W. Struckmeier

10 A REGIONAL GROUNDWATER SYSTEM ANALYSIS OF THE MUNSTER BASIN, FEDERAL REPUBLIC OF GERMANY

10.1 INTRODUCTION

10.1.1 Location and Geographical Setting

The Münster Basin is a prominent geological structure in north-western Germany. It represents at the same time one of the most prominent and well defined aquifer systems of western Europe.

The Münster Basin covers an area of about 11,000 km^2, its maximum dimensions in an east-west direction being 150 km and 80 km in north-south direction. The basin has a trapezoidal form and is bounded by a distinct surface water divide on three sides (south, east, north-east), while the western margin can be delineated according to the geological setting. The surface generally declines from the south-east where altitudes of up to 500 m are attained, to the north and west where the ground surface occurs between 30 and 50 m above mean sea level. In the centre of the basin, several hilly areas with heights between 100 and 150 m a.s.l. cause a differentiation of the generally flat topography.

The area of the Münster Basin is covered by the upper catchment basins of the rivers Ems (3,700 km^2), Lippe (4,900 km^2), Vechte (650 km^2), the tributaries of the IJssel-Sea (800 km^2), as well as the widely canalized Emscher (1,700 km^2) (see Fig. 10.1.1).

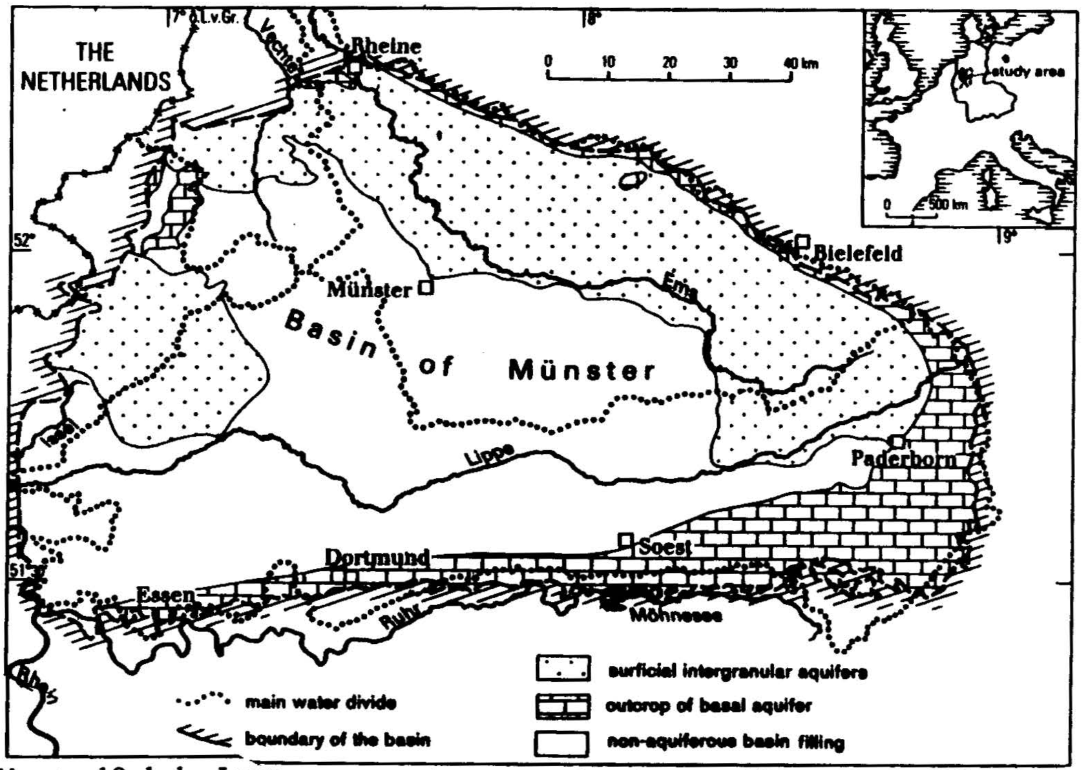

Figure 10.1.1 Location, catchments and major aquifers of the Münster Basin

The climate of the Münster Basin is influenced by humid Atlantic air masses and prevailing westerly winds. The mean annual precipitation varies from 650 mm to more than 1200 mm, the maximum values being located at the south-eastern edge of the basin where the clouds have to cross the eastern mountain ridge. In the centre of the basin, precipitation is fairly even, ranging between 700 and 800 mm/y. The distribution of rainfall throughout the year is rather even, too, with a slight maximum in July/August and a secondary maximum in December. Most of the precipitation is rainfall, snow and mist accounting for less than 20% of the total amount of precipitation. Owing to actual evapotranspiration rates of 450 to 500 mm/y, excess rainfall occurs everywhere in the Münster Basin, and is the basis for groundwater recharge and surface runoff.

