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# 2.11 Groundwater salinisation

SONJA MARTENS & KNUT WICHMANN

***SUMMARY:*** *About one-third of total freshwater consumption in the world depends on groundwater resources. Low cost use of groundwater is only feasible when the salt concentration is below certain limits. Therefore a reliable monitoring network is essential for detecting and monitoring saltwater movement in aquifers and improving the understanding of the processes which control groundwater salinisation. Potential sources for groundwater salinisation such are seawater intrusion, leaching of salt deposits and upcoming of deep natural saline water. These processes could be initiated or facilitated by human activities, such as heavy pumpage of fresh groundwater. Groundwater salinisation may occur as a local or regional problem. Different case studies show that it represents an essential issue for sustainable water management in many regions all over the world.*

Groundwater use amounts to about one-third of total freshwater consumption in the world. The occurrence of freshwater is usually limited to a layer of some hundred metres in the underground. In greater depths saltwater occurs. An economic utilisation of groundwater for public water supply, industry and agriculture is only possible when the salt content of the groundwater does not exceed certain limits. Saltwater can, in extreme cases, lead to the abandonment of supply wells when concentrations of dissolved ions exceed drinking-water standards since their removal generally needs expensive and technically advanced water treatment measures.

The chemical composition of groundwater is primarily dependent on its origin. Also, chemical-physical, microbial and hydraulic interactions between groundwater and the porous medium determine the concentration of chloride, sodium, sulphate and further ions. Additional sources due to human activities may influence the groundwater composition and create anthropogenic contamination.

The expressions »groundwater salinisation« and »salinisation« have not been clearly defined so far. FREEZE & CHERRY (1979) recommend a simple groundwater classification (*Table 2.11-1*) based on total dissolved solids (TDS). The concentration of TDS can be determined by weighing the solid residue obtained by evaporating a measured volume of filtered sample to dryness. To put the concentration ranges in perspective, it may be useful to note that water containing more than 2,000 mg/L TDS is generally too salty to drink. Seawater has a total dissolved solids concentration of about 35,000 mg/L (35‰), of which dissolved chloride is the largest component (about 19,000 mg/L).

***Table 2.11-1:*** Groundwater classification based on TDS ranges (in mg/L) (FREEZE & CHERRY 1979).

| *Category* | *Total dissolved solids (mg/L)* |
|---|---|
| Freshwater | 0 to 1,000 |
| Brackish water | 1,000 to 10,000 |
| Saline water | 10,000 to 100,000 |
| Brine | > 100,000 |

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In Germany, the limits of the Drinking Water Ordinance (2001), e.g. 250 mg/L for chloride, 240 mg/L for sulphate and 200 mg/L for sodium, are decisive for utilisation as drinking water. The higher the salt content of water, the higher is its electrical conductance. Therefore, the Drinking Water Ordinance sets a limit of 2,500 µS/cm for the electrical conductivity at 20°C. The EC-Directive 11/1998 sets the same limits with the exception of sulphate (*Table 2.11-2*).

The chloride concentration of groundwater is the most commonly used indicator of saltwater occurrence. However, other indicators such as the total dissolved solids concentration or electrical conductivity of groundwater samples are also frequently used. GRUBE et al. (2000) recommend the use of 1,000 mg/L TDS or an electrical conductivity of about 2,000 µS/cm for differentiating between freshwater and saltwater.

## Salinisation sources

Groundwater salinisation may result from geogenic sources, such as seawater intrusion in coastal aquifers, contact with salt deposits, and upcoming of deep natural saline water. In some cases, salinisation is initiated or facilitated by anthropogenic activities. Groundwater salinisation may occur locally or regionally. *Fig. 2.11-1* shows generalised groundwater flow patterns and natural salinisation processes in an aquifer system.

