on these islands is high and the occurrence of saline groundwater is widespread but manifests itself mostly at localized spots only. Climate in this zone is humid with relatively large amounts of rainfall. This leaves the people in these areas in most cases with sufficient surface water to meet their water demands. Secondly, the map denotes areas as having saline groundwater even when only a fraction of the depth profile is actually containing groundwater with a high salinity level. This is for example the case in The Netherlands, where high groundwater salinity is found almost anywhere at a few hundred metres of depth, but usually overlain by 100 to 200 metres of fresh aquifer strata, often separated from saline groundwater by aquitards. This leaves sufficient fresh groundwater to be pumped for drinking water production for this small but densely populated country. The number of 1.1 billion people potentially affected in the entire world by groundwater salinity should therefore be considered as a worst-case figure.

5 MANAGEMENT OPTIONS

This inventory has not looked into management options since the effective design and implementation of measures for control is very much dependent on the local context. Some potential measures have a mitigation objective and aim at keeping groundwater salinity levels below harmful thresholds. Other measures have a more adaptive approach and accept the high groundwater salinity encountered but adjust groundwater use in such a way that the salinity level is not harmful. Among the hydraulic measures to be considered are the optimisation of the pattern and intensity of groundwater abstractions and the development of hydraulic barriers with injected water to reduce further seawater intrusions and up-coning ((Edwards and Evans, 2002)). Furthermore, the creation of strategic fresh water reserves (fresh water lenses) by means of artificial aquifer recharge (like in the Comprehensive Everglades Restoration Plan (CERP) in the Upper Floridan Aquifer in South Florida as described by Barlow (2003)), by conjunctive use of surface and brackish water and by desalinisation of inland brackish groundwater for the provision of drinking water. Sufficient drainage in irrigated areas avoiding water-logging (FAO-AGL, 2000) and the application of smaller quantities of chemical inputs in agriculture reduce the salinity build-up in rural areas. So does sufficient treatment of the waste water that is increasingly being used as a source for irrigation in water scarce regions. It is obvious that access to information is essential in order to develop optimal solutions for groundwater salinity issues encountered.

6 CONCLUSIONS AND REQUEST FOR FEEDBACK

To be able to control saline and brackish groundwater, researchers, water resources specialists, policy makers and politicians need information on the scope, distribution, origin, dynamics and severity of groundwater salinity. This study is a contribution to providing such essential information for this broad group of stakeholders. It aims to enhance their general understanding of groundwater salinity, promote early diagnosis of possible changes and widen their inspiration for selecting effective measures for interventions, optimally tuned to the zones concerned. This study has not looked into these management options, as explained in the previous section. Rather it was its intention to disseminate knowledge on the origin of saline and brackish groundwater at shallow and intermediate depths, and to show on a world map where the larger known occurrences of such groundwater are located.

The description of the different genetic types of saline and brackish groundwater shows a large variation in origin, related to different mechanisms active in past and present times. The number of genetic types is rather large and It may be clear that their proper identification is a prerequisite for the design of adequate measures for control.

The presented map is a first attempt to map world-wide brackish and saline groundwater occurrences at shallow and intermediate depths. The authors are fully aware of its many limitations and consider it a first step towards developing a more consolidated and verified map. A full report describing the approach and various saline groundwater occurrences in more detail can be found on IGRAC's website: www.un-igrac.org. Many improvements will be possible as the present version of the map is based on a limited amount of data and information so far accessed. For improvements, less easily accessible (often non-published) data and information needs to be collected, studied and incorporated. It is assumed that major improvement can be reached by encapsulating much more locally available knowledge and wisdom. To enable tapping the required additional local sources of data,, information and knowledge the readers of this paper are kindly requested to provide feedback. This may consists of comments, corrections, adjustments or additions to the current version of the map. Obviously, all feedback contributions will be acknowledged in the future versions of the report and map. Detailed instructions for providing feedback can be downloaded from IGRAC's website.

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