The long-term water balance of the Münster Basin, established on the basis of rainfall and runoff data, is presented in Table 10.1.1.

Table 10.1.1 Water balance of the Münster Basin (1959-1976)

	Precipitation (P)	Runoff (R)	Evapotranspiration (P-R)
Winter	379 mm	231 mm	148 mm
Summer	395 mm	98 mm	297 mm
Year	774 mm	329 mm	445 mm

Mean air temperatures for January range between -1°C in the south-eastern uplands and +2°C in the south-western Ruhr region, while in July they are between 15 and 18°C, respectively.
Over the bulk of the area, agriculture, pasture and forestry are the prevailing forms of land use. However, industrial and urban areas are widespread, especially in the south-west between Duisburg and Dortmund (the Ruhr industrial region).

10.1.2 Geological setting

The Münster Basin is an up to 3000 m deep, asymmetric syncline which has its deepest parts in the northwest.

The basement of the basin is made up of Palaeozoic sediments of the Rhenisch Massif which dip gently towards the north; at the western and northern margin of the basin pre-Cretaceous Mesozoic sediments form the basin's base.

The basin fill is mainly Cretaceous and Quaternary. It comprises Lower to Upper Cretaceous in the northern part, while only Upper Cretaceous strata are present in the south where it transgrades onto the Palaeozoic Massif and the Lower Mesozoic with an unconformity. The dip of the Cretaceous beds is 2-5°N in the south, but steep to vertical in the north-east (the Teutoburger Wald ridge). In the north-west, the

Cretaceous crops out in several anticlines, while in the west it is unconformably overlain by clayey Tertiary sediments that increase in thickness towards the west.

10.2 AQUIFER SYSTEM OF THE MÜNSTER BASIN

The aquifer system of the Münster Basin comprises three major hydrogeological units (Fig. 10.2.1) on top of the basement, i.e.

i the basal Cretaceous aquifer unit (Lower Cretaceous to Turonian)

ii the Coniacian and Lower Santonian aquiclude ("Emscher-marl")

iii several coherent or isolated, surficial aquifers of the late Cretaceous and the Quaternary drift cover

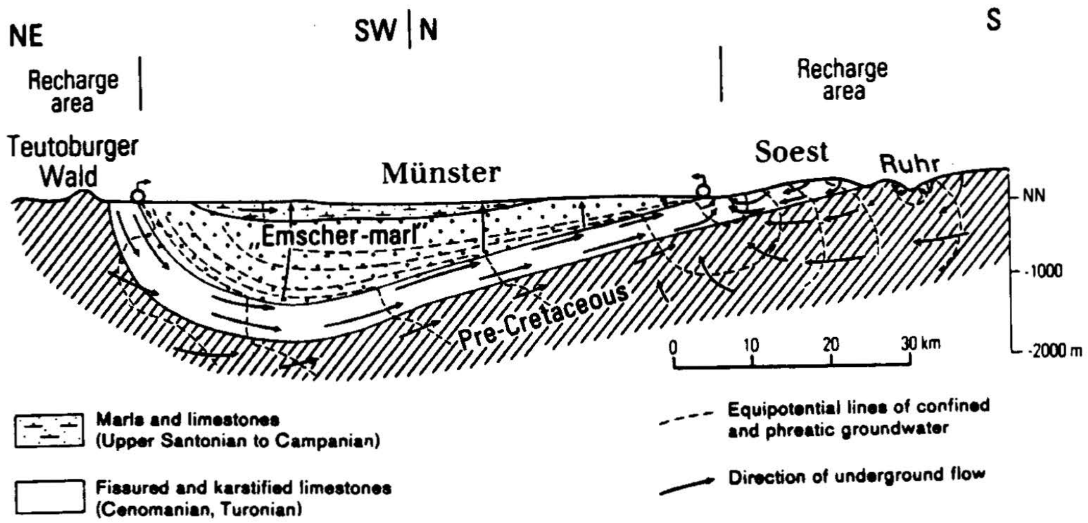

Figure 10.2.1 Schematic hydrogeological cross-section through the Münster Basin (after Karrenberg, 1974)