### *Seawater intrusion*

Saltwater intrusion is common in coastal areas where aquifers are connected with seawater. Seawater intrusion

***Table 2.11-2:*** Limits according to the German Drinking Water Ordinance (TrinkwV 2001) and the EC-Directive 11/1998.

| *Parameter* | *German Drinking Water Ordinance 2001* | *EU-Directive 11/1998* |
|---|---|---|
| Chloride | 250 mg/L | 250 mg/L |
| Sulfate | 240 mg/L | 250 mg/L |
| Sodium | 200 mg/L | 200 mg/L |
| Elektrical conductivity | 2,500 µS/cm at 20 °C | 2,500 µS/cm at 20° C |

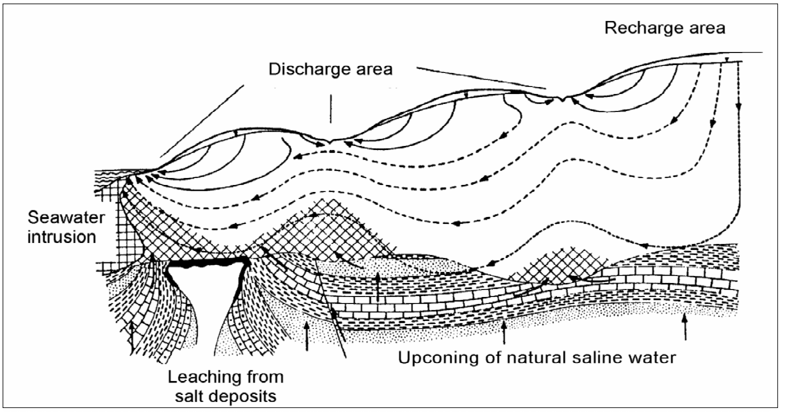
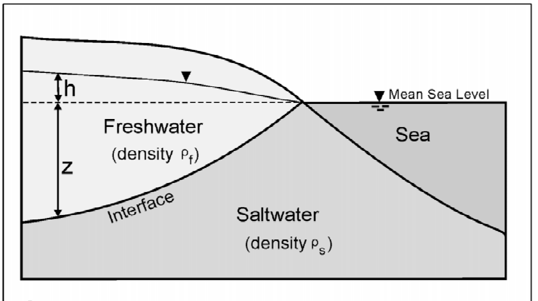



***Fig. 2.11-1:*** Natural salinisation processes in sediment and solid rock (after HAHN 1982).

and the transition zone in which freshwater and saltwater mix is controlled among other variables by morphology, geology, groundwater recharge and the amount of freshwater flow through the aquifer.

Groundwater salinisation in coastal areas has already been recognised more than hundred years ago. At the same time, DRABBE & GHIJBEN (1888/89) and HERZBERG (1901) developed a first model to determine the freshwater/saltwater interface. *Fig. 2.11-2* displays the idealised Ghijben-Herzberg relation assuming hydrostatic equilibrium between saltwater and freshwater separated by a sharp transition zone. In nature, this transition zone is a few metres wide.

The Ghijben-Herzberg relation offers the opportunity of predicting the depth of the interface below sea level. For example, the relation yields $z = 40 \times h$ for a saltwater density of 1,025 kg/m³ and a freshwater density of 1,000 kg/m³; this means that the depth of the freshwater/saltwater interface below Mean Sea Level (MSL) is 40 times the elevation of the freshwater table above MSL. This relation further implies that a one metre decrease or increase of the freshwater table can cause in the equilibrium state a 40 metres increase or decrease of the saltwater/freshwater interface respectively. The natural process of seawater intrusion is often intensified by groundwater withdrawal in coastal areas.




$$z = \frac{\rho_f \cdot h}{\rho_s - \rho_f}$$

***Fig. 2.11-2:*** Ghijben-Herzberg relation for an idealized unconfined coastal aquifer.

### Natural saline groundwater

Natural saline groundwater is occurring on regional scales where saline water underlies freshwater aquifers at variable depths. The occurrence of saline water is controlled by a variety of factors, including distribution and rate of groundwater recharge, hydraulic aquifer characteristics, residence time, flow velocities, and nature of discharge areas (RICHTER & KREITLER 1993). Chemical composition and distribution of deep natural saline waters are often heterogeneous as the source can be residual water originating from the precipitation of evaporites, solution of rock salt, fossil seawater, or any mixture of the above.