The Palaeozoic and Lower Mesozoic basement is made up of a varied sequence of schists, greywackes, sandstones, siltstones, claystones, marlstones, limestones and evaporites, several thousand metres thick. It generally forms an aquiclude, with only the sandstone and anhydrite portions being locally aquiferous. Moreover, the salinity of the groundwater encountered in the basement at depths of more than 200-300 m is high, and thermal brines occur at a depth of 1000 m below surface.

The basal Cretaceous aquifer unit comprises, at the northern and eastern margin of the basin, several local, Lower Cretaceous sandstone layers, a few tens to almost 400 m thick. The bulk of this aquifer unit is, however, made up of a limestone sequence of Cenomanian and Turonian age, the thickness of which totals several hundreds to almost 600 m. This unit is present everywhere in and at the margin of the Münster Basin in the form of pure to marly limestones; towards the south-western edge it grades into a sandy facies.

The aquifer unit crops out at the southern margin of the basin, the outcrop extending in width in an eastward direction from several kilometres (at Dortmund) to more than 40 km (the Paderborn Plateau). The wide outcrop is due to the very gentle dip (2-4°C) of both the limestone strata and the land surface. These areas are highly karstified between Dortmund and Paderborn. The outcrops are much narrower on the north-eastern and north-western margins of the basin.

In the marginal outcrop areas, the outer extension of which coincides with the surface water divide of the basin in the south, east and north-east (see Fig. 10.1.1), groundwater is recharged from precipitation and flows towards the centre of the basin. Most of the groundwater is forced, however, to discharge in overflow springs along the contact of the overlying "Emscher-marl" aquiclude. Here, big karstic overflow springs with a total discharge of more than 10 m^3/s are situated. Underneath the "Emscher-marl", the groundwater is confined and further inward becomes saline. The flow decreases largely towards the centre of the basin, however karstification zones may reach far beneath the "Emscher-marl".

The "Emscher-marl" aquiclude consists of an < 800 m thick sequence of marls and marly claystones of the Coniacian and Lower Santonian, which overlie the basal Cretaceous aquifer. It generally separates the basal aquifer from the surficial aquifers and prevents the deep saline groundwater discharging at ground surface. Over large areas in the centre of the basin the aquiclude crops out or is overlain by a thin cover of clayey drift deposits.

A number of subregional or local aquifers are spread over the Münster Basin. They are of late Cretaceous (Santonian, Campanian) and Quaternary age. The Cretaceous sediments occur either in a limestone/marlstone hard rock facies or in a loose sandy-marly facies. The Quaternary aquifers are all sandy and gravelly.

10.3 THE GROUNDWATER SYSTEMS OF THE MÜNSTER BASIN

On the basis of the groundwater system theory of Toth (1963), Freeze and Witherspoon (1967) and further developed by Engelen (1981), several groundwater systems are recognizable in the Münster Basin:

i one large regional groundwater system
ii several subregional groundwater systems, and
iii numerous local groundwater systems

The groundwater systems may comprise part of one aquifer or several adjacent aquifers. Each groundwater system is characterized by its size and hierarchical place, the boundaries, the form and internal flow pattern, the system flux, and its energy conversion capacity.

10.3.1 Regional groundwater system

The regional groundwater system of the Münster Basin is encountered chiefly within the basal Cretaceous aquifer unit. Its boundary is the outcropping contact of the basal aquifer which in many areas coincides with the water divide of the basin. Only in the west is the boundary formed by a thick Tertiary, clayey sequence acting as a barrier for groundwater flow.

The natural base level of discharge of the regional groundwater system is around 50-100 m above mean sea level. However, this natural base level has been lowered considerably by the abstraction of mine water in the < 1200 m deep coal mines of the Ruhr area.