Natural salinisation of freshwater occurs where saltwater from saline aquifers discharges at the land surface or mixes with freshwater in the subsurface (RICHTER & KREITLER 1993). Freshwater and saltwater are usually separated by a transition zone of variables thickness. The position of this interface may vary in response to varying flow conditions. E.g. human activities like heavy pumpage of freshwater can influence the natural process and cause an upcoming of the saltwater/freshwater interface.

### Contact with salt deposits

Many sedimentary basins are known to contain large salt deposits some occurring at great depths, others occurring close to land surface. Salt deposits located within local or regional groundwater flow systems are being dissolved, predominantly along the tops and margins, causing groundwater salinisation (RICHTER & KREITLER 1993). Shallow salt deposits pose a higher potential of freshwater salinisation than deeper ones. The TDS concentration in the surrounding of salt domes can increase to more than 250 g/L already in depths of 200–300 metres below surface. Where groundwater is in direct contact with salt deposits even a saturation concentration may be reached.

### Anthropogenic sources

Besides geogenic salinisation of groundwater the following anthropogenic activities have to be considered as potential salinity sources (GRUBE et al. 2000):

- abandoned industrial sites; waste deposits
- infiltration of wastewater; damaged sewers
- bank filtration from rivers with a high mineral content
- agriculture and forestry
- road-salting
- oxidation of artificially drained peat and carbon deposits

The human activities have different effects on magnitude and spatial distribution of salt concentration. Depending on the kind and duration of the source the concentration may vary considerably.

## Case studies

As a large part of the world's population lives in coastal areas, the following international case studies focus on seawater intrusion.

### Cebu (Philippines) (SCHOLZE et al. 2003)

Metropolis Cebu is located on the east coast of the island of Cebu (Philippines) (*Fig. 2.11-3*). The topography is mountainous, with a major mountain range running parallel to the north-north-east to south-south-west axis of the island rising to heights of more than a thousand metres.

Rivers run from the main water divide in the centre of the island in either north-western or south-eastern direction to the coastal plains. In the area of Metro Cebu, there are three water sheds which are defined by topographic divides. One of the watersheds, the Coastal Aquifer Watershed with an area of approximately 264 km², is the main contributor of groundwater to the Coastal Aquifer. The Coastal Aquifer Watershed can be subdivided into three geologic formations; a) the alluvial sediments, b) the Carcar Limestone, and c) volcanic and other sedimentary rocks. The region near the coast is covered by alluvial unconsolidated sediments forming flat land areas. Underlying these alluvial sediments is a semi-consolidated to consolidated limestone. Further inland, up to 8 km from the sea, the Carcar Limestone forms a hilly part of the coastal area with elevations up to 200 m. The Carcar Limestone is the major aquifer in the Metro Cebu region and utilised by the Metropolitan Cebu Water District and private users to a high extend. The Corraline massive limestone is karstified containing interconnected fissures, fractures, and dissolution channels, which are products of tectonic activity and erosion.

Within the last 20 years urbanisation and industrialisation have taken place in the eastern coastal region of the island. 1.69 million people lived in Metro Cebu in 2000, the average annual growth rate was around 3%. As a result, the groundwater demand enormously increased. The water supply of Metro Cebu mainly (98%) depends on groundwater. The rate of pumped groundwater is in the same range as the groundwater recharge. Thus, the hydraulic equlibrium between groundwater renewal and discharge in Cebu City region is disturbed and the water supply situation is critical.