The regional groundwater system of the Münster Basin falls into two subsystems, i.e. a marginal fresh water subsystem and a central saline water subsystem (see Fig. 10.3.1).

The marginal area of the regional groundwater system is characterized by:

- high recharge from precipitation particularly in the karstified outcrop areas in the south-east, causing a high system flux and high discharges of overflow springs at the "Emscher-marl" contact which is the subsystem's natural base level of discharge
- fresh and young groundwaters
- phreatic conditions in the outcrop area grading into confined conditions in the areas covered by the "Emscher-marl"

The characteristics of the central part of the regional groundwater systems are:

- a very low system flux or almost stagnant conditions, but locally increased fluxes owing to mine water pumping or pumped boreholes at spas
- zero or very low recharge (inflow) to the subsystem
- saline and old groundwater, generally increasing with depth in salinity and temperature
- always confined or artesian conditions

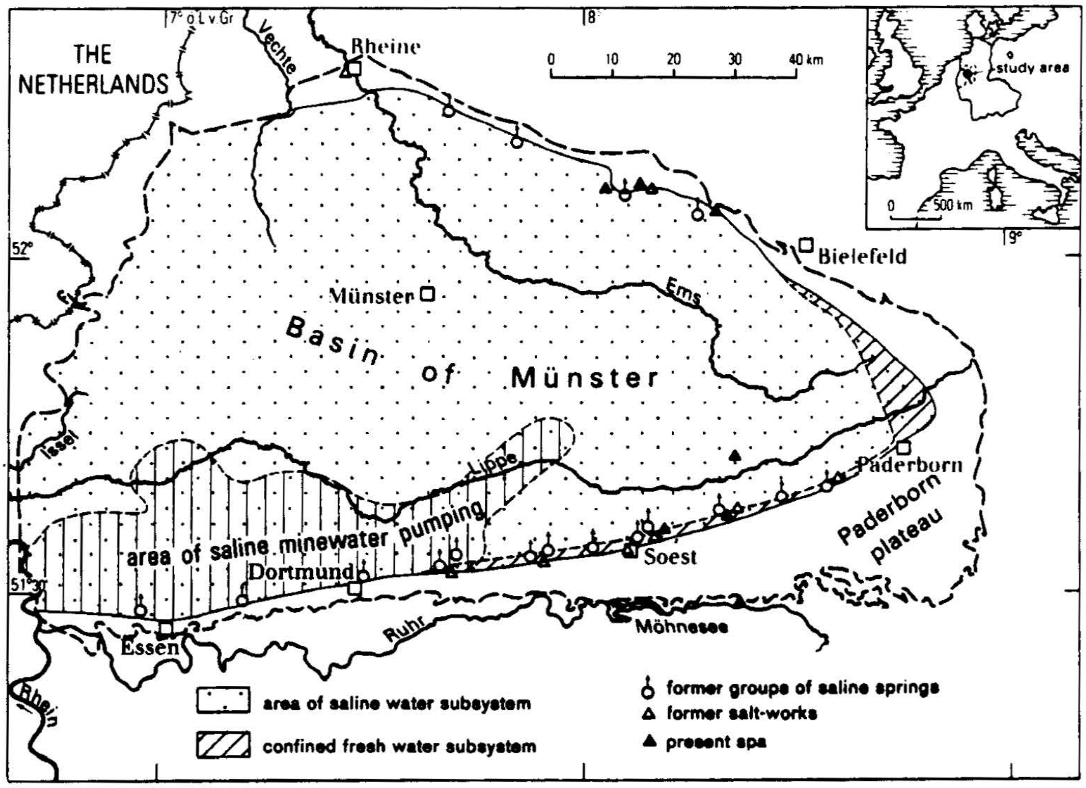

Figure 10.3.1 The regional groundwater subsystems, former saline springs and salt-works, as well as present-day spas of the Münster Basin