The intrusion of saltwater into the coastal aquifer system, covering an area of 180 km², has led to a decrease of the freshwater resources over the last decades. Some wells in the downtown area are already abandoned due to saltwater intrusion and the extraction rates of other wells had to be reduced to prevent saltwater upcoming. The chloride concentration has been monitored over decades

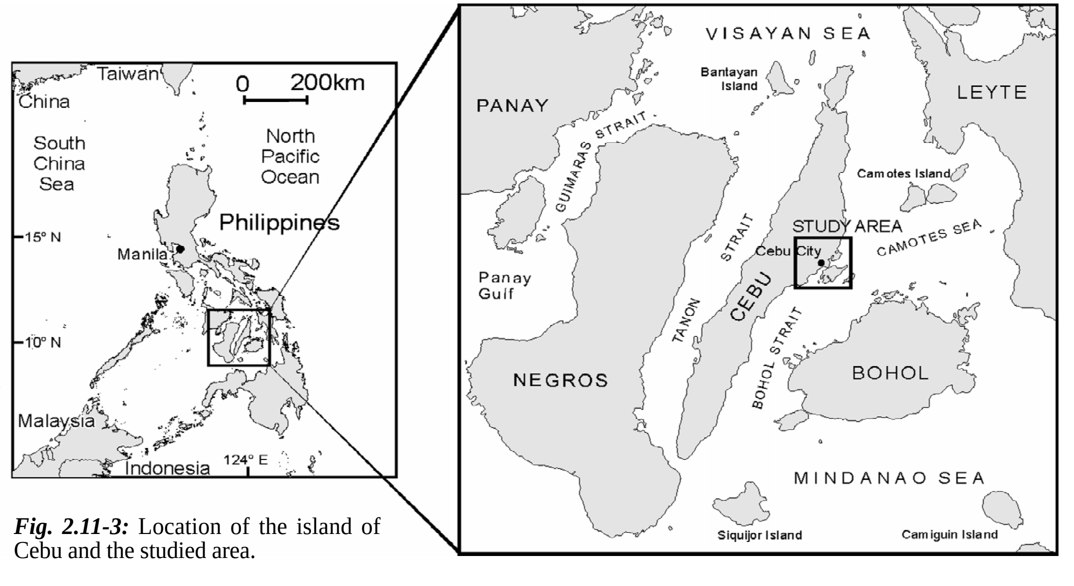



**Fig. 2.11-3:** Location of the island of Cebu and the studied area.

for assessing seawater intrusion (*Fig. 2.11-4*). In some areas, the 50 mg/L chloride concentration isoline of 1995 has progressed two kilometres inland since 1979. Depth-dependent field measurements of the electrical conductivity show an increase over depth in some observation wells (*Fig. 2.11-5*). This is probably caused by saltwater upcoming due to local pumping.

A numerical groundwater and transport model is used to predict the future behaviour of the coastal aquifer of Metro Cebu. The simulations include different scenarios of groundwater extraction and increasing water demand. The overall results are used for recommendations for the long-term protection of the groundwater resources in the Cebu City region.

### *Egypt (Sherif 1999)*

The Nile Delta aquifer, one of the most important Egyptian water reservoirs, is also threatened by seawater intrusion. Salinisation is attributed to natural and artificial conditions, including pumping and irrigation. Additionally, the effect of future global warming and sea level rise is expected to affect the groundwater in the Nile Delta in two ways. First, the flooding of lowlands along the shore line with seawater will cause salinisation of shallow aquifers. Second, the sea level rise will impose an additional hydraulic pressure head at the sea side boundary causing more seawater intrusion into the deeper coastal aquifer. Solutions to mitigate the seawater intrusion include scavenger wells and artificial recharge of groundwater. Sherif (1999) recommended a dynamic monitoring network for piezometric head and salinity for a better assessment of the situation in the Nile Delta aquifer.

### *Israel (Melloul & Zeitoun 1999)*

Another example of seawater intrusion can be found at the coastal aquifer of Israel. The aquifer forms a major component of the country's water resource system and has been developed for domestic, agricultural, and industrial purposes. The upper aquifers are usually affected through seawater intrusion whereas the deeper aquifers are affected by fossil saline sources. Chloride concentrations in the coastal aquifer range from 250 mg/L in greater distance to the shoreline, where the major extraction is practised, to more than 1,000 mg/L near the shoreline where seawater intrusion has already significantly affected groundwater quality.

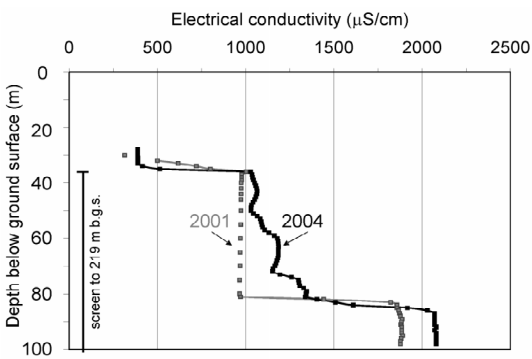
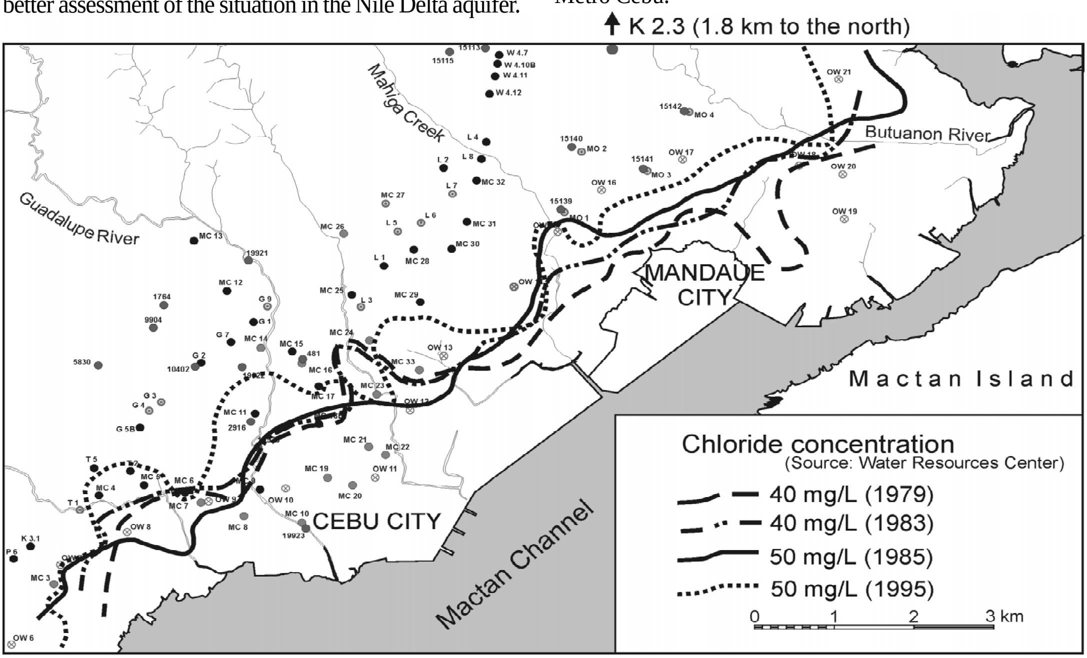



***Fig. 2.11-5:*** Observation well K 2.3 (see *Fig. 2.11-4* for location); measurement of electrical conductivity in 2001 and 2004.