Both subsystems are closely interconnected, whereby the fresh, marginal subsystem is superimposed on the saline, central subsystem. The hydraulic equilibrium between the subsystems is changing with time, which is evident in the areas where both subsystems meet. The contact between the basal aquifer and the "Emscher-marl" has long been known as a spring line, where saline and fresh water springs occur, often in close vicinity. The saline springs have been used since historical time for salt production. In a scientific report, Huyssen (1855) mentioned numerous saline springs and salt-works chiefly at the southern and northern margins of the Münster Basin (Fig.10.3.1). Today, some 130 years after Huyssen's observations, the saline springs and saltworks at the "Emscher-marl" contact have disappeared. Only a few spas have "survived" the loss of the saline spring water; they however, have to pump their saline medical water from boreholes that are sunk through the "Emscher-marl" into the basal aquifer. The discharge of the confined or artesian saline waters tapped in the boreholes tends to decrease with time, as does the salinity of the water. However, both discharge and salinity usually increase after periods of rainfall: this trend is due to the pressure conditions in the interface area of both subsystems (Fig. 10.3.2), since deeper parts of the saline subsystem are mobilized by the highly recharged and expanding, overlying fresh subsystem (Michel & Struckmeier, 1985).

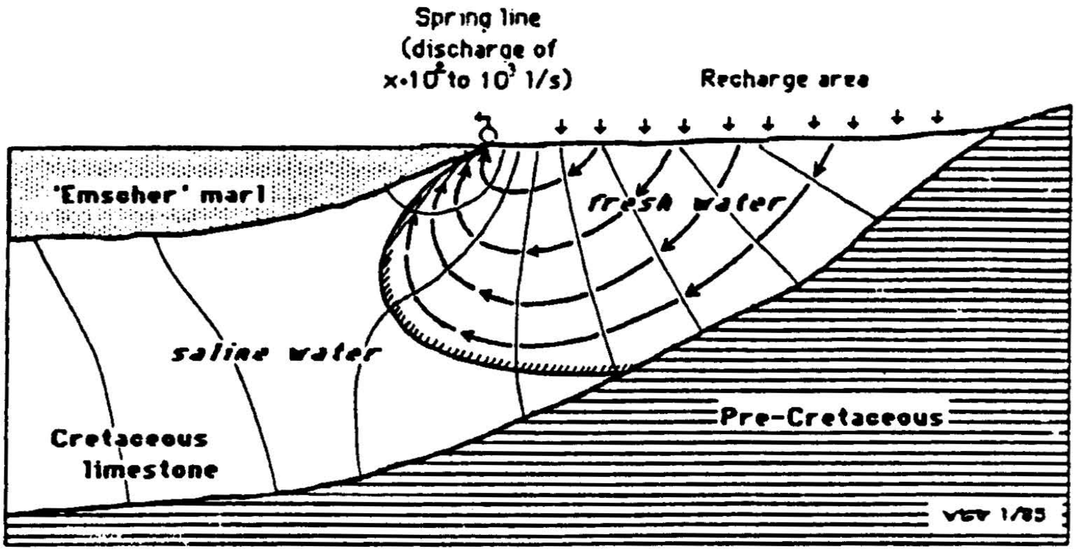

Figure 10.3.2 Schematic cross-section of the outcrop area of the basal Cretaceous aquifer with fresh and saline subsystems (vertical scale 5 times exaggerated)

From the aforementioned it is obvious that in this area the former natural base level of discharge of the saline subsystem at aprox. 90-100 m a.m.s.l. (which largely coincides with the "Emscher-marl" contact) is no longer effective. Factors responsible for the lowering of this natural base level are, in addition to the very little or absent inflow of the saline subsystem:

i a natural expansion of the active marginal fresh subsystem, and

ii an artificial weakening of the saline subsystem by the mine water pumping in the Ruhr area and spa water abstraction

While the "Emscher-marl" contact is usually assumed to mark also the contact zone between the fresh and saline subsystems, fresh groundwater has been encountered in the very south-eastern part of the Münster Basin, beneath the "Emscher-marl" aquiclude (Hederer, 1977; Schneider & Schneider, 1977). Here, the confined fresh subsystem occupies the karstic basal aquifer in an area extending several kilometres west of the "Emscher-marl" contact (Fig. 10.3.1). The interface zone between both subsystems follows approximately the +100 to +110 m isopotential line of the karst groundwater, thus being above the actual discharge base level of the saline subsystem.