***Fig. 2.11-4:*** Seawater intrusion in the coastal aquifer of Metro Cebu.



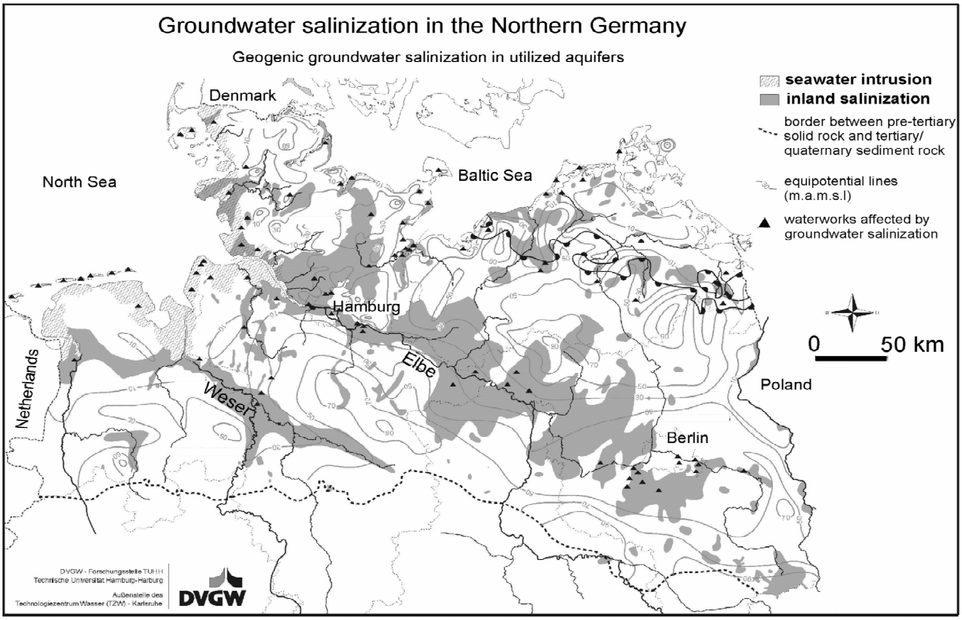



*Fig. 2.11-6:* Geogenic groundwater salinisation in Northern Germany (GRUBE et al. 2000).

### Northern Germany (GRUBE et al. 2000)

*Fig. 2.11-6* displays the regional groundwater salinisation and affected water works in Northern Germany. GRUBE et al. (2000) estimate that 5,200 km², this is 4.5% of the entire region, is affected by inland salinisation and approximately 28,000 km² (24.5%) by seawater intrusion.

Seawater intrusion mainly appears at the North Sea, especially in the Elbe and Weser estuaries. The coastal area is affected up to 20 km from the shoreline. The main reason is the rise of the sea level after the melting of the ice masses of the last glaciation. Furthermore, seawater intrusion is intensified by the drainage of the coastal marshes, the predominance of west winds and the effects of storm tides.

Besides seawater intrusion, inland groundwater salinisation can be seen at different areas. The upcoming of saltwater is often connected to large groundwater discharge areas in the valleys of the rivers Elbe and Weser. Furthermore, numerous salt deposits pose another cause of the geogenic salinisation. There are some few tens of salt deposits which are subject to constant leaching processes as their upper parts lie less than 400 m below the surface. Due to this process the deeper aquifer in the Elbe River valley has already become salinised on a regional scale.

## Conclusion and recommendations

The natural occurrence and movement of saltwater has been changed by the utilisation of groundwater resources for human uses over the last decades. World-wide, increasing water demands have often lowered groundwater levels and caused saltwater intrusion into aquifers. Recent population increases along coastal zones suggest that demands for groundwater resources will steadily rise in the future. The need for water will pose a number of challenges like the optimal exploitation of fresh groundwater resources and the control of seawater intrusion to engineers and public decision makers.

Reliable monitoring networks for piezometric heads and salinity indicators are indispensable for assessing groundwater salinisation and practising sustainable water management. Observation-well networks and regularly repeated groundwater analysis are necessary for detecting and monitoring saltwater movement in aquifers. It has to be mentioned that rising salt concentrations in pumping wells have to be observed carefully because the flow velocities of saltwater are relatively small in comparison to freshwater. This also means that the reversion, meaning the push back of approaching saltwater bodies, is not possible within a moderate period of time. Numerical groundwater flow and transport models increase the ability to predict the future behaviour of a groundwater system and support the development of an optimal water resource management. Therefore, responses of the hydrogeological system to different scenarios for pumping, land use and climate change could be simulated.

The results of monitoring networks and groundwater modelling, if applicable, should be used for practical recommendations for the long-term protection of the groundwater resources. Potable water abstraction and a sustainable groundwater management are only secured when a saltwater/ freshwater interface is not moving towards supply wells♦