The presence of a fresh water subsystem beneath the "Emscher-marl" is mainly due to a natural expansion of this subsystem, as evidenced by the rather old ages of the groundwater encountered (about 10,000 to 20,000 years according to Geyh & Michel, 1981). The deep karst groundwater is increasingly used for water supply in the Paderborn and Bielefeld area, but no harmful influence from the central saline subsystem is expected as long as pressure heads of the karst groundwater are kept higher than the highest actual base level of discharge of the saline subsystem.

The pumping of the mine water in the pits of the Ruhr coal district at a depth of several hundred metres withdraws large amounts of groundwater from a very deep base level in the saline subsystem. The quantity of saline water and brines pumped for more than 100 years exceeds 10^{10} m^3 (Semmler, 1960). According to rough calculations this pumping could have caused a progression of the interface between the fresh and saline subsystems in the order of several metres to 1 km in the marginal parts of the basal aquifer. Consequently, this human industrial impact may have resulted in the cessation of the flowing saline springs at the "Emscher-marl" contact, owing to the progression of the interface beneath the "Emscher-marl" aquiclude.

Further isotope investigations are required, however, to confirm the conceptual ideas of the regional groundwater systems as outlined above.

10.3.2 Subregional and local groundwater systems of the Münster Basin

Several subregional groundwater systems within the Münster Basin are chiefly confined to the aquiferous facies of the uppermost Cretaceous (Santonian, Campanian) and Quaternary which form significant aquifers in the western and eastern parts of the basin. They all lie on top of the "Emscher-marl" aquiclude and are usually separated from the regional aquifer system.

A subregional groundwater system is encountered in the fissured limestones, grits, and marlstones which underlie the hilly areas of the Baumberge and Schöppinger Berg in the north-western Münster Basin north of Coesfeld. This area is the main watershed point in the centre of the basin, where the drainage divides of the major river catchments diverge. The groundwater flows radially and is discharged in numerous springs at the margin of the system where groundwater flow is reduced owing to the thinning out of the limestone beds.

A larger groundwater system is developed in the Santonian sand facies of Haltern in the western part of the Münster Basin. Here, an interstitial aquifer covering an area of approx. 770 km^2 and attaining a thickness of more than 200 m (on average 100 m) contains one of the most exploited groundwater reservoirs of Northrhine-Westfalia. The total volume of the system is assessed to reach some 17 . 10^9 m^3, the effective porosity amounting to 22% (Hilden, 1975). The mean annual recharge is calculated at 190 million m^3, so the ratio of recharge to the total reserve is about 1%, i.e. the total reserve is recharged in about 100 years. The mean annual abstraction totals some 100 million m^3 of groundwater. However, despite the fact that this volume is only a little more than half of the calculated recharge, the water levels in some piezometers have tended to decline since 1970, supposedly as a consequence of the drawdown of the big water works in the Lippe valley.

Several other subregional groundwater systems are located in the foreland of the Teutoburger Wald ridge in the northeastern Münster Basin. They are developed in the large glacial outwash plain and the system of glacial channels between the River Ems and the Teutoburger Wald. The thickness of the sandy deposits which are underlain by the "Emscher-marl" aquiclude, is several tens of metres, as a rule. Owing to this shallow depth, numerous groundwater systems of lower order and size have developed which discharge into the River Ems and its tributaries. Their flux is, however, high since recharge rates in the sands in the order of 300 mm/y are not uncommon. At the south-eastern edge (the Senne) they overlie directly the marginal freshwater subsystem of the basal aquifer, from where they supposedly receive an additional inflow at the "Emscher-marl" contact.
Several water supplies are already developing the groundwater of the Quaternary systems, and additional exploitation possibilities are being investigated.

10.4 CONCLUSIONS

The method of groundwater system analysis that has been applied to the Münster Basin has revealed the basin-wide relations in the hydrogeological conditions. It is evident that the changes in the groundwater conditions which have occurred over the past century can be reasonably explained by interpreting all data in the framework of an overall regional groundwater system consisting of a marginal, expanding, freshwater subsystem and a central, shrinking, saline water subsystem. The natural expansion of the fresh subsystem driven by a high recharge is additionally favoured by the abstraction of saline mine water in the Ruhr district and of saline medical water in the spas.

The subregional and local groundwater systems are in general not affected by these impacts, since they are separated by a thick regional aquiclude (the "Emscher-marl") from the regional groundwater system.